European Green Dimensions: Fundamental, Applied, and Industrial Aspects

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The monograph is devoted to problems European Green Course: opportunities and consequences for Ukraine; European Green Course initiatives; Roadmap for Ukraine's participation in the European Green Course; Overcoming climate change in the framework of the European Green Course; Adaptation to the effects of climate change; Green business: new market opportunities and innovative products; Energy efficiency, renewable energy; Conservation of biodiversity as a condition for the sustainability of ecosystems; Water resources management: water quality, wastewater treatment; Protection of atmospheric air; Environmental control and monitoring systems; Industrial and household waste management.
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CONTENT

FOREWORD

The imperative for a sustainable future has never been more pronounced. Across the globe, societies grapple with the intertwined challenges of environmental degradation, climate change, and the urgent need for a paradigm shift in our economic and social models. At the heart of Europe's ambitious response to these critical issues lies the European Green Deal, a comprehensive strategy aimed at making the continent climate-neutral by 2050. This landmark initiative transcends mere environmental policy; it represents a fundamental re-imagining of Europe's growth model, encompassing energy, industry, agriculture, and societal well-being.

It is within this dynamic and transformative context that this collective international monograph, «European Green Dimensions: Fundamental, Applied, and Industrial Aspects» takes its crucial place. This volume emerges as a timely and vital contribution to the growing body of literature dedicated to understanding, analyzing, and ultimately facilitating the transition towards a greener and more sustainable Europe. Its publication is made possible through the generous support of the Project «EUROPEAN GREEN DIMENSIONS» 101081525−JM EUGD−ERASMUS-JMO-2022-HEI-TCH-RSCH, a collaborative endeavor uniting the expertise and resources of Petro Mohyla Black Sea National University (Ukraine), the University of the West of England (United Kingdom), and the University of Presov (Slovakia). This transnational partnership underscores the inherent internationality of the green transition and the necessity of shared knowledge and collaborative efforts in addressing global environmental challenges.

The genesis of this monograph is deeply rooted in the recognition of Ukraine's pivotal position within the European landscape and the profound implications of the European Green Deal for its future development. As a nation aspiring towards closer integration with the European Union, Ukraine stands at a critical juncture. The opportunities presented by the Green Deal – from new economic pathways and technological advancements to enhanced environmental standards and improved quality of life – are immense. However, so too are the challenges associated with adapting to new regulatory frameworks, transforming existing industries, and embracing sustainable practices across all sectors of its economy and society.

This monograph seeks to provide a multifaceted exploration of the European Green Deal and its ramifications, with a particular focus on the opportunities and consequences for Ukraine. It delves into the fundamental principles underpinning the Green Deal, examines its key initiatives across various sectors, and proposes a potential roadmap for Ukraine's effective participation in this transformative agenda. By bringing together diverse perspectives from leading scholars, researchers, and practitioners across Europe, this volume offers a comprehensive and nuanced understanding of the complexities involved.

The scope of this monograph is intentionally broad, reflecting the all-encompassing nature of the European Green Deal itself. It navigates a range of critical themes that are central to achieving a sustainable future.

The monograph is devoted to topics: European Green Course: opportunities and consequences for Ukraine; European Green Course initiatives; Roadmap for Ukraine's participation in the European Green Course; Overcoming climate change in the framework of the European Green Course; Adaptation to the effects of climate change; Green business: new market opportunities and innovative products; Energy efficiency, renewable energy; Conservation of biodiversity as a condition for the sustainability of ecosystems; Water resources management: water quality, wastewater treatment; Protection of atmospheric air; Environmental control and monitoring systems; Industrial and household waste management.

Through the collective wisdom and diverse expertise of its contributors, this monograph aims to serve as a valuable resource for policymakers, researchers, businesses, educators, and all stakeholders interested in understanding and contributing to the European green transition, with a particular emphasis on Ukraine's journey within this transformative process. It is our sincere hope that the insights and analyses presented in these pages will contribute to informed decision-making, foster collaboration, and ultimately accelerate the realization of a sustainable and prosperous future for Europe and beyond.

The successful completion of this monograph is a testament to the dedication and collaborative spirit of all involved. We extend our sincere gratitude to the authors for their insightful contributions, the reviewers for their rigorous assessments, and the project team for their unwavering support. We are confident that «European Green Dimensions: Fundamental, Applied, and Industrial Aspects» will serve as a significant contribution to the ongoing dialogue on sustainable development and the crucial role of the European Green Deal in shaping our collective future.

Professor Olena Mitryasova

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PREDICTING THE LEVEL OF PM2.5 AIR POLLUTION USING ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING ALGORITHMS

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ABSTRACT

Air pollution is one of the main environmental problems of our time, which has a serious impact on human health and the environment. This paper presents the development of an intelligent air quality forecasting system based on machine learning algorithms. The purpose of this paper is to analyse existing approaches to predicting PM2.5 (Particulate Matter 2.5) air pollution levels using machine learning algorithms, as well as to assess the possibilities and prospects of their use to improve the efficiency of environmental monitoring and safety. The model, which uses the Random Forest Regression method, predicts the level of air pollution, in particular the concentration of PM2.5, taking into account time parameters (year, month, day, hour). The main sources of PM2.5 pollution and their impact on human health, including short-term and long-term effects associated with high concentrations of these particles, are considered. Comparison of the forecasting results on training and test data showed high accuracy of the model, in particular 98% on training and 91% on test data. The main advantages of the system are highlighted: increased forecast accuracy, adaptability to seasonal and daily fluctuations, the ability to process large amounts of data in real time, and the ability to integrate into smart cities to improve environmental monitoring. The results of the work have prospects for practical use in environmental research and monitoring of air pollution in urban areas.

Keywords: air quality forecasts, PM2.5, machine learning, Random Forest Regression, environmental monitoring

INTRODUCTION

Air quality is one of the key environmental issues facing the world today. Air pollution, in particular fine PM2.5 (Particulate Matter 2.5), has a serious impact on human health, the environment and the climate. PM2.5 particles up to 2.5 micrometres in diameter can penetrate deep into the lungs and enter the circulatory system, increasing the risk of developing serious diseases such as lung cancer, chronic obstructive pulmonary disease, cardiovascular disease, and cognitive impairment. According to the World Health Organisation (WHO), about 9 out of 10 people in the world breathe polluted air, and air pollution is one of the main health risks, particularly for pregnant women and children.

In the context of rapid urbanisation, rising transport emissions, industrialisation and climate change, air pollution remains one of the main threats to public health. Traditional methods of air quality monitoring are often ineffective due to limitations in data collection and the ability to predict changes over time. Therefore, there is an urgent need to integrate modern technologies to predict the level of pollution and respond to potentially dangerous situations in a timely manner.

One promising approach to solving this problem is to use artificial intelligence (AI) and machine learning algorithms to predict air pollution levels. These technologies are able to analyse large amounts of data, identify hidden patterns and make predictions that allow not only to assess the current state of the air but also to predict its changes in the future. AI-powered systems allow for more accurate PM2.5 estimates, adaptation of forecasts to seasonal and daily fluctuations, and take into account the impact of various environmental and anthropogenic factors. From the perspective of environmental monitoring and safety, the use of intelligent systems allows for continuous monitoring of the air, timely detection of rising pollution levels and warning of potential hazards. This approach is particularly important for smart cities, where the integration of sensor technologies and predictive models allows for effective environmental management and prompt response to changes in air quality.

The use of machine learning techniques, including algorithms such as Random Forest, XGBoost and other regression models, can significantly improve the accuracy of air pollution forecasts. In addition, such a system reduces the cost of traditional monitoring methods and ensures continuous and scalable data collection, which contributes to more effective real-time environmental safety management.

The purpose of this paper is to analyse existing approaches to predicting PM2.5 air pollution levels using machine learning algorithms, and to assess the possibilities and prospects of their use to improve the efficiency of environmental monitoring and safety.

LITERATURE REVIEW

Air quality is a key factor affecting human health and the environment. Air pollution has both short- and long-term effects that affect millions of people around the world, causing respiratory illnesses, allergic reactions and cardiovascular problems [1, 2]. In addition, polluted air negatively affects ecosystems, contributes to climate change and reduces the quality of life in urban and industrial areas. Air pollution, in particular the concentration of fine particulate matter PM2.5, is one of the major challenges facing the modern environment and public health [3; 4]. Emissions from transport, industry, power plants and agriculture contribute significantly to air pollution. According to the World Health Organisation (WHO), polluted air kills more than seven million people each year, with PM2.5 being the main factor that increases the risk of cardiovascular disease, lung cancer and chronic respiratory diseases [5].

PM2.5 is a fine particle with a diameter of up to 2.5 micrometres that is found in the air. Due to their small size, these particles can penetrate deep into the lungs and enter the circulatory system, making them one of the most dangerous air pollutants [6-8].

The main sources of PM2.5 pollution [1; 3; 9]:

- Emissions from transport (cars, aviation, railways).
- Industrial production (thermal power plants, cement plants, metallurgy).
- Domestic fuel combustion (wood, coal, biomass).

- Forest fires and dust storms.
- Secondary particles formed as a result of chemical reactions in the atmosphere.

Monitoring of PM2.5 is critical because high concentrations of these particles can cause serious health problems with both short- and long-term effects [9].

Short-term effects:

- Respiratory system problems - mucosal irritation, cough, shortness of breath.
- Exacerbation of chronic diseases - asthma, chronic bronchitis.
- Impact on the cardiovascular system - increased risk of heart attack and stroke.

Long-term effects:

- Reduced life expectancy – prolonged exposure to PM2.5 leads to the development of lung cancer, heart disease, atherosclerosis.
- Decreased cognitive function – studies show that constant exposure to PM2.5 can contribute to the development of Alzheimer's disease.
- Risks for pregnant women and children - increased likelihood of pregnancy complications, impaired development of the nervous system in children.

According to the WHO [5], 9 out of 10 people in the world breathe polluted air, and PM2.5 is a major risk factor for chronic diseases. Stationary monitoring stations have been used for decades to assess air quality, but they have a number of limitations [10; 11]. Firstly, such stations are located only in certain points of cities and regions, which does not provide full spatial coverage. This is particularly critical in areas with high traffic volumes or near industrial plants, where pollution levels can fluctuate significantly [12−14]. Secondly, fixed systems are expensive to install and maintain, which limits their availability in small towns and developing countries. Third, traditional methods are often based on analysing air samples with a long-time lag (hours to days), which makes it difficult to respond to environmental threats in a timely manner (Table 1).

In addition, many government monitoring systems are not integrated with other analytical platforms, such as transport or meteorological systems [13; 15]. This makes it impossible to effectively analyse the relationship between air quality, traffic, weather conditions and urban planning. Many platforms also do not provide data in a citizen-friendly format, making it difficult to assess health risks.

Predicting air pollution levels is a complex task, as its dynamics is influenced by a large number of variables: meteorological conditions, industrial emissions, traffic flow, terrain, etc. Traditional statistical models and physical simulations do not always provide sufficient accuracy due to the complexity of computations and the limited amount of input data [16; 17].

Artificial intelligence (AI) and machine learning (ML) methods have made significant progress in this area, allowing for the processing of large amounts of data in real time and high accuracy in predicting air pollution levels [12]. The use of deep neural networks allows us to identify hidden patterns in changes in pollutant concentrations, which was difficult to do using classical approaches [13]. By processing data from thousands of IoT sensors, satellite images, and meteorological stations, we can quickly identify sources of pollution and develop effective measures to reduce it (Table 2).

Table 1 − Comparison of traditional machine learning methods

Method	**Linear and polynomial regression**	**Support Vector Machine**	**Random Forest**
The principle of operation	It is used to predict the concentration of pollutants based on historical data.	SVM finds the optimal boundaries between classes (e.g., 'clean air' vs. 'polluted air').	It combines several decision trees, each analysing a specific aspect of pollution.
Example of usage	Linear regression can predict PM2.5 levels based on previous measurements and weather conditions.	Predicting the probability of exceeding the permissible level of pollution.	Prediction of PM2.5 concentrations using data on wind, humidity, and previous pollution levels.
Advantages	Determines the relationship between the level of pollution and other factors (temperature, wind, humidity).	Works well in tasks of classifying pollution levels	Handles non-linear dependencies well. Can work with missing data.
Disadvantages	Limited accuracy, poor performance in conditions of sudden changes in parameters.	High computing costs on large data sets.	It is difficult to interpret the results (why the model made a certain prediction).

Table 2 − Deep learning in air quality forecasting

Network	**The principle of operation**	**Example of usage**	**Advantages**	**Disadvantages**
Artificial Neural Networks, (ANN)	A network of layers of neurons processes large amounts of data, searching for complex relationships. Input data can include satellite images, sensor data, and weather reports.	Predicting changes in air quality 24 hours before they occur. Determining the impact of industrial emissions on long-term changes in air quality.	High accuracy with large amounts of data. Works well with non-linear relationships between factors.	Requires significant computing resources.
Recurrent neural networks (RNN) and Long Short-Term Memory (LSTM)	Analyse data in a time context. Take into account the impact of previous values on future forecasts.	Long-term forecasting of pollution levels based on trends in recent months/years.	They take into account the influence of previous events better than conventional neural networks. Good for predicting time and serial data.	Complexity of training (large number of parameters). Requires significant computing power
Convolutional neural networks (CNN)	They are used to analyse images (for example, satellite images of the atmosphere).	Analysis of NASA and ESA satellite images to identify regions with elevated levels of NO_2 and SO_2.	Effective detection of pollution on a large scale. Ability to analyse changes in air quality over time.	A large number of calculations. Dependence on the quality of satellite images.

Recently, hybrid AI models that combine several approaches for more accurate forecasting have become popular (Table 3).

Table 3 − Hybrid models (combined AI methods)

Method	**The principle of operation**	**Example of usage**
Random Forest + LSTM	Random Forest is used to process instantaneous changes in factors (temperature, wind, emissions). LSTM analyses long-term trends.	Forecasting air quality for a week in advance.
CNN + LSTM for analysing satellite images	CNN analyses images (identifies areas with high levels of pollution). LSTM predicts changes based on historical data.	Detecting the spread of smoke from forest fires.

In addition to more accurate forecasting, artificial intelligence offers a number of other benefits. For example, models can send alerts to users based on their location and health status. This allows people with chronic diseases (e.g., asthma) to receive timely information about elevated levels of hazardous particles (PM2.5) in their region [14; 15]. In addition, AI helps optimize environmental policy by analysing the impact of industrial and transportation emissions and suggesting measures to reduce them, such as changes in the transportation system or increasing the number of green spaces.

In this regard, an important task is to develop and implement effective methods for monitoring and forecasting air pollution levels, in particular PM2.5 levels. Traditional methods of measuring air quality, such as stationary monitoring stations, mostly only provide current pollution indicators, which is insufficient to respond to changes in the state of the air in a timely manner [12-14]. One of the most important problems of such methods is the limitation in space and time, as monitoring is carried out only at certain points, which does not give a complete picture of the situation in the region or country as a whole [17].

To solve this problem, researchers are increasingly turning to the latest technologies, including artificial intelligence and machine learning. The use of machine learning algorithms to predict PM2.5 levels allows for the automatic processing of large amounts of data from various sources and accurate modeling of the dynamics of air quality changes. In [18-20] has been demonstrated that the use of models such as linear regression, decision trees, and ensemble modeling methods (e.g., Random Forest and XGBoost) allows for high accuracy in predicting PM2.5 levels, taking into account various factors such as time of day, weather conditions, urbanization, and emissions from pollution sources.

Several studies have focused on predicting air pollution levels using artificial intelligence and machine learning algorithms. In the work [21] proposed an agent-based traffic regulation and recommendation system to control on-road air quality by modeling road infrastructure and managing traffic flow based on pollution levels. Zhang et. al. [22] utilized extreme learning machines to predict air pollutant concentrations in Hong Kong, showing improved performance quantitatively and qualitatively. In the work [23] developed prediction models for air pollution in Tehran based on PM10 and PM2.5 pollution concentrations, highlighting the significant contribution of these pollutants to air pollution in the city. Authors [24] examined the association between prolonged exposure to air pollution and SARS-CoV-2 mortality and infectivity in Italy, emphasizing the impact of air pollution on public health. In the work [25] presented an attentive multi-task prediction model for atmospheric particulate matter, demonstrating superior accuracy performance compared to other models. Authors [26] analysed the impact of weather and air pollution parameters on COVID-19 spread in India using a gradient boosting machine algorithm, incorporating PM2.5 and PM10 as input parameters.

Authors [27] constructed a land use regression model optimized with random forest to predict the spatial distribution of PM2.5 pollution in Fenwei Plain, providing valuable insights for air pollution control strategies. [28] proposed using decision tree-based machine learning for air quality prediction, focusing on data mining techniques. [29] reviewed air pollution forecasting based on wireless communications and suggested implementing an intelligent system using backpropagation neural networks for accurate prediction of polluting gases in the atmosphere. Overall, these studies demonstrate the potential of artificial intelligence and machine learning algorithms in predicting PM2.5 air pollution levels and providing valuable insights for air quality control and public health.

Artificial intelligence (AI) plays an important role in modern environmental monitoring, helping to analyse large amounts of data, identify patterns, and make accurate predictions. Various countries and companies are implementing AI solutions to predict pollution levels and improve air quality.

One example is SmartAQNet in Germany, an AI system that predicts pollution levels using data from government environmental stations, IoT sensors, satellite images, and weather stations. The use of machine learning (ML) to analyse pollution factors and recurrent neural networks (RNN) to predict pollution levels has increased the accuracy of forecasts by 40% compared to traditional models. As a result, the system helps governments make decisions on traffic restrictions during periods of heavy pollution.

Google has developed the Air View initiative, where Google Street View cars are equipped with air quality sensors. The data is transmitted to a cloud platform where it is analysed using deep learning (DL) and geospatial AI, which allows determining the dependence of pollution on traffic, weather conditions, and time of year. As a result, detailed pollution maps were created for London, Copenhagen, and San Francisco, which are used to optimize urban planning.

China, where smog is a serious environmental problem, is actively using AI to combat pollution. IBM, in cooperation with the government, has developed the Green Horizon system that uses Random Forest and deep learning to analyse environmental data. AI models predict the impact of weather conditions on pollution levels, which allows predicting smog in 72 hours with an accuracy of 80% and optimizing environmental strategies of cities.

Clarity Movement, a startup, is implementing miniature IoT sensors and AI to predict air quality in real time. The use of neural networks and edge computing allows for the acquisition of operational data. Sensors have been installed in San Francisco, Paris, and other cities, and citizens can receive information through mobile applications.

NASA uses AI to analyse satellite data (Sentinel-5P, Aqua, Terra) to detect global pollution. Convolutional Neural Networks (CNN) helps to analyse satellite images, identify sources of CO_2 and NO_2 emissions in industrial regions, and develop models to combat climate change.

BreezoMeter has created an AI application that predicts air quality in specific areas and provides recommendations to users. Using Big Data from sensors, weather stations, and satellites and Predictive Analytics methods, the app has become popular in the US, EU, and Japan, and is being integrated into Smart Cities programs.

Despite significant progress, the introduction of AI in environmental monitoring faces challenges:

1. Limited amount of quality data. Many regions do not have an extensive network of environmental sensors, which makes it difficult to train AI models. The solution may be to use Data Fusion methods and create open environmental databases.

2. High implementation costs. The creation of public-private partnerships (PPP) and the use of cloud-based AI solutions will help to reduce costs.

3. Difficulty in explaining AI solutions (Black Box Problem). The use of Explainable AI (XAI) will allow to explain forecast models more clearly.

4. Forecast errors due to climatic and anthropogenic factors. Combining AI models with physical models of atmospheric pollution will improve forecast accuracy.

5. Cybersecurity and privacy. Data encryption and decentralization of information collection, in particular via blockchain, will ensure the protection of environmental AI systems.

In the coming years, the development of AI will significantly change the approach to air quality monitoring:

1. Expanding the network of IoT sensors in cities and transport, which will provide dynamic real-time mapping of pollution via 5G.

2. Analysis of satellite images using AI to identify sources of pollution.

3. Integration of AI into Smart Cities, automatic regulation of the urban environment, and creation of digital twins of cities to predict the environmental situation.

4. Mobile applications with AI tools will help people choose the best routes for walking taking into account the level of pollution.

5. Predicting environmental crises such as smog, fires, and accidental emissions will allow cities and businesses to prepare in advance.

6. Using blockchain to create transparent environmental databases will increase the credibility of environmental monitoring.

METHODS AND EXPERIMENTAL PROCEDURES

To build the forecasting model, we used data on the concentration of PM2.5 particulate matter, as well as time features (year, month, day, hour), which are key factors in determining the level of air pollution. The input data were obtained from open environmental platforms, including NASA Earth Data, Air Quality Open Data Platform, and local air monitoring stations.

Prediction algorithms. Several machine learning methods were used to model PM2.5 levels in order to select the most effective approach. Among the algorithms considered:

- Linear Regression is a basic method that allows to estimate the linear relationship between time parameters and pollutant concentration.

- Random Forest Regression is an ensemble method that uses a set of decision trees to improve the accuracy of forecasts and take into account nonlinear dependencies in the data.

- XGBoost is a gradient boosting algorithm that provides high performance through optimized learning and regularization processes.

The quality of the models was assessed using the MAE (Mean Absolute Error), RMSE (Root Mean Squared Error), and R^2 (coefficient of determination) metrics, which allow to determine the accuracy and consistency of forecasts.

Software implementation. A web application was developed to provide interactive access to the forecast model. The frontend is based on *ReactJS* and *TailwindCSS*, which provides a user-friendly interface for entering data and receiving forecasts in real time. The backend is implemented using *FastAPI*, which provides fast request processing. The data exchange between the client and the server is carried out via *Axios*, which allows users to pass parameters to the machine learning model and receive forecasting results.

Experimental validation. To validate the developed system, we conducted testing using training and test data sets. The results of different models and their comparison with real PM2.5 values allowed us to determine the optimal algorithm for forecasting.

THE RESEARCH RESULTS AND DISCUSSIONS

The project's frontend was built using the ReactJS and TailwindCSS libraries. It allows users to make air quality predictions by sending input data to a machine learning model through the api backend from the frontend (Fig. 1).

The backend of this project was created using FastAPI. After the user clicks on the "Submit" button in the frontend, a query is sent to FastAPI via axios, and then FastAPI sends this query to the machine learning model to make a prediction.

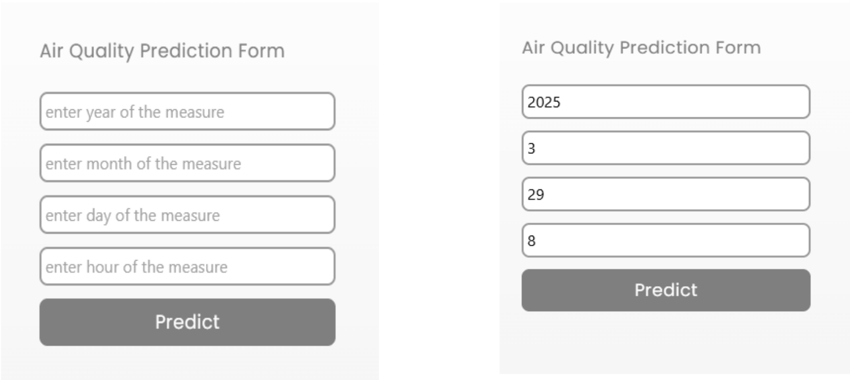

Fig. 1. Screenshots of the AirSense AI web application for PM2.5 forecasting.

Our proposed intelligent air quality forecasting system based on machine learning algorithms demonstrates high efficiency in predicting PM2.5 concentration levels, taking into account time parameters (year, month, day, hour) (Fig. 2). Thanks to the analysis of large amounts of historical data and modern AI methods, such as neural networks, gradient boosting, and recurrent models (LSTM, GRU), the system is able to predict changes in air pollution levels with high accuracy. The accuracy of the model has been studied: on training data, it is about 98%, and on test data, it is about 91%.

Fig. 2. Screenshots of using the web application to predict the level of PM2.5 concentration, taking into account time parameters (year, month, day, hour).

The developed intelligent system AirSense AI predicts the level of air pollution, in particular the concentration of PM2.5, based on time parameters. Comparison of the effectiveness of three machine learning algorithms (Linear Regression, Random Forest Regression, and K Neighbors Regression) showed that Random Forest Regression has the highest prediction accuracy (Table 4).

Table 4 − Comparison of the accuracy of training and test data of Linear Regression, Random Forest Regression, and K Neighbors Regression models.

Model Name	Training Accuracy	Testing Accuracy
Linear Regression	0.051812	0.042505
Random Forest Regression	0.987630	0.916692
K Neighbors Regression	0.940275	0.862848

The results show that the Random Forest Regression method provides better consistency of forecasts compared to linear regression, which cannot fully reflect nonlinear dependencies.

A literature review showed that similar studies have already been conducted using other approaches [30]. Other studies, such as [31], used traditional statistical methods (ARIMA, SARIMA), but they had a limited ability to adapt to dynamic changes.

The use of Random Forest Regression in this study demonstrates an advantage in prediction accuracy over time series and even deep learning methods under certain conditions.

The proposed intelligent air quality forecasting system based on machine learning algorithms has a number of significant advantages that ensure its effectiveness compared to traditional methods of predicting air pollution levels.

1. *Increased accuracy of forecasts*. The use of machine learning algorithms allows the model to identify hidden dependencies between different factors that affect changes in PM2.5 levels, which is not always possible using classical statistical methods. This ensures high accuracy of forecasts, in particular in cases where traditional approaches cannot adequately reflect the complex relationships between different pollution parameters.

2. *Adaptability to seasonal and daily fluctuations*. One of the key advantages of this system is its ability to adapt forecasts to seasonal and daily changes. The model takes into account cyclical fluctuations in air quality, which depends on the time of year, weather conditions, and the level of urbanization, allowing for more accurate and up-to-date forecasts in different time periods.

3. *Fast processing of large amounts of data.* Thanks to integration with IoT sensors, satellite data and weather stations, the system is able to process large amounts of information in real time, which allows for prompt access to the latest data on the state of the air. This approach significantly improves the ability to monitor pollution and allows for timely response to changes in air quality.

4. P*ossibility of integration into the Smart Cities system*. The forecasting model can be integrated into existing urban environmental monitoring systems, which facilitates a rapid response to rising pollution levels. This creates opportunities for the development of smart cities, where the use of highly accurate forecasts can effectively manage the level of pollution and optimize urban environmental policies.

Despite the high accuracy of the forecasts, our study has a number of limitations that should be taken into account when interpreting the results. First, the limitations of the input parameters: the model predicts PM2.5 levels only based on temporal factors, which does not take into account other important environmental variables such as temperature, humidity, or wind, which can also significantly affect pollutant concentrations. In this regard, it would be advisable to add additional parameters to improve the model's accuracy.

Second, the model is based on data from only a few local monitoring stations, which may limit its generalizability to other regions with different air pollution conditions. Additionally, sensor imperfections may affect the accuracy of the data obtained, especially in the context of variable sensor quality and data collection methodology.

Several directions are suggested for further improvement of the forecasting system. First, the set of input parameters could be expanded to include meteorological data (temperature, humidity, wind speed), as well as data on traffic and industrial emissions, which would improve the accuracy of forecasts. Second, it is worth exploring the use of more sophisticated models that can better handle long-term dependencies in the data.

Integration of this model into environmental monitoring systems within Smart Cities can significantly improve the rapid response to the growing level of air pollution, which is important for public health.

CONCLUSION

As part of the study, a prognostic model was developed to determine the level of air pollution by fine particulate matter PM2.5. The model, built using the Random Forest Regression method, demonstrated high accuracy of predictions, reaching a value of 91.67% on the test data. These results indicate the high efficiency of using ensemble machine learning methods to predict environmental parameters that determine air quality.

A comparative analysis of three different machine learning methods: linear regression, Random Forest Regression, and K Neighbors Regression, showed that Random Forest Regression is the most effective method for modelling PM2.5 concentrations, as it is able to take into account nonlinear dependencies and provides more stable results. This confirms the advantages of using ensemble methods when predicting complex environmental parameters.

One of the main limitations of the studied models is the use of only temporal features as input parameters for predicting the level of pollution. In view of this, a promising area for further research is the integration of additional environmental factors such as air temperature, humidity, traffic intensity, and emissions from industrial enterprises. Taking these parameters into account will significantly improve the accuracy of forecasts and provide a more comprehensive approach to air quality monitoring.

The developed model has significant potential for practical use in environmental monitoring, in particular in integration with smart city systems and environmental platforms. This will allow local governments and public organizations to detect increases in air pollution in a timely manner, taking the necessary measures to minimize the negative consequences for public health.

Further research should be aimed at improving the existing model by using more sophisticated algorithms, which will allow for more efficient handling of large amounts of data and improved forecasting in mixed and unpredictable environmental situations. In addition, an important area is to test the model in different regions with different air pollution conditions, which will increase the versatility and adaptability of the developed system.

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DIFFERENCE BETWEEN SUSTAINABILITY LAW AND THE LAW OF ENVIRONMENTAL SUSTAINABILITY IN ENVIRONMENTAL DISPUTE RESOLUTION

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ABSTRACT

This work provides the concept of sustainability law as a new, more balanced approach to environmental and climate law. It is shown that in Ukraine, as in other countries, there is a situation where each of the scientists, experts, and representatives of public associations involved in the work of ensuring sustainable development focuses primarily on those goals of sustainable development that are directly related to their expertise, ignoring other purposes. This leads to conflicts, including socio-political and legal ones. The positive side of such opposition of expert groups is that thanks to this, a system of checks and balances is formed in society, which we consider necessary for achieving sustainable development.

Key words: environmental law, climate law, sustainability law, sustainable development.

INTRODUCTION

The United Nations (UN) has launched a number of initiatives in the field of sustainable development, including the creation of the Guiding Principles on Business and Human Rights and the 17 Sustainable Development Goals (SDGs). Of particular importance for companies, including law firms, are the 10 principles of the UN Global Compact (Global Compact), which relate to corporate sustainability. The goal of the UN Global Compact is to raise business awareness and galvanize action in support of achieving SGD by 2030. Manufacturing and service firms in many countries, including law firms, are beginning to view sustainable practices as an important aspect of their ability to compete in today's markets. The ultimate goal for law firms seeking to be sustainable should be to ensure that sustainable environmental, social and governance objectives are embedded in the firm's culture and decision-making structure, so that they are a constant factor in how the firm does its work and makes decisions [1].

The relevance of research. The hostilities led to significant destruction of both civilian infrastructure and objects of the economy, in particular, the energy sector of Ukraine. In the near term, there is uncertainty regarding the end of these destructions and the possibility of restoring these facilities, but strategic planning needs to be done here and now. At the same time, the European Union is undergoing a slow but forced transition from the so-called post-industrial economy to the latest re-industrialization due to relations with China. Today, it is necessary to carry out a preliminary analysis of potential conflicts, including legal ones, which will arise in such conditions, and ways to resolve these conflict situations. This research is related to such fundamental tasks as the development of environmental law in general, maintenance of economic, ecological and social security of Ukraine, restoration of Ukraine's economy after the war.

Analysis of recent publications. A report published by the United Nations Environment Programme and the Sabin Center for Climate Change Law at Columbia University found that climate change lawsuits have increased by 146% between 2017 and 2022. Some of the groundwork for litigating climate change as a human rights issue was laid by environmental cases in the 1990s, such as class action lawsuits on behalf of communities affected by toxic chemicals and oil spills [2]. For example, the European Court of Human Rights, ECHR, ruled in favor of a group of elderly Swiss women, claiming that their government had violated their human rights because it had not adopted tough enough policies to combat climate change. That inaction, they argued, contributed to more frequent, more intense heat waves that significantly affected their quality of life -- and in an appealable ruling, the court agreed.

The victory in Switzerland is part of a growing variety of climate litigation that will soon undergo an even more rapid transformation, with climate cases promising not only potentially large payouts, but also significant cash rewards for the lawyers who win them. The ECHR decision ordered Switzerland to develop some new policies, but it did not actually specify what those policies should look like. However, if such lawsuits begin to result in fines, writes Isobel Asher Hamilton, law firms that specialize in taking large companies to court in contingencies are in for a lucrative business model [2].

Against the background of the flourishing movements for a clean environment, a parallel and partly related process is taking place: Europe and the United States have experienced a significant reduction in industrial employment. Although US manufacturing has been the leading driver of employment growth for decades, US manufacturing has declined over the past half century as the economy has shifted to the service sector.

Recent economic and geopolitical issues have exposed the tightness of global supplies. Organizations in Europe and the United States are recognizing the importance of reindustrialization for economic growth, job creation, health protection, technological progress and innovation. With expanding industrial sectors and fast supply chains, firms can cope with a more secure, growing regional economy.

Escalating geopolitical tensions, such as tensions between the United States and China, the war in Ukraine and the European energy crisis, have reinforced the risks of placement of industry in distant countries. The need to ensure the security of delivery in your country and with the military partner countries of the same political goals makes you take a fresh look at established traditions of onshoring and nearshoring. If the national sector is able to satisfy its basic needs, it effectively minimizes its vulnerability during periods of economic uncertainty and geopolitical threats reducing dependence on external sources.

Reindustrialization goes beyond the boundaries of the economic world. It helps to ensure the safety of workers, future jobs, the development of local talents, the raising of social awareness and the improvement of other risks. Domestic supply chains are more transparent than offshore chains. The convergence of supply chains closer to domestic markets strengthens oversight, supports more sustainable practices and the implementation of cyclical models [3].

After the war, the Mykolayiv Oblast will need reconstruction of the local economy, including industry. The region is a prime starting point for the development of alternative energy. The number of sunny days in the Ochakiv region is close to 300 days a year. About 10% of the entire wind potential of Ukraine accounts for the territory of Mykolaiv Oblast [4]. It will be still insufficient to meet the budget, create new jobs and save old ones, so some of the assets will not be able to meet all sustainability requirements from the very beginning and the improving of sustainability indicators will have to be planned in their development strategies.

In parallel with the recovery of the economy, the renewal of the reserve fund will be needed, which, having suffered from destruction and mining of the territory, will therefore require Ukraine to increase the number of reserves territory in accordance with Ukraine's obligations to increase the number of protected areas under the Association Agreement with the EU [5]. As a result of the war, approximately 20% of the area of all environmental territories of Ukraine is insecure, under threat of destruction, 17 Ramsar Sites with an area of 627.3 thousand hectares and approximately 160 territories of the Emerald Network with an area of 2.5 million hectares and 4 biosphere reserves will be lost [5]. Preservation of biological diversity is an important component of the state's environmental policy, as Ukraine has 35% of Europe's biodiversity. As of 01.01.2022 for Ukraine, the conservation index was equal to 6.8% [6].

The term "sustainable development law" cannot be called something that is actively used in Ukrainian sources, but "sustainability law" is gradually entering circulation in the English-speaking environment. It is considered as an interdisciplinary discipline, somewhat broader, but close to the concept of "environmental law", a partial version of which is "climate law". At the moment, the European Law Institute has an interdisciplinary educational program for advanced training (Special Interest Group (SIG)) on sustainable and environmental law (Sustainability and Environmental Law). We use the term "sustainability law", the difference of which from the term "environmental law" will be revealed below in the article, because it is concise and generally understandable to specialists in the field of sustainable development. We do not use the term "sustainable law" because it is sometimes used in a slightly different sense (the ability to justify a claim) in the English language. We also distinguish between the concepts of "law for environmental sustainability" and "sustainability law".

The rule of law is an important concept at the heart of the UN. At its first universal session in 2013, UNEP’s Governing Body adopted "Decision 27/9, on Advancing Justice, Governance and Law for Environmental Sustainability". In the Decision, Members States recognised the growing importance of rule of law in the field of the environment in order to reduce violations of environmental law and to achieve sustainable development overall. They held that ‘the violation of environmental law has the potential to undermine sustainable development and the implementation of agreed environmental goals and objectives at all levels and that the rule of law and good governance play an essential role in reducing such violations’ [7].

Environmental law pays special attention to environmental protection, liability for violations of environmental standards, support for sustainable development, and international cooperation. One of the main principles of environmental law is the principle of preventing harmful effects on the environment. This involves not only responsibility for activities that may harm the ecosystem, but also preliminary study of the possible negative consequences of any actions. Environmental law is aimed at creating and maintaining environmental sustainability in the interests of present and future generations [8].

Lees, Emma & Pedersen, Ole highlight the problem of performativity in environmental law. Performative law is law “just for show.” If the law expresses a commitment to goals and aspirations that are legally binding, but which are ultimately difficult to formally enforce, this can take on a very symbolic or gestural aspect. Environmental law is particularly vulnerable to performativity. This is due to the nature of the environment as an object of law and the characteristics of most contemporary environmental legislation [9].

Roy Chaudhuri, Nairita departs from the existing approach, which considers the fields of natural resource law and environmental law separately, and proposes an integrated analysis of both with all their complexities [10].

Anatoliy Getman views environmental law as a complex interplay between law, the environment, and sustainable development. He discusses the evolution of this kind of law and its implications for legal systems around the world, emphasizing its role in shaping environmental policy and promoting justice. Among other aspects of European Environmental Law, he has conducted a detailed study of the rights of indigenous peoples and their role in environmental governance, recognizing the unique perspectives and contributions of indigenous communities to environmental conservation and legal frameworks that protect indigenous knowledge and territories [11].

The book [5] describes in detail the problems of funding nature reserves during the war, which revealed some of the systemic problems that existed in the state before that. When it comes to helping protected areas, it is important to understand that one should not count on the mass nature of such assistance. The low popularity of the nature reserve institutions among ordinary Ukrainians and, even more so, the low awareness of them among citizens of other countries significantly limits the opportunities to find dedicated benefactors. In addition, people (who are not involved in the field of nature conservation) do not really understand that in order to help the protected area, animals and plants on it, it is necessary to provide assistance to the special administration of the nature reserve institution, because it is the coordinator of the executors who carry out all nature conservation measures on the territory, protect it, research and popularize it. Therefore, the teams of the nature reserve institutions have to self-organize and form their own volunteer initiatives that delivere food, generators, cars to the affected institutions during the war time. It is worth noting that Ukrainian donors do not work systematically, but respond to the acute challenges of today. Few people strive to support something all the time (although there are incredibly bright exceptions to this statement), but they donate with great enthusiasm on days of special danger, and especially during the hours of staying in bomb shelters during massive shelling. Therefore, for Ukrainians, aid is strongly tied to emotional factors. As practice has shown, most donors did not understand all aspects of the institution's work, so a surge in sending contributions was observed when help was needed for animals. However, the war showed that animal feed was not the most costly and critical need. Nevertheless, uninformed about the specifics and multidisciplinary nature of the work of the nature reserve institutions, donors in their mass are willing to finance the purchase of feed mainly. Gradually, public organizations spread the message in the media that helping such institutions means helping their employees. After all, it is their presence that distinguishes a nature reserve from an arbitrary plot on the map. Therefore, a separate direction of the nature reserve institution's work is to cover its daily activities.

In the post-war period, it is planned to create, together with other institutions, an informal or official entity (association, union, etc.), which could be a hub for providing assistance and communicating with Ukrainian and foreign donors. Such an association can be an independent public organization or foundation that contacts directly with the nature reserve institutions without the mediation of government bodies. Assistance can be provided in the form of financial support, the transfer of humanitarian goods, the transfer of necessary equipment, materials, machinery, etc. to the institution’s balance sheet.

Tran Duy, Minh writes that environmental conflicts manifest themselves as political, social, economic, ethnic, religious, or territorial conflicts, conflicts over resources or national interests, or any other type of conflict. To prevent them, the author suggests environmental impact assessment, community involvement, and participatory decision-making. Shared decision-making involves bringing together stakeholders from different sectors to participate in the decision-making process. This approach can help build trust and foster collaboration among stakeholders, leading to more sustainable outcomes [12]. We want to highlight this “shared decision-making” approach. We consider it the most effective for ensuring sustainable development of territories.

Highlighting previously unresolved parts of the general problem analyzed in this article. The paper is devoted to the insufficiently studied problem of applying sustainable principles in resolving potential conflicts, including legal ones, in the restoration of the economy sector of Ukraine in the war and post-war years.

The novelty of the study. The scientific novelty lies in expanding knowledge in the field of environmental and climate law and substantiating their differences from the sustainability law.

Methodological and general scientific significance. Comparative and systemic methods, theoretical analysis of scientific literary sources, their synthesis and generalization of information were used as research methods. To analyze the collected materials and information, qualitative assessment methods were used, first of all. This study is interdisciplinary at the edge of ecology, law, management and economics.

THE RESEARCH RESULTS AND DISCUSSIONS

Based on documents on sustainable development adopted at the global and interstate levels, Ukraine is developing its own national and regional development strategies and reforming legislation. The guiding principles of the Sustainable Development Strategy of Ukraine until 2030 [13] are: protection of human rights, rule of law, good governance, public participation, participation of business representatives and social partners, integration of policy and management, solidarity within and between generations, use of the best available knowledge, the principle of prevention, the “user pays” principle, the “polluter pays” principle. In this wording, it is clear that most of the principles are anthropocentric.

According to the Presidential Decree No. 722/2019 validating Sustainable Development Goals of Ukraine until 2030 [14], the achievement of 17 Sustainable Development Goals must be implemented by involving scientists, experts, and representatives of public associations. The goals of sustainable development of Ukraine for the period up to 2030 are guidelines for drafting of forecast and program documents, drafts of normative legal acts with the purpose of ensuring the balance of economic, social and environmental dimensions of sustainability development of Ukraine. In practice, an undesirable side effect arises: each of the involved scientists, experts, and representatives of public associations focuses primarily on those sustainable development goals that directly relate to their expertise and then works for years in the mode of “if we ensure the achievement of one or two goals, we ensure sustainable development as a whole.” It leads to conflicts and confrontations along with subtle attempts to actually prevent the achievement of other goals. Everyone would notice that experts on economic growth always focus on economic growth, but there are also less obvious contradictions. For example, experts on goal “5. Ensuring gender equality, empowerment of all women and girls” sometimes fight for solutions that are not fully consistent with goals 3, 4, 8, 10; and experts on goals 6, 11, 13, 14, 15 turn a blind eye to goals 1, 2, 7, 8, 9, 10. The positive side of such confrontation of expert groups is that thanks to this, a system of checks and balances is slowly formed in society, however, at the level of regional, sectoral, state and supranational governance, it is important not to take sides, but to remember that sustainable development implies a relatively equal achievement of each of the 17 goals.

Table 1 provides examples of goals and objectives of the Strategy [13] that may contradict each other and interfere with each other’s achievement. When resolving conflicts, including through litigation, it is important to remember that sustainable development involves achieving the maximum possible achievement of all goals and objectives set out in the relevant documents. Accordingly, we consider it inappropriate to file claims based on the failure to achieve a specific sustainable development goal, taken out of the context of the concept as a whole. It is more appropriate to file claims based on the failure to meet specific technical requirements, for example, relating to emissions or discharges of pollutants, etc.

It is also worth paying attention to “Strategic Goal 7. Ensuring security and access to justice, creating accountable and inclusive institutions. 7.2. Ensuring access to justice and protection of rights for all”. The protection of rights “for all” includes people who are economically dependent on the availability of arable land and enterprises in their region, and not only people who are involved in the budget sector, freelance, NGOs and the tourism business, and therefore are less interested in the development of industry in the regions in which they live. The same applies to the concept of “the public”. Often, when covering problems in media, they don’t fully include in the social group “the public” those people who work at the enterprise and live in the settlement where the enterprise is city-forming, which is not correct.

Below is given a typical example of misinterpretation of such documents. The following quote from the Strategy under discussion is read by many as:

“By 2030, ensure the creation of **sustainable food production** systems and introduce agricultural practices that increase resilience and productivity and increase production, **contribute to the conservation of ecosystems, strengthen the ability to adapt to climate change**, extreme weather events, droughts, floods and other natural disasters, and **gradually improve the quality of land and soil**.”

At the same time, the following falls into the blind spot for the eye and mind:

“By 2030, **ensure the creation of** sustainable **food production systems and introduce agricultural practices that increase** resilience and **productivity and increase production**, contribute to the conservation of ecosystems, strengthen the ability to adapt to climate change, extreme weather events, droughts, floods and other natural disasters, and gradually improve the quality of land and soil.”

Table 1 − Comparative analysis of some tasks of the Strategy for Sustainable Development of Ukraine until 2030

Strategic goals and objectives of the Sustainable Development Strategy of Ukraine until 2030:	
Examples of tasks that are not focused on solving environmental problems and may lead to an increase in man-made environmental burdens.	*Examples of tasks that are eco-friendly but may interfere with the tasks listed in the left column.*
1. Promoting inclusive, balanced, low-carbon economic growth and sustainable infrastructure, in particular: ensuring annual growth in gross domestic product on average at a level of not less than 4% for the period 2019-2020, 6% for the period 2021-2025 and 7% for the period 2026-2030. By 2030, increase the share of the processing industry in gross value added to 30%. Form an organizational infrastructure to support entrepreneurship in the form of technology parks, business incubators, networks providing services to enterprises, in particular on the basis of public-private partnership; promote the development of cluster networks. 3. Overcoming poverty and reducing inequality, including gender inequality, in	5. Ensuring the transition to models of balanced consumption and production, balanced management of natural resources and strengthening climate change response measures, in particular: by 2030, reduce greenhouse gas emissions in all sectors of economic activity to a level that will not exceed 60% of the 1990 emission level; by 2030, increase forest cover to 20% of the country's area; promote an increase in greenhouse gas absorption by increasing forest cover, balanced land use, renaturalization of wetlands, conservation of eroded arable land and the restoration of steppe and meadow ecosystems on them. 6. Preservation of terrestrial and marine ecosystems and promotion of the balanced use of their resources, in particular: by 2030,

<table>
<tr><td>particular: by 2025, eliminate extreme poverty (in Ukraine, defined as daily consumption of less than $5.05 at purchasing power parity); by 2030, halve (to 36%) the share of households that are considered poor according to UN criteria based on material well-being; by 2030, ensure the gradual approximation of the minimum wage and minimum pension to no lower than the actual subsistence minimum; achieve and maintain income growth for the poorest 40% of the population at a level higher than the national average; expand women's economic opportunities in the context of employment, income, and development of entrepreneurial potential.</td><td>ensure a significant reduction in any pollution of the marine environment, in particular, completely stop the discharge of untreated wastewater by facilities located within the coastal strip of the Azov and Black Seas, and prevent spills of oil and other hazardous substances from sea vessels; by 2030, increase the area of territories and facilities of the nature reserve fund to 15% of the country's territory, in particular, in mountainous regions not less than 2.5% of the country's territory; by 2030, ensure the protection of marine and coastal ecosystems by increasing the area of the nature reserve fund in coastal regions to 10%.</td></tr>
<tr><td colspan="2">Examples of tasks that are eco-friendly but do not interfere and even contribute to economic development, in particular by creating new jobs (such as the waste recycling industry).</td></tr>
<tr><td colspan="2">1) Strategic Goal 5. Ensuring the transition to models of balanced consumption and production, balanced management of natural resources and strengthening climate change response measures, in particular:
• By 2025, introduce the use of environmental accounts in the country's statistical accounting system.
• By 2030, achieve balanced management of natural resources and their efficient use and reduce the resource intensity of GDP by 40%.
• By 2030, reduce food losses in production and distribution chains by 20%, as well as post-harvest losses.
• Contribute to ensuring "green" public procurement in accordance with national priorities and EU standards.
• By 2030, ensure systematic information to consumers and producers on the importance and benefits of balanced consumption and production and the formation of a modern culture of consumption, in particular the economical use of resources.
• By 2030, implement a national education strategy for sustainable development.
• Improve the legislative framework in the field of waste management and create a modern infrastructure for the collection, sorting, processing and disposal of waste, including hazardous industrial and electronic waste, as secondary raw materials, attract investments in the field of waste management and by 2030 ensure a 20% reduction in the volume of production and consumption waste.
• By 2030, increase the amount of solid household waste that is recycled, disposed of and incinerated to 50%.</td></tr>
</table>

Perceiving sustainable development at the planetary and national levels as a way to maximize the indicators of the prosperity of natural ecosystems at the expense of all other indicators is a mistaken approach. Modern approaches to sustainable development automatically assume the improvement of economic indicators that contribute to poverty reduction. Similarly, the

Strategic Goal 3 "**Ensure healthy lives** and promote well-being **for all at all ages**" is interpreted by ecologists unambiguously as a call to reduce environmental pollution and any impacts (ecotoxicological, noise, electromagnetic, radiation, etc.) on humans. In fact, for real protection of public health, not only a healthy environment is necessary, but also high-tech medicine, which in practice exists only in countries with highly developed economies and developed infrastructure, which pollutes the environment even in the post-industrial era. Also, either high incomes of the population or a developed social state with large taxes from a developed economy are needed to ensure the financing of high-quality medicine. As for the Strategic Goal 11 "**Make cities and human settlements** inclusive, **safe, resilient, and sustainable**", here the development of science and technology is even more necessary than natural landscapes and healthy ecosystems. This becomes especially obvious during war - the absence of high-tech weapons produced at enterprises nullifies the rest of the measures to ensure the “sustainability” of the settlement.

In the history of environmental law, there have been many confrontations between indigenous peoples and economic objects managed by other peoples, often − global corporations. In our opinion, this has formed a certain pattern that does not always correspond to the real problem around which the conflict arise. Namely, it is quite common for the economic object to be managed by representatives of the same people living in the territory, or even representatives of the local residents themselves. Accordingly, the drama of “us versus them”, which is often played out in the media, acquires excessive theatricality, distracting from the fact that, unlike indigenous peoples who are engaged in gathering, hunting and fishing, live according to their own internal laws, other people often critically need the presence of an economic object in their region that will pay taxes and create jobs. Thus, the claim of the “the public” as representatives of the indigenous population against a global corporation and the claim of the “the public” as part of the local population who are not employed by a given enterprise against the owners of the enterprise (and in fact, also the rest of the local population who depend on this enterprise) – these are not identical situations from the point of view of state and regional governance.

In Europe and the US, the above-mentioned “us versus them” approach contributed to rapid deindustrialization once. At first, it had clear advantages, building a so-called post-industrial society, but in the end, it resulted in a decrease in real incomes of the population due to the loss of jobs that pay higher than most positions in retail and the service sector, and the decline of engineering education. In return, newly industrialized countries such as India and China rose in the GDP ranking, which actually weakened the global competitive position of post-industrial countries.

Ukraine, if it succeeds, will join the European Union and other Western unions now, at the stage of reindustrialization, but by inertia, many people who influence the processes think in the paradigm of a post-industrial society, focusing mainly on the interests and beliefs of people whose income and well-being is minimally tied to the actual production of goods. History shows that such development of the economy and the state as a whole is neither effective nor actually sustainable.

The court case "elderly women versus the Swiss government" was mentioned above. We consider it necessary to ask the question: what would have happened if the result of the court in Switzerland had been not to force the state to develop new policies, but a large fine, as is often the case. Whose pocket would this bill be paid for by – Swiss citizens, young families? Greta Thunberg's famous speech comes to mind, where she reproached older generations for not handing over the planet to the younger generation in its original pure form. We find it ironic that the elderly women from Switzerland did not realize that their country's environmental problems arose with the direct participation of their generation and themselves personally.

Lawyers involved in climate claims often view their activities as businesses, thinking in terms of the “most profitable model for their firms.” Accordingly, we cannot view these lawsuits as a "hero versus antihero" situation. It is more correct to talk about a "one business versus another business" situation. This still does not mean that the other business cannot and should not lose and pay for environmental pollution and ecosystem destruction. Nevertheless, if we talk about human rights from the perspective of sustainable development, these lawsuits should take into account the following issues in a complex:

- How many jobs are created for locals in this region;

- How much tax polluters pay in this region (this local region);

- Whether these taxes can be used to direct regular payments aimed at preventing and mitigating the risks and damage that the enterprise causes to nature and human health.

It is also worth noting that tourism businesses are often formed near nature reserves. Tourism businesses are usually relatively environmentally friendly, and therefore environmental groups often unite with their representatives to fight other economic entities in the area. However, tourism businesses are also profit-oriented and are not fully antagonistic to other businesses in the community. Their lower impact on the ecosystem is usually linked inextricably to their limited ability to combat unemployment and the lower taxes they pay, filling local budgets. We believe that in environmental issues, different types of businesses in the state and community should move away from confrontation and seek ways for useful cooperation in creating an environmentally safer infrastructure. This may include waste removal logistics shared by industry, municipal services, and protected areas, ecological logistics for the supply of resources, production of goods for local consumption, sponsorship of industrial facilities over reserves and cultural sites, joint regional advertising campaigns aimed at improving the image of the settlement, joint environmental educational campaigns, etc.

You can often hear that the right to live in a healthy environment is a fundamental human right. However, this is not the only right and not the only human need. It is also necessary to ensure a basic income for a person, security, comfortable infrastructure, etc. And the court's decisions should consist precisely in the development of comprehensive measures, such as those that do not lead to the deprivation of local residents of jobs and incomes for a long time (otherwise, it is necessary to consider how these jobs will be replaced with new ones and who will be responsible for this).

To resolve legal conflicts in the environmental sphere, we consider it useful to use the experience of England and Wales [15]:

1. Avoiding environmental litigation: conduct a pre-emptive risk assessment; engage with stakeholders; stay current with regulatory changes; review contracts and agreements.

2. When disputes arise: conduct early assessment; seek legal advice; consider alternative dispute resolution; communicate effectively.

3. Navigating court procedures: understand the process; gather robust evidence; work closely with your legal team; stay informed and involved.

4. Mitigating risks post-litigation: learn from the experience; implement changes; monitor regulatory compliance; build resilience.

Mitigating risks post-litigation ensures that your business not only recovers from the experience but also emerges more compliant.

Australian competition and consumer commission [16] suggests that businesses start protecting themselves from lawsuits at the stage of PR campaigns, product labeling and advertising: "If a business can transition to more sustainable business operations and it wants to tell consumers about it, it should be direct and open. Transitioning to a more sustainable business model takes time. It is often not a straight line. Businesses should be cautious about aspirational goals and should not make claims unless there are legitimate plans in place to meet these goals. An example is a business that can't reduce its greenhouse gas emissions in the short term. Instead, the business is offsetting their impact on the environment. The business can make this clear to consumers". This approach helps build more trusting relationships with local communities and leaves less room for manipulation by competitors and opponents.

CONCLUSION

1. The list of 17 sustainable development goals by 2030 is generally accepted on a planetary scale today. It is understood that sustainable development will be achieved if all 17 of its goals are achieved. In Ukraine, as in other countries, however, it often happens that each of the experts involved in the implementation of sustainable development strategies focuses primarily on those sustainable development goals that directly relate to his expertise, ignoring other goals. This leads to conflicts, including socio-political and legal ones. The positive side of such confrontation of expert groups is that a system of checks and balances is formed in society, the presence of which we consider necessary for achieving sustainable development. When making environmental decisions in peacetime, it is always necessary to take into account the risks that may arise in the future in potential wartime. It is advisable to consult with military experts.

2. If you want to file a lawsuit on environmental issues, it would be more correct if a group of environmental activists or an environmental organization conducted a sociological study first in the community for which this object is important from an economic point of view. If this is an object of national importance, then along with the rights of all those who are directly or indirectly affected by it, the interests of the state and the entire population of the country should also be taken into account. Even when making environmental decisions in peacetime, it is always necessary to take into account the risks that may arise in the future in potential wartime. It is advisable to consult with military experts.

3. Environmental disputes are often perceived by the public as a struggle for the triumph of truth, a way to restore justice. In this context we believe that in an environmental lawsuit against enterprises, it would be logical to demand the installation of treatment facilities and the introduction of environmental solutions, as well as compensation for clearly calculated damage. Demanding approximately the amount that is actually in the company's accounts and will most likely bankrupt the organization raises questions about the plaintiff's motives and goals. Instead of trying to bankrupt each other, different types of businesses and organizations in the state and the community should look for ways to usefully cooperate. We consider this approach to be the foundation for sustainable development.

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TRANSFORMATION OF PHYSICAL AND CHEMICAL PROPERTIES OF SOILS IN THE UKRAINE STEPPE ZONE AS A RESULT OF CLIMATE CHANGE

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ABSTRACT

The article provides a comprehensive analysis of the impact of climate change on the spatial differentiation and physical and chemical characteristics of soils in the Steppe zone of Ukraine, which is one of the most vulnerable areas in the context of global warming due to increased aridization and soil degradation. Based on long-term climatic data, significant changes in temperature and hydrological regimes have been identified. A study of the scale of degradation processes showed a significant increase in water and wind erosion, an increase in the area of eroded and saline lands, and a decrease in the productivity of agricultural landscapes, which threatens the region's food security.

Predictive models indicate irreversible changes in the soil cover, including a reduction in the area of chernozem soils and their transformation into less fertile chestnut and saline soils, accompanied by deterioration of agrochemical indicators and loss of biodiversity. To counteract these negative trends, the necessity of adapting the land use system, which includes the use of resource-saving agricultural technologies, improvement of irrigation systems using alternative water sources, precision farming, and the creation of protective forest belts and buffer zones to reduce erosion and stabilize the microclimate, is substantiated.

The results obtained can be used in environmental monitoring, agronomic forecasting, land management, and the development of adaptive strategies for agriculture under climate change, which is a key factor in the sustainable development of the agricultural sector of Ukraine.

Keywords: steppe zones, climate change, soil cover, aridization, erosion processes.

INTRODUCTION

Climate change, which in modern conditions is becoming increasingly widespread and intense, is one of the determining factors affecting the functioning of ecosystems and the state of natural resources, in particular, soil cover, which is the basis for biological productivity of territories and food security. The steppe zone of Ukraine, which is characterized by a combination of high average annual temperatures, uneven precipitation and high evaporation, is particularly vulnerable to climate change, as these factors contribute to the intensification of soil degradation, which in turn reduces soil fertility and worsens the ecological state of the region. Rising average annual temperatures and a gradual decrease in available moisture reserves lead to the transformation of the physical and chemical properties of soils, including changes in their structure, a decrease in humus content, deterioration of the microbiological composition and overall fertility, which has a very negative impact not only on the agricultural potential of the area, but also on the conservation of natural biodiversity and the maintenance of ecological balance.

Analysis of recent research and publications. Scientific studies conducted by Berezhniak E., Naumovska O., Berezhniak M. [1], Lubskyi M., Khyzhniak A., Orlenko T. [9] demonstrate that climate change causes significant transformations in the structure of soil cover, changes the moisture balance in ecosystems and affects the humus layer, which is a key element of land fertility. Further studies conducted by a group of authors led by Zhou T. Lu W. [22] and Shevchenko O. [17] emphasize the importance of developing adaptation mechanisms aimed at minimizing the negative impact of climate change on soil cover. In this context, of particular interest are the works of Skok S. [19], Holoborodko S., and Dymov O. [4], who conducted a comprehensive assessment of the quality of soils in the steppe zone of Ukraine in the context of global climate change and identified the main factors affecting their fertility and resistance to degradation processes. Despite significant scientific progress in this area, a number of unresolved issues remain, including the development of effective mechanisms for adapting agricultural landscapes to new climatic conditions.

The purpose of the article is to investigate the impact of climate change on the spatial distribution and physical and chemical properties of soils in the steppe zone of Ukraine, in particular, to assess the trends of degradation processes.

Objectives of the study:

- To analyze long-term trends in average annual temperatures, precipitation and evaporation in the Steppe zone of Ukraine based on climate data, determining their impact on the condition and transformation of soil cover;

- Identify key degradation processes (erosion, salinization, loss of humus, structural disruption) induced by climate change and assess their contribution to the destabilization of agroecosystems;

- to substantiate priority adaptation measures for rational land management aimed at preventing soil degradation in the context of climate instability;

- to create predictive models to assess future changes in soil cover, including its spatial reorganization and potential transformation into less productive types.

Materials and methods. 1) Temperature analysis. The research methodology was based on the integration of traditional and innovative approaches to temperature data collection, where the key role was played by long-term meteorological observations obtained from a network of steppe zone stations, combined with satellite remote sensing data that record temperature parameters of the soil surface at high spatial resolution. The information base covered the time span from the mid-twentieth century to the present, which made it possible to identify long-term climate trends and cyclic fluctuations that are critical for predictive models. Particular attention was paid to a detailed analysis of temperature regimes at different time scales - from daily averages to seasonal and annual indicators, since these parameters determine the intensity of moisture evaporation, the dynamics of soil moisture supply, and, as a result, affect the agroecological potential of the region.

2. The study of the steppe zone climate covered three periods: the current stage of intense warming (1990/91-2007/08, III-CP), as well as two previous cycles - 1972/73-1989/90 (II-CP) and 1954/55-1971/72 (I-CP). The data obtained from the Rozivka Research Station of the Institute of Grain Farming cover a period of 60 years and reflect the climatic norm of the southeastern Steppe. The analysis included estimates of air temperature and precipitation in warm and cold seasons, as well as for certain times of the year. To take into account the biological cycles of crops, the researchers used the hydrological year (from fall to fall), and the impact of weather conditions on yields was assessed through the Selyaninov Hydrothermal Coefficient (HTC). This indicator was calculated for the period May-September at temperatures above 10°C.

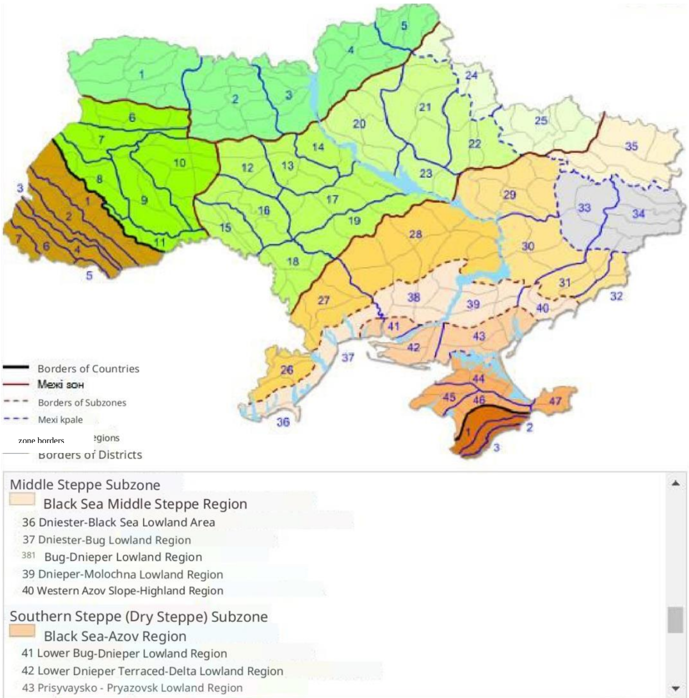

Fig. 1. Cartographic zoning of the steppe habitats of Ukraine [3].

The steppe zone of Ukraine, which is the area of distribution of the world's most fertile chernozem soils formed in unique bioclimatic conditions, has undergone a radical anthropogenic transformation, expressed in the almost complete plowing of natural ecosystems, where about 82% of the territory has been converted into agricultural land, which has led to systemic degradation of the soil cover, which is manifested in a catastrophic decline in the humus layer, disruption of soil structure and intensification of erosion processes, in particular on a scale where only officially recorded eroded lands occupy more than 38% of the region's area (equivalent to 12 million hectares), of which 5.2 million hectares are constantly exposed to the destructive effects of wind erosion, leading to the formation of microlandscapes with reduced bioproductivity (Fig. 1.) [19].

Climate change, which is reflected in the progressive increase in average annual temperatures and the growth of aridity indices, creates a synergistic effect, increasing the intensity of both water (soil washing away during storm precipitation) and wind erosion (mechanical detachment of soil particles), which is especially dangerous in the southern regions, where there is an escalation in the frequency and intensity of dust storms, which arise from a combination of waterlogged soils in the spring, their subsequent drying out in the summer and a lack of vegetation cover, which together transform steppe ecosystems into environmental risk zones with a high probability of loss of soil fertile layer and irreversible changes in the agroclimatic potential of the territories (Fig. 2.) [3].

Fig. 2. Soil degradation processes in the Southern Steppe [7].

The climate of the steppe zone of Ukraine is undergoing transformations under the influence of global warming, which, according to the scientific findings of the Intergovernmental Panel on Climate Change (IPCC) under the UN, is directly related to the greenhouse effect, a natural phenomenon that has existed since the formation of the Earth's atmosphere. This effect is exacerbated by anthropogenic emissions of gases such as carbon dioxide (CO_2), methane (CH_4), nitric oxide (N_2O), and chlorofluorocarbons, collectively known as CFCs. Increasing concentrations of these substances, especially CFCs, lead to changes in the quality of the atmosphere. Over the past two decades, the share of CO_2 in total greenhouse gas emissions has been approximately 50%, CH_4 - 18%, N_2O - 5.8%, and CFCs - 15%. Experts in the field of soil science identify carbon dioxide and methane as key factors in global warming. Over the past century, their content in the atmosphere has increased by 25%, which significantly affects the heat balance of the planet. Scientists emphasize that if there were no greenhouse gases, the average temperature of the surface layer of the atmosphere would be approximately -18°C, which would make the Earth uninhabitable. However, a number of researchers have expressed doubts about the excessive role of CO_2 and CH_4 in climate change, considering such claims to be insufficiently substantiated or exaggerated [7; 12].

According to the monitoring data of the Ukrainian Hydrometeorological Center, a systematic analysis of climate trends in the steppe zone indicates an intensification of warming processes that have become pronounced since the late 1980s, This is reflected in an increase in average annual temperature by 0.35 °C (Table 1), while in the southeastern segment of the steppe corridor, a similar trend is observed with an increase in annual temperature by 0.25 °C, which, together with a slight increase in total annual precipitation to 105 % of the climatic norm, creates a paradoxical situation where local humidity increases do not compensate for the catastrophic increase in evaporation.

Table 1 − Dynamics of quantitative indicators of precipitation, air temperature, sum of active temperatures and hydrothermal coefficient (HTC) in the context of influence on the spatial differentiation of soil cover of the steppe zone of Ukraine for the period 1977−2023 [19; 21].

Years	Precipitation, mm	Air temperature, ºC	Sum of temperatures, ºC	HTC	Evaporation rate, mm
1977–2007	467	10.30	3899	0.90	584
2008–2017	389	11.63	4317	0.67	648
2017–2023	395	12.34	4477	0.63	673

Detailed calculations show that over the last decade, the evapotranspiration index for the warm period (t ≥ 5°C) increased from 572 to 673 mm, while the average annual precipitation remained at 388 mm, which led to the formation of a stable imbalance model where the level of moisture loss through evaporation systematically exceeds its supply through precipitation, creating prerequisites for the progression of aridization processes, especially intensified in the Southern Steppe over the past five years, which manifested itself in the degradation of the water-heat regime of soils, a critical decrease in the agroecological potential of territories and accelerated desertification [6].

Table 2 − Deviations of the average monthly air temperature (To) and precipitation (r, %) from the climatic norm for soils of the steppe zone [13].

Indicator	Months of the hydrological year												Middle
	IX	X	XI	XII	I	II	III	IV	V	VI	VII	VIII	
Steppes of Ukraine (1990-2008)													
To	-0.3	0.6	-1.3	-0.7	1.5	1.1	0.7	0.4	-0.4	0.5	0.9	0.6	0.3
r, %	125	122	117	95	87	99	123	102	100	108	89	119	100
Southeastern part of the Steppe (1990−2020)													
To	-0.1	0.3	-0.2	-0.4	1.1	0.6	0.9	0	-0.4	-0.2	0.2	0.3	0.25
r, %	103	128	111	83	93	100	127	113	85	109	93	124	104

Predictive models indicate the potential catastrophic nature of further temperature increases in the absence of a compensatory increase in precipitation, which threatens not only the full-scale drying of steppe ecosystems but also the collapse of bioproductive systems due to the depletion of moisture reserves and a radical drop in soil fertility in the steppe zone of Ukraine. A comparative analysis of three climatic periods of equal chronological length revealed differentiated precipitation dynamics characterized by a progressive increase in their amount in the autumn, spring and summer seasons (Table 2), while the winter period demonstrates the opposite trend with a decrease in precipitation, while the total annual humidity over the hydrological cycle has undergone significant changes - an increase of 32 mm in the II-CP and 45 mm in the III-CP relative to the baseline I-CP, which was accompanied by a transformation of the ratio between warm and cold seasons: While in the first year of the study, winter precipitation accounted for 42.0% of the annual volume, in the following periods (second and third years) their share decreased to 39.1% and 38.7%, respectively, indicating a systemic restructuring of the seasonal distribution of precipitation [13].

Temperature parameters demonstrated ambiguous dynamics: the annual average in the I-CP was recorded at 9.0 °C, while in the II-CP it decreased to 8.2 °C, which caused a cascade of changes in the chronology of stable transitions of average daily temperatures due to critical values (0, 3, 5, 15 °C) and the duration of periods with temperatures above these limits (Table 3), which is of key importance for agroecosystems, since the vegetation cycle of cold-resistant cereals is initiated when the threshold of +5 °C is overcome, heat-loving crops are activated at +9 °C, and the peak bioproductivity of vegetation cover is achieved in the phase of prolonged temperatures above +16 °C, which makes changes in the timing and duration of these temperature periods a crucial factor for planning crop rotations, yield forecasting, and adaptation of agricultural technologies to transformed climatic conditions (Fig. 3.).

The structure of sown areas in the steppe zone of Ukraine shows the dominance of cereals and industrial crops (winter wheat, barley, corn, sunflower, soybeans, and rapeseed) in agricultural activities, which is due to their global demand. However, the intensification of agriculture, which is accompanied by an increase in the level of plowing to 81.5% in the Steppe (in particular, to 90.4% in the Kherson region), has led to the destabilization of agricultural landscapes, exacerbated by changes in climate conditions.

This is reflected in the progressive decrease in soil moisture availability: in recent years (2018-2020), the precipitation deficit in Kherson region has reached 784-812 mm compared to the average of 4948 mm in 1950-2020, which leads to drying of the upper soil horizons, reduction of the humus layer, and degradation of the soil cover structure of the steppe zone. The climatic features of the steppe zone, in particular the subtropical temperature regime (3230-3430°C of active temperatures) with a sharp seasonality (hot summers with dry winds, mild winters), directly affect soil formation processes [14]. An increase in the average annual temperature by 1°C, even with an increase in precipitation, causes a shift in the boundaries of zones of sufficient moisture (Polissya, Forest-Steppe) towards an unstable hydrological regime, which provokes a redistribution of soil types.

The conditions of the coastal climatic subzone, within which the steppe zone of Ukraine is located, are characterized by intense air heating and a progressive decrease in precipitation, which creates climatic instability with catastrophic consequences for the soil cover. For example, a long-term analysis of meteorological data has shown that an increase in average annual temperature by 1.0-1.2°C is combined with a decrease in annual precipitation by 70 mm, which leads to a shift in the boundaries of agroclimatic zones and the transformation of soil regimes. Thus, increased heat availability contributes to the intensification of biological processes in the soil: accelerating the mineralization of organic matter, reducing the humus layer and degrading the aggregate structure, which is especially critical for chernozems, which are losing their fertility and gradually turning into less stable types (chestnut, saline).

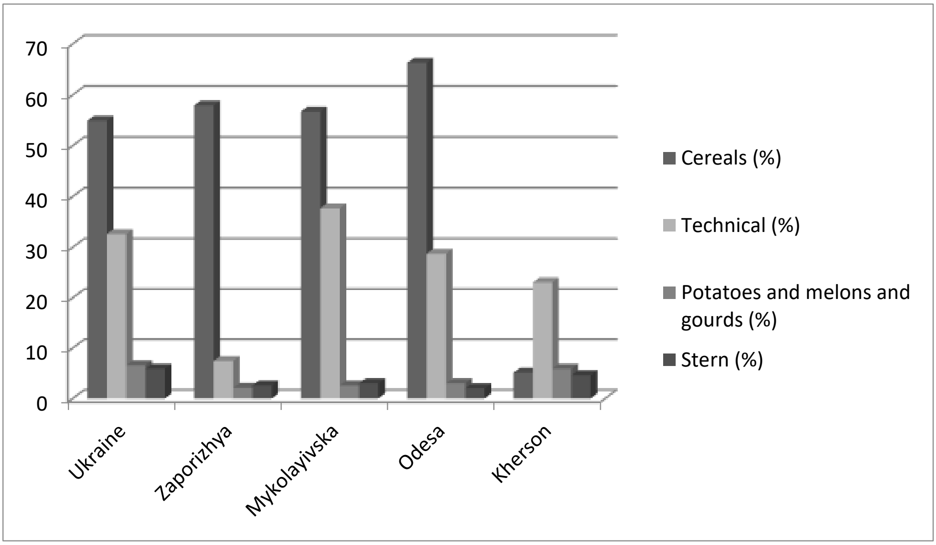

Fig. 3. Spatial and temporal distribution of crop areas in Ukraine and the Southern Steppe (2023): correlation with zonal soil cover features and adaptation of agroecosystems to climate change [13].

For example, the black soils of the steppe zone, traditionally rich in organic matter, lose moisture due to intensified evaporation, which leads to their salinization or transition to less fertile chestnut soils. In addition, an increase in the temperature amplitude (up to 65-70°C) and frequent dry winds intensify erosion processes, especially in plowed areas where the soil loses its protective vegetation cover. This significantly changes the spatial dynamics of soils: the area of dehydrated and saline areas is growing, while areas of stable agriculture are shrinking [2]. Thus, climate change not only transforms the agro-ecological potential of the steppe regions, but also reformats the physical and chemical properties of soils, reducing their productivity and resistance to further anthropogenic stress (Fig. 4).

A key factor in soil destabilization is the imbalance of moisture supply caused by changes in the seasonality of precipitation and increased evaporation. In particular, 72% of atmospheric moisture comes during the warm season, when high air temperature and insolation lead to rapid evaporation of water from the surface layers of the soil, which causes the formation of dry horizons with low water retention capacity [5]. This process is exacerbated by unstable snow cover, which does not ensure effective groundwater recharge during spring melt, as well as the formation of ice crusts that impede meltwater infiltration and deepen the moisture deficit in the Ukrainian steppes.

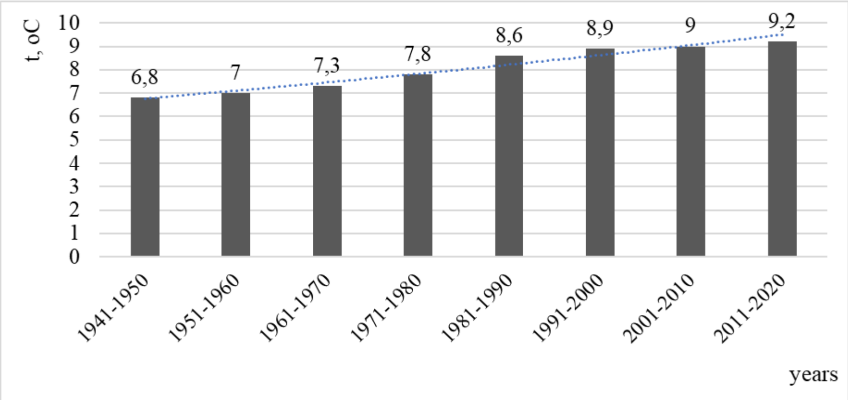

Fig. 4. Dynamics of the average annual distribution of precipitation in the climatic subzones of the steppes of Ukraine [1].

Spatially, such changes are reflected in the increase in the area of arid areas with saline or dense clay soils, while traditional black earth massifs are shrinking, losing their connection to previous climatic conditions. The increase in the sum of active temperatures (up to 3420°C) also changes the geography of soil formation: in the southern regions of the Steppe, the process of erosion is intensifying due to frequent dry winds that destroy the upper fertile layer, while in the central and eastern regions, dehumidification prevails due to excessive insolation. Thus, climate change not only reduces the quality of soils (porosity, pH, micronutrient content), but also redistributes their types in space, strengthening the trend towards desertification and reducing the area suitable for intensive agriculture [9].

In 2023, the climatic conditions of the steppe zone of Ukraine showed significant deviations from the norm, in particular, the amount of precipitation in cold and warm periods decreased by 3-5%, which led to the formation of a persistent moisture deficit. Particularly noteworthy is the increase in the frequency of ineffective localized showers, the intensity of which repeatedly exceeded climatic norms during the month, which significantly limited the soil's ability to accumulate moisture. About 61% of the intense precipitation recorded in the summer season contributed to increased surface runoff, which not only reduced water infiltration but also led to the degradation of the top fertile soil layer through mechanical erosion.

The increase in the average annual temperature significantly affected the moisture availability of the soil cover, which is reflected in the climate balance indicators, calculated as the difference between precipitation and potential total evaporation. Thus, in 2023, the moisture deficit in the study area reached 460 mm, which exacerbated the drought problem and intensified desertification processes. Climatic anomalies were also accompanied by an increase in extreme weather events, such as hail, intense winds, and dust storms, which became catalysts for water and wind erosion. This resulted in an increase in humus losses (up to 1.37 t/ha annually), land dehumidification, and leaching of nutrients such as nitrogen, phosphorus, and potassium, which led to a 52% decrease in grain yields [17].

The spatial and temporal distribution of humus in Steppe soils is closely related to their genesis (Table 3), but over the past three decades, its content has decreased by 35% due to increased erosion activity. The loss of each centimeter of the humus horizon is accompanied by deterioration of the soil structure, disruption of its water-air regime, a decrease in moisture capacity by 22%, and a drop in potential grain yield by 0.5-2 c/ha. Data from the Xth round of agrochemical surveys show that 53% of the region's agricultural land has an average level of humus, while 51% has a high potassium content and 27% has an increased phosphorus concentration. This disproportion is explained by the intensification of metabolic processes in soils amid increasing heat availability, but 53% of the land is still classified as low-productive (quality class XIII), which emphasizes the critical need to adapt soil management to climate realities. Thus, climate change in the steppe zone of Ukraine transforms not only the hydrothermal regime, but also the spatial organization of the soil cover, causing a decrease in its fertility and environmental sustainability [21].

Table 3 − Spatial and temporal dynamics of soil availability by natural-zonal distribution (Polissya, Forest-Steppe, Southern Steppe) in the context of climate transformations: observation periods 1985−2023 (compiled by the author on the basis of [13; 20])

Observation period, years	Zonal division					
	Polissya	The level of security	Forest-steppe	The level of security	Southern Steppe	The level of security
V (1985–1991)	2.5	Middle weight	3.52	Overweight	3.92	Overweight
VI (1992–1996)	2.34	Middle weight	3.45	Overweight	3.75	Overweight
VII (1997–2002)	2.31	Middle weight	3.35	Overweight	3.61	Overweight
VIII (2003–2010)	2.27	Middle weight	3.34	Overweight	3.60	Overweight
IX (2011–2019)	2.33	Middle weight	3.32	Overweight	3.54	Overweight
X (2019–2023)	2.42	Middle weight	3.34	Overweight	2.55	Middle weight

The integral assessment of soil fertility, considering the content of humus, phosphorus, potassium, zinc, manganese, and copper, with a positive coefficient for climatic conditions (0.68), amounted to 62 points, which is equivalent to 41 points after correction. This corresponds to Class VI of satisfactory quality according to the classification scale. The indicator highlights the significant impact of climatic factors on the agrochemical characteristics of the soil cover, particularly due to rising temperatures and changes in the moisture regime, which lead to the redistribution of nutrients in space [11].

Expanded in the steppe zone, crops such as winter wheat, sunflower, rice, and barley occupy large areas of agricultural land, reflecting minimal use of material and labor resources. However, their cultivation is intensifying against the backdrop of an increasing share of crop production in the agricultural structure, reaching 78.1% in 2023, which is 13.8% higher than the figures of a decade ago.

The average annual temperature increase, on the one hand, accelerates plant phenological phases, reduces the risk of freezing, and extends the growing season, which, with an increase and additional application of fertilizers, theoretically allows for two harvests per year. On the other hand, extreme temperature fluctuations lead to an increase in productive moisture reserves in the soil, a decrease in nutrient concentrations, and, consequently, an expansion of cereal crop areas. This intensifies anthropogenic pressure on the soil cover due to the rising level of land plowing.

Forecast scenarios indicate a possible increase in greenhouse gas emissions by 92% by 2030, accompanied by a rise in average temperature by 1.6°C, leading to cascading changes in ecosystems: soil degradation due to water resource deficits, decreased crop yields, and increased costs for land reclamation and fertilizer application. These processes affect the spatial dynamics of soil properties, particularly the redistribution of humus, mineral elements, and the degree of erosion in Ukraine's steppe zone [20].

In the face of such challenges, adapting agriculture to climate change is becoming a priority. A promising direction is the introduction of leguminous crops, whose yields increase by 20% in the context of rising temperatures and moisture deficits, helping to stabilize the nitrogen balance of soils.

To compensate for insufficient water availability, innovative approaches are proposed, including the use of treated wastewater for irrigation, the creation of drainage systems to collect rainwater runoff, and the application of artificial coverings made from non-woven materials or natural vegetation mulch to reduce evaporation. To combat erosion, it is critically important to restore shelterbelts, reduce plowed areas, and transform part of the land into natural landscapes with stable ecosystems. These measures will contribute to stabilizing the soil cover and preserving its productivity under conditions of climate instability. Thus, climate change not only transforms the hydrothermal regime of the steppe zone but also affects the spatial heterogeneity of soils, necessitating a comprehensive approach to land resource management, considering their agrochemical dynamics and the ecological potential of steppe soils.

Conclusions. Validated predictive models reflecting the impact of climate change on the spatial distribution of soil types indicate a gradual increase in the area of low-productivity, degraded lands. This trend is driven by a combination of negative processes, among which the most critical are the gradual reduction of the humus horizon, disruption of the natural soil structure, and transformation of soil water-physical characteristics. These changes hinder the effective accumulation and retention of moisture in the soil profile.

The analysis confirms that if current climate change trends persist – particularly the ongoing rise in average annual temperatures, the reduction in atmospheric precipitation, and the increase in evaporation – chernozem soils, traditionally highly productive and valuable for agricultural production, may gradually transform into less fertile soil types, such as chest.

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TECHNOLOGY AND HARDWARE SELECTION OF THE ENVIRONMENTAL MONITORING FOR ELECTROMAGNETIC STRESS IN THE CONDITIONS OF MILITARY OPERATIONS

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ABSTRACT

This paper focuses on technology and hardware selection for organizing environmental monitoring of electromagnetic stress under military operation conditions. Specific attention is given to the technical requirements and selection criteria for hardware solutions capable of reliably capturing radio-frequency electromagnetic radiation data in challenging environments. Military operations intensify electromagnetic radiation exposure without adequate monitoring, potentially causing lasting negative impacts on both human populations and ecosystems.

The study highlights a comprehensive approach for assessing the impact level of radio-frequency radiation on the surrounding ecosystem. Particular attention is given to the technical requirements and selection criteria for hardware solutions capable of reliably capturing radio-frequency electromagnetic radiation data under challenging conditions.

The advantages and limitations of hardware platforms and devices, such as spectrum analyzers and specialized sensors, are discussed. A rationale for hardware selection is provided, taking into account factors such as sensitivity, spectral range, reliability, portability, and ease of integration into broader environmental monitoring systems.

Measurements of electromagnetic radiation levels were conducted using the Tenmars TM-192D device in the city of Mykolaiv. The results indicated exceedances of the maximum permissible levels of electromagnetic radiation at three observation points. However, due to the limitations of the equipment used for data collection, it was not possible to accurately determine the frequency range of the detected exceedances.

To assess the causes of these exceedances, a comprehensive approach employing a spectrum analyzer should be applied. The study presents the perspective that the combined use of the tinySA spectrum analyzer and the Tenmars TM-192D magnetic field meter enables a comprehensive approach to environmental monitoring of electromagnetic stress. Due to their high portability, cost-effectiveness, and technical efficiency, these devices are considered an

optimal choice for conducting research under difficult conditions, particularly in areas affected by military operations.

Keywords: electromagnetic stress monitoring, devices, criteria, socio-ecosystem

INTRODUCTION

One of the important threats in military conditions is the increased electromagnetic stress, which we have already discussed in detail above. In the conditions of modern military operations, accompanied by the intensive use of radar systems, radio communication systems, electronic warfare (EW), and other high-frequency technologies, research into the impact of electromagnetic radiation (EMR) on the environment and human health is becoming particularly relevant. The accumulation of scientific data indicates the multifaceted nature of the problem: from assessing safe levels of electromagnetic fields and developing regulatory documents to implementing environmental monitoring systems and identifying potential risks over long time intervals.

Socio-ecosystems are characterized by a complex structure, where technical elements (power lines, communication systems, industrial facilities) are closely intertwined with ecological ones (vegetation, animal communities, aquatic ecosystems). Radiofrequency radiation, as well as other parts of the electromagnetic spectrum, can directly or indirectly affect:

● Ecological balance: changes in species composition, disruption of natural food chains, fluctuations in populations of species sensitive to electromagnetic fields.

● Public health: sleep disorders, stress, depressive disorders, and possible mutagenic or carcinogenic effects with prolonged exposure to high levels of radiation.

● Economy and infrastructure: disruptions in electronic systems that are critical to transportation, energy supply, and economic activity.

As a result, the socio-ecosystem may lose its ability to self-regulate and enter a state of crisis [1], [4].

The aim of the work is to develop criteria for assessing the impact of electromagnetic radiation on the socio-ecosystem, a monitoring program, and an algorithm. To achieve the goal of assessing the electromagnetic effect on the socio-ecosystem, comprehensive approaches are used, covering both methods of collecting primary data and methods of processing and analyzing it. The main methods, tools, and algorithms used to obtain and interpret data are presented.

METHODS AND EXPERIMENTAL PROCEDURES

Methods commonly employed in observations aimed at determining the characteristics of electromagnetic stress on biological objects were utilized.

To assess the characteristics of electromagnetic stress on biological objects, a set of methods and technical tools was employed, enabling the collection of accurate and representative data on the effects of electromagnetic fields.

Measurements of electromagnetic radiation parameters were conducted using the Tenmars TM-192D device (Fig. 1).

Fig. 1. Use of the Tenmars TM-192D device.

Measurements were carried out following the algorithm described below. Prior to the commencement of measurements, the device was calibrated according to the manufacturer's instructions. The battery charge level and the operational integrity of the device were verified. Several representative points in the city of Mykolaiv were selected (Figure 2) to collect the most accurate data on electromagnetic stress. Measurements were conducted at a height of 1.5 meters above ground level, corresponding to the average human body position. The device was held in a vertical position, with its sensors oriented toward the presumed source of electromagnetic radiation.

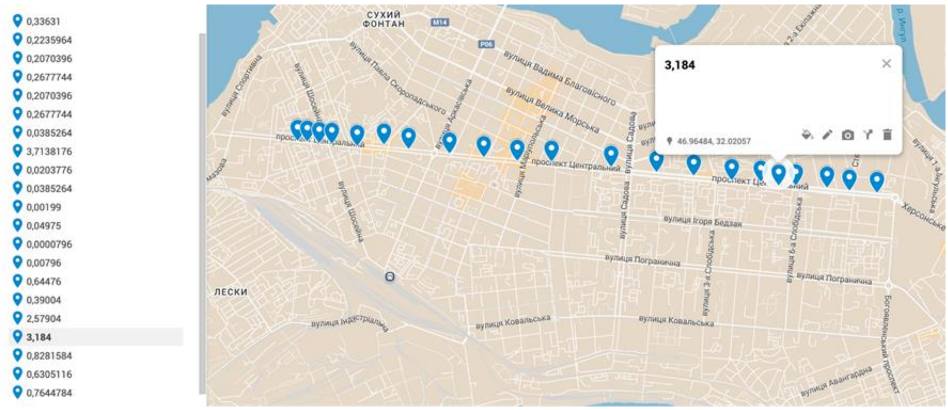

Fig. 2. Measurement locations of electromagnetic radiation (EMR) power flux density in the city of Mykolaiv.

The analysis of the results was conducted in accordance with the Order of the Ministry of Health of Ukraine No. 1040 dated November 29, 2013, *"On the Approval of the Methodology for Calculating the Distributions of Electromagnetic Field Levels"*, taking into account the *"State Sanitary Norms and Rules for the Protection of the Population from the Effects of Electromagnetic Radiation"*, approved by the Order of the Ministry of Health of Ukraine No. 239 dated August 1, 1996. According to these documents, the maximum permissible levels (MPL) of electromagnetic fields are established as follows in the frequency range of 30–300 MHz — 3 V/m, in the frequency range of 300 MHz–300 GHz — 2.5 μW/cm² [11].

Power flux density is the amount of power carried by an electromagnetic wave through a unit area perpendicular to the direction of wave propagation. It is typically expressed in units of W/m². For a plane electromagnetic wave in free space, the power flux density S is related to the electric field strength E and the magnetic field strength H by the following equations:

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$$Seq = \frac{E^2}{Z_0} = Z_0 \times H^2 = E \times H \quad (1)$$

where:

Z_0 is the intrinsic impedance of free space,

E is the electric field strength (V/m),

H is the magnetic field strength (A/m),

S is the power flux density (W/m²).

In many practical measurement methodologies, the quantities E or H are typically measured, and the power flux density S is calculated using the above formulas. Since the measurements were performed in microteslas (μT), and magnetic flux density B is related to the magnetic field strength H by the formula 2:

$$H = \frac{B}{\mu_0} \quad (2)$$

where:

$$\mu 0 = 4\pi \times 10 - 7 \mu 0 = 4\pi \times 10 - 7 \text{ H/m} \quad (3)$$

is the magnetic constant (permeability of free space), In cases where it is necessary to directly convert the data into microwatts per square centimeter (μW/cm²), a simplified formula was used in our calculations:

$$S_{eq} = 79.6 \times B^2 \quad (4)$$

where B is the magnetic flux density expressed in micro Teslas (μT).

These calculations are valid in the far-field zone of the emitter, where the electric and magnetic fields are mutually perpendicular and also perpendicular to the direction of wave propagation.

RESULTS AND DISCUSSIONS

The radio-frequency spectrum is typically divided into sub-bands (VLF, LF, MF, HF, VHF, UHF, SHF, EHF, etc.). For military purposes, the following bands are of particular importance:

• **HF (3–30 MHz):** long-range radio communications, especially in areas without satellite coverage.

• **VHF (30–300 MHz) and UHF (300–3000 MHz):** used in ground-based communication systems, tactical radios, television and radio broadcasting.

• **SHF (3–30 GHz):** radars, satellite communication channels, Wi-Fi, and 5G.

Each frequency band has unique wave propagation, absorption, and reflection characteristics. In military applications, “transparency windows” in the atmosphere, where signal attenuation is minimal, are often sought. This allows for target detection over long distances or the effective transmission of information ([1], [2], [4]).

Since radio-frequency radiation does not ionize molecules, its direct effects are most often associated with thermal effects: molecules absorb wave energy and heat up. However, scientists actively discuss the possibility of non-thermal effects of RF radiation, such as impacts on cell membranes, changes in ion channel functioning, and disruptions to the bioelectrical activity of neural tissue [2], [8].

At high power levels (e.g., radar systems, electronic warfare (EW)), strong local or systemic heating of tissues may occur, potentially leading to burns and internal organ damage. Although rare, this situation cannot be ignored under military conditions.

According to research [2], [5], changes in bird behavior influenced by the Earth's magnetic field have been observed, and studies indicate disorientation in insects, particularly bees, which possess highly sensitive receptors.

Regarding human impact, published data suggest potential risks from prolonged exposure to low-intensity RF radiation: headaches, sleep disturbances, fatigue, and in some experiments, DNA damage. However, establishing clear cause-and-effect relationships remains challenging due to multifactorial influences and the lack of long-term studies under real military conditions [2], [7].

Non-thermal effects also include potential changes in neuronal electrical activity. In studies on radar operators, "microwave sickness" effects were reported, such as fatigue and increased irritability.

Military systems that generate radio-frequency radiation include:

• **Radars:** operating across various bands (from VHF to SHF, sometimes EHF), powerful pulsed radars can detect aerial targets at hundreds of kilometers, creating high EM radiation levels in the near field.

• **Electronic warfare (EW) systems:** involve active emitters that overload enemy receivers. Some EW systems can produce high-power directed pulses capable of "burning out" electronics.

• **Communication systems:** including tactical radios, satellite links, and digital data transmission systems.

Thus, in military operations, RF radiation serves a dual role: enabling communication and functioning as a means of attack. As communication means, RF radiation facilitates information transmission among units, military branches, and command structures, involving both traditional (radio, telephone) and modern wireless technologies. Communication systems enable real-time coordination, instruction reception, and battlefield information sharing.

As a means of attack, RF radiation is used to jam enemy communication systems, disrupting command chains, reducing reconnaissance capabilities, and interfering with enemy coordination.

Radio jamming is a specific form of electronic attack targeting communication or navigation systems by generating interference signals that impede the normal operation of electronic systems. This creates a complex environmental and social situation, as military forces may deploy high-power transmitters near populated areas, often without informing local populations about radiation levels and associated risks. In some cases, "electromagnetic warfare" occurs, where opposing sides attempt to jam or intercept each other's signals. From an environmental perspective, increased RF intensity can adversely affect biodiversity and infrastructure, particularly if civilian systems (e.g., medical equipment, traffic control systems) are susceptible to interference ([6], [8]). Thus, for socio-ecosystems exposed to electromagnetic stress during military operations, environmental monitoring becomes essential.

The main objectives are measuring radiation intensity, determining the frequency spectrum, and assessing exposure duration. The choice of instruments largely depends on the type of radiation sources: communication systems, electronic warfare, or radar systems.

Additionally, measurement conditions must be considered, including open fields, urban areas, or combat zones. Equally important is the required measurement accuracy, which affects the reliability of results, as well as the mobility and sensitivity of the equipment. We have analyzed the technical characteristics of the equipment suitable for such monitoring, detailed below. The equipment used for electromagnetic radiation measurements must match the frequency range of interest. For radio communication, the frequency range spans from 30 MHz to 300 GHz. Radar systems typically operate within the 1 GHz to 40 GHz range. Electronic warfare systems may cover frequencies from several kilohertz to hundreds of gigahertz.

The sensitivity of measuring equipment is a critical parameter, especially in areas with low electromagnetic radiation (EMR) levels. In such environments, where radiation levels may be near detection thresholds, high sensitivity enables the detection of even minor changes in the electromagnetic background. This is particularly important in environmental studies, where it is necessary to assess the impact of electromagnetic fields on ecosystems, flora, fauna, and human health. In low-EMR zones, sensitive instruments not only help detect potential pollution sources but also monitor temporal changes, crucial for understanding trends and environmental impacts. High sensitivity ensures data accuracy, which is critical for scientific research and analysis.

Mobility and autonomy of the equipment are also essential, especially in field conditions.

Ease of transportation is critical because researchers often operate in remote areas with limited access to electricity. Equipment that is bulky or heavy complicates data collection processes. Autonomy, meaning the duration of operation without recharging, is equally important. In the field, where power sources may be scarce, it is vital for equipment to function for extended periods without recharging. This enables longer experiments and data collection sessions, improving the quality and reliability of results. Thus, **sensitivity, mobility, and autonomy** are key characteristics for effective electromagnetic field monitoring under field conditions. These features ensure accurate and reliable assessment of electromagnetic impacts on the environment, human health, and ecosystem preservation.

The groups of instruments applicable for organizing environmental monitoring of electromagnetic stress on socio-ecosystems during military operations are presented below, according to defined characteristics such as sensitivity, mobility, and accuracy.

The first group consists of **spectrum analyzers**: these instruments allow for the analysis and visualization of electromagnetic signals. Spectrum analyzers help researchers understand which frequencies dominate in the measurements and identify potential sources of radiation. Among professional spectrum analyzers, the **Rohde & Schwarz FSV3000** (Fig. 3) and **tinySA** (Figure 2) are distinguished.

Fig. 3. Professional Spectrum Analyzer Rohde & Schwarz FSV3000.

The technical capabilities of the **Rohde & Schwarz FSV3000** spectrum analyzer include a wide frequency range, making it versatile for measuring signals across different frequency bands. This device can operate within a range from **9 kHz to 30 GHz**, allowing it to analyze a broad spectrum of electromagnetic signals, including radio communications, television and radio broadcasting signals, as well as wireless system signals. Additionally, the **FSV3000** is capable of analyzing complex signals, which is important for studying emerging communication technologies such as **LTE**, **5G**, and multiple access systems. However, this spectrum analyzer also has its limitations. Firstly, its **high cost** may be a barrier for use in small companies or research laboratories with limited budgets. Secondly, the **large size** of this equipment may complicate transportation and fieldwork, where compactness and mobility are crucial characteristics. Thus, the **Rohde & Schwarz FSV3000** is a powerful and functional spectrum analyzer that offers a wide range of capabilities for electromagnetic signal analysis, but its high cost and size may restrict its use in certain cases [1].

Fig. 4. Professional Spectrum Analyzer tinySA.

The **tinySA** is a **compact spectrum analyzer** designed for measuring low-frequency signals. It is widely used due to its combination of functionality, portability, and affordability.

The main characteristics of the **tinySA** include:

1. Frequency range from **100 kHz to 350 MHz**,
2. Resolution down to **1 kHz**,
3. High-definition color display with an intuitive interface,

The main advantages of the **tinySA** are its compactness, mobility, affordability for both beginners and professionals, and its extended software capabilities [1].

Compact radiometers, such as the **Narda SRM-3006** (Fig. 45), are important tools for measuring electromagnetic radiation (EMR) under various conditions.

Due to their light weight and portability, these devices are widely used in environmental studies, workplace safety monitoring, and other areas where quick assessment of radiation levels is necessary.

Fig. 5. Narda SRM-3006.

The features of the **Narda SRM-3006** (Figure 3) include the ability to provide fast and efficient EMR level measurements. The device can measure electromagnetic fields across a wide frequency range, making it versatile. Its compact design makes it convenient for use in field conditions and for measurements in hard-to-reach locations. The device's built-in functions, such as automatic calibration and a user-friendly interface, enhance ease of use, even for individuals without specialized training.

However, like any equipment, the Narda SRM-3006 also has limitations. One of its main disadvantages is less precise spectral analysis compared to professional spectrum analyzers. While the radiometer can quickly provide measurement results, it may not always be capable of detailed analysis of complex signals, which can be critical in scientific studies. Thus, although compact radiometers like the Narda SRM-3006 are excellent for quick EMR level assessments, their use may be limited in cases requiring detailed spectral analysis or precise measurements of complex signals.

The second group consists of **electromagnetic field (EMF) sensors**.

EMF sensors are designed to measure the intensity of electromagnetic fields in the environment. They are used in various areas, including environmental research, monitoring industrial emissions, workplace safety control, and scientific studies. Sensors may vary in their characteristics, operating principles, and applications depending on specific needs. One of the main functions of EMF sensors is measuring the strength of electric and magnetic fields across different frequency ranges. This allows the collection of data on the effects of various radiation sources, such as radio communication, electronic devices, radar systems, and others.

Devices like the **Tenmars TM-192D** (Fig. 6) belong to this group. It includes a data logger for measuring low-frequency electromagnetic fields in the range of 30–2000 Hz. It is recommended for monitoring electromagnetic field intensity in workplaces and residential areas. The device records radiation intensity in the ranges of 20/200/2000 mG or 2/20/200 μT, with selectable measurement units and an accuracy of ±2.5% +6 digits. Its frequency range is 30–2000 Hz.

Functions include data hold, recording of maximum and minimum values, battery charge indicator, overload indication, automatic range selection, and a built-in clock with a calendar. The data logger can store up to 500 or 9999 datasets. The device features a 4-digit display with a maximum resolution of 0.1/1 mG or 0.001/0.01/0.1 μT. Sampling frequency is 2.5 times per second. Power is provided by a 9V battery, ensuring up to 100 hours of operation. Operating conditions are 5–40°C and up to 80% humidity; storage conditions are -10–60°C and up to 70% humidity. Device dimensions: 173×80×32 mm; weight: 230 g.

Among the many advantages of the Tenmars TM-192D, its ease of use stands out, enabling even untrained users to quickly obtain measurement results. High sensitivity to low EMR levels makes it ideal for monitoring areas with low electromagnetic backgrounds. The ability to operate across a wide frequency range increases its versatility and applicability in various research fields. Thus, the **Tenmars TM-192D** is a reliable and efficient instrument for electromagnetic field measurements, meeting modern environmental monitoring requirements and providing accurate data on electromagnetic radiation levels.

Fig. 6. Tenmars TM-192D.

Measurements of electromagnetic radiation were conducted using the **Tenmars TM-192D** device, which provides accurate and reliable results for electromagnetic field intensity ([10]).

The measurement results and calculated radiation parameters are presented in Table 1.

Table 1 − The measurement results and calculated radiation parameters.

№	Date	Magnetic Field, µT	Power flux density (µW/cm²)
1	2025.04.08 08:00	0.065	0.33631
2	2025.04.08 08:01	0.053	0.2235964
3	2025.04.08 08:04	0.051	0.2070396
4	2025.04.08 08:09	0.058	0.2677744
5	2025.04.08 08:15	0.022	0.0385264
6	2025.04.08 08:16	0.015	0.01791
7	2025.04.08 08:19	0.021	0.0351036
8	2025.04.08 08:20	0.216	3.7138176
9	2025.04.08 08:21	0.016	0.0203776
10	2025.04.08 08:22	0.022	0.0385264
11	2025.04.08 08:25	0.005	0.00199
12	2025.04.08 08:26	0.025	0.04975
13	2025.04.08 08:28	0.001	0.0000796
14	2025.04.08 08:30	0.01	0.00796
15	2025.04.08 08:31	0.09	0.64476
16	2025.04.08 08:33	0.07	0.39004
17	2025.04.08 08:34	0.2	3.184
18	2025.04.08 08:35	0.18	2.57904
19	2025.04.08 08:36	0.102	0.8281584
20	2025.04.08 08:39	0.089	0.6305116
21	2025.04.08 08:40	0.098	0.7644784

Based on the measurements and calculations presented in Table 1, the maximum permissible levels of electromagnetic radiation were exceeded at three observation points. However, due to the limitations of the equipment used for data collection, it was not possible to determine the exact frequency range of the exceedances.

In our opinion, the combined use of the tinySA spectrum analyzer and the Tenmars TM-192D magnetic field meter enables a comprehensive approach to environmental monitoring of electromagnetic stress. Due to their high portability, economic affordability, and technical efficiency, these devices are an optimal choice for research in challenging conditions, including combat zones. Based on the analysis of equipment and our own research, we propose recommendations for the integration of instruments into a monitoring system for electromagnetic stress.

At the first stage, it is necessary to determine which measurement devices will be used in the monitoring system. These may include the tinySA spectrum analyzer and the Tenmars TM-192D sensor.

CONCLUSION

Under the conditions of armed conflict, electromagnetic stress significantly increases due to the use of electronic warfare (EW) systems, active radars, high-power transmitters, and other technologies. For socio-ecosystems exposed to radio-frequency radiation during military operations, environmental monitoring becomes critically important, given the high probability of additional electromagnetic stress affecting both humans and biosphere. For monitoring the radio-frequency impact on socio-ecosystems adjacent to military operations, we consider that devices measuring emissions up to a few gigahertz are sufficient.

The hardware used in radio-frequency radiation monitoring includes spectrum analyzers, radiometers, and electromagnetic field sensors.

Among the types of devices analyzed, according to technical characteristics (accuracy, mobility, sensitivity, autonomy), the tinySA spectrum analyzer and the Tenmars TM-192D electromagnetic field sensor are identified as optimal choices.

The tinySA spectrum analyzer is an effective tool for detailed spectrum analysis and localization of radiation sources, featuring a wide frequency range (100 kHz to 350 MHz) and a resolution of up to 1 kHz.

The Tenmars TM-192D sensor enables the collection of data on electromagnetic stress levels in urban, rural, or natural areas and provides the ability to assess the impact of radiation on ecosystems, operating within a broad frequency range of 30–2000 Hz. Measurements conducted with the Tenmars TM-192D device indicated exceedances of maximum permissible electromagnetic radiation levels at three observation points. However, due to equipment limitations, determining the exact frequency range of these exceedances was not possible. The combination of tinySA and Tenmars TM-192D capabilities provides a comprehensive approach to environmental monitoring of electromagnetic radiation. High portability, economic accessibility, and technical efficiency make these devices an optimal choice for research in challenging environments, including combat zones.

Future work will include conducting instrumental studies of electromagnetic field parameters near radars and performing correlation analysis of the effects on biosphere.

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ASSESSMENT OF THE RISK TO PUBLIC HEALTH FROM AIR POLLUTION IN THE CERTAIN REGIONS OF UKRAINE

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ABSTRACT

The paper presents the results of the risk assessment of non-carcinogenic effects on human health due to air pollution in the certain regions of Ukraine (the south-eastern regions). The main sources of air pollution are examined. An assessment of the level of technogenic loading was carried out using the module of technogenic load on the air basin, as well as the atmospheric air quality was assessed. The assessment of non-carcinogenic risk to human health is based on calculating the hazard coefficient and the total hazard index. According to the long-term research the pollutants that can pose risks to human health (in most cases they are nitrogen dioxide, formaldehyde, phenol) have been identified.

Keywords: air pollution, risk, non-carcinogenic effect, technogenic load, hazard index.

INTRODUCTION

Since the beginning of military actions on the territory of Ukraine in February 2022, the issues of air quality assessment have become increasingly relevant. During combat operations, various harmful substances are released into the air in large quantities. This can contribute to constant increasing their concentrations and increasing the general level of atmospheric pollution.

The level of air pollution is generally formed due to production activities and transport loading. Some regions of Ukraine are significant industrial centers, which forms a technogenic impact on the state of the air basin. Such regions include the study area - the south-eastern regions of Ukraine (the Zaporizhzhya, Dnipropetrovsk, Kharkiv, Donetsk and Luhansk regions).

High levels of air pollution are also a risk factor for public health. Currently, a great number of methods for assessing risks due to air pollution have been developed. They allow to obtain approximate risk assessments based on such indicators as a hazard class, a rate of excess of the maximum permissible concentrations (*MPC*), as well as taking into account characteristics and nature of the pollutants impact on the human body [1].

METHODS AND EXPERIMENTAL PROCEDURES

The aim of the study was to assess the risk of non-carcinogenic effects on public health due to air pollution in the north-eastern regions of Ukraine in the pre-war period.

When assessing the environmental hazard to human health due to air pollution, two types of risk are determined - carcinogenic and non-carcinogenic. Thus, for each pollutant, an average lifetime daily dose can be calculated using the formula:

$$LADI = \frac{(C / W) \cdot V \cdot F \cdot D}{T}, \quad (1)$$

where *LADI* – an average lifetime daily dose, mg/(kg • day);

C – concentration of the pollutant in the environment, mg/m^3;

W – individual body weight, kg;

V – consuming the given contact environment by an individual, m^3/day;

F – frequency of contact event with a carrier, days/year;

D – the period for which the current exposure conditions are extrapolated, years;

T – dose averaging period, days [2, 3].

At the same time to assess the carcinogenic risk for each pollutant, the risk indicators are calculated:

$$CR = SF \cdot LADI, \quad (2)$$

where *CR* – probability of developing cancer, usually expressed in units of 1:1000000;

SF – probability of developing cancer in the event of receiving a single dose of *LADI*, 1/mg/kg • day [2, 3].

In turn, assessing the risk of developing non-carcinogenic effects for individual substances is carried out on the basis of calculating the hazard ratio:

$$HQ = LADI / Rf, \quad (3)$$

where *HQ* – hazard ratio, dimensionless quantity;

Rf – reference (safe) dose, mg/kg" [2, 3].

In the work [4] it is proposed to use the following formula in cases where there is no information on the reference (safe) dose *Rf*:

$$HQ = Ci / C_{MPC}, \quad (4)$$

where *Ci* – average concentration of the *i*-th pollutant, mg/m^3.

Also, the risk of developing non-carcinogenic effects to assess the combined effect of chemicals is characterized based on calculating the hazard index:

$$HI = \sum HQi, \quad (5)$$

where *HQi* – hazard coefficient for individual pollutants [5, 6].

The criteria for characterizing the hazard are given in Table 1.

Table 1 – Classification of non-carcinogenic risk levels for public health.

Risk characterization	Hazard coefficient (*HQ*)
The risk of harmful effects is considered to be negligible	< 1
A threshold value that does not require urgent measures, but cannot be considered sufficiently acceptable	1
The probability of harmful effects increases in proportion to the increase in *HQ*	> 1

THE RESEARCH RESULTS AND DISCUSSIONS

The South-eastern regions of Ukraine are actually the centers of developing and functioning industry in Ukraine. One of the leading industries is metallurgical industry. The largest air pollutants are enterprises of ferrous and non-ferrous metallurgy, heat and power, chemistry, mechanical engineering and food industry. They produce approximately 90.0% of all pollutant emissions.

For most major polluting enterprises, a general decrease in pollutant emissions was noted for the period 2012–2021, which may be partly the result of increased emissions controls, modernization of production facilities or changes in production activities. In 2014–2015, a slight increase in emissions was noted for some enterprises, which may be related to the unstable situation due to the outbreak of hostilities. 2020 is characterized by a general decrease in emissions for most enterprises, possibly due to the economic consequences of the COVID-19 pandemic or changes in production. Military operations in eastern Ukraine likely affected the functioning of enterprises in the region.

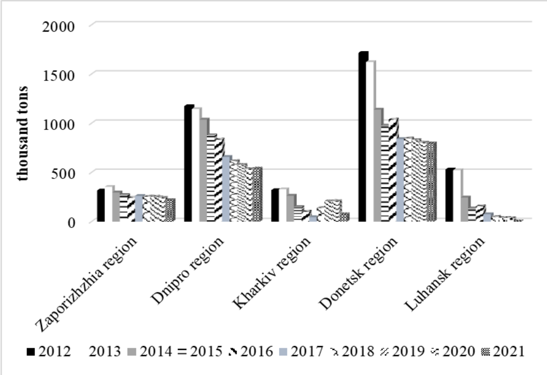
The analysis of pollutant emissions from the stationary sources showed that the Donetsk and Dnipropetrovsk regions were characterized by maximum indicators, the Kharkiv, Zaporizhia and since 2014 Luhansk regions were characterized by minimum emission indicators. As for mobile sources, the maximum emission indicators were noted for the Dnipropetrovsk, Donetsk and Kharkiv regions, the minimum indicators were for the Luhansk region. In general, in the pre-war period there was a general trend towards a decrease in emissions from stationary and mobile sources in all analyzed regions.

Based on the information on the pollutant emission indicators, an assessment of the level of technogenic loading on the air basin in the studied regions was performed using the technogenic load module (M_{AB}) (Fig. 1). The presented figure shows that in fact the pollutant emission indicators and the obtained indicators of the air load module (M_{AB}) have the same tendency. The maximum load level among the examined regions was noted in the Donetsk region, the minimum was in the Kharkiv region. Also, a significant level of technogenic impact was noted in the Dnipropetrovsk region and in 2012-2013 it was in the Luhansk region.

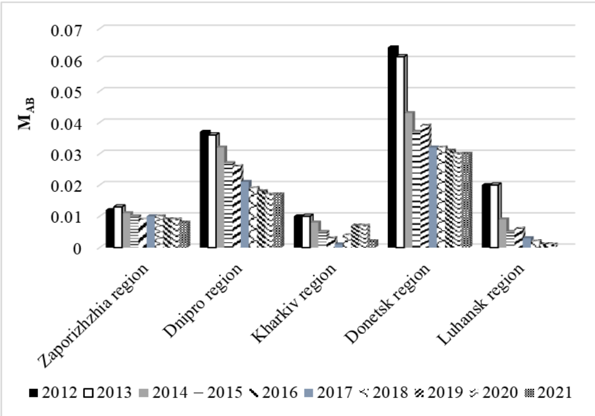
The assessment of atmospheric air quality in the individual cities of the southeastern regions of Ukraine for the period 2012-2021 (Fig. 2) by the value of the air pollution index I_5 showed that the maximum level of pollution in the pre-war period was noted in the cities of the Dnipropetrovsk region, as well as in the city of Mariupol, the Donetsk region. The minimum level of pollution was noted in the city of Kharkiv, although this region belongs to the industrially developed regions of Ukraine.

The assessment of non-carcinogenic risk to human health due to air pollution was performed individually for each region.

Table 2 shows calculations for the city of Zaporizhia based on the official data given in [7 – 16]. Thus, the list of pollutants for which there is a probability of increasing the plausibility of developing harmful effects includes nitrogen dioxide, formaldehyde and phenol constantly. Calculation of the hazard index (*HI)* (Fig. 3) showed that in recent years the value of the indicator has slightly decreased, primarily due to a decrease in the content of nitrogen compounds in the air basin of the city.



a) emissions of pollutants



b) loading

Fig. 1. Technogenic load on the south-eastern regions of Ukraine.

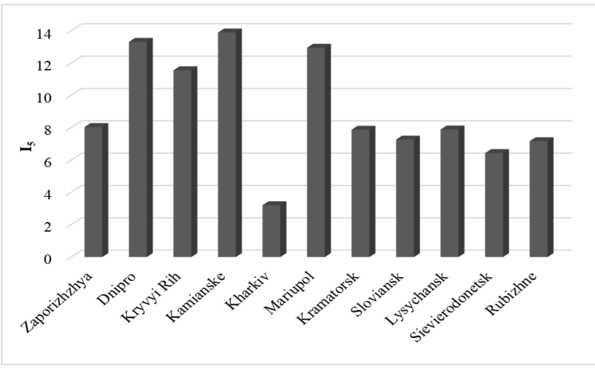


Fig. 2. Averaged values of I_5 for the cities of south-eastern Ukraine.

Table 2 – Results of determining non-carcinogenic risk for the city of Zaporizhzhia

Pollutant	***HQ***									
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
Dust	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.8	0.7	0.9
Sulfur dioxide	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.2
Nitrogen dioxide	2.3	2.5	2.2	2.2	2.0	2.2	2.0	2.0	1.8	1.8
Nitrogen oxide	1.2	1.2	1.0	1.0	1.0	1.0	0.8	0.8	0.8	0.8
Oxide carbon	0.7	0.3	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.4
Formaldehyde	1.7	2.0	1.7	1.7	1.7	1.3	1.3	1.7	1.7	1.7
Phenol	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Hydrogen fluoride	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.2	0.2
Hydrogen chloride	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2

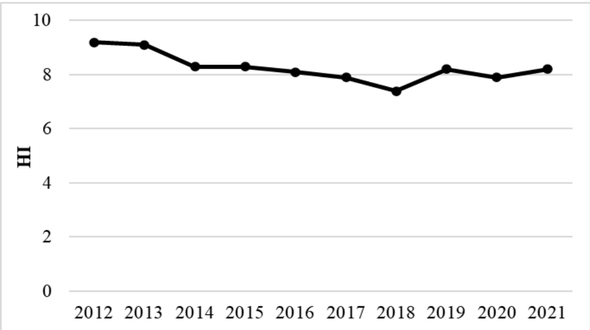


Fig. 3. Hazard index values for the city of Zaporizhzhia in 2012 – 2021.

Table 3 shows the results of calculating non-carcinogenic risk for the cities in the Dnipropetrovsk region based on the data provided in [17 – 25]. Thus, in Dnipro, the list of pollutants for which there is a probability of increasing the plausibility of developing harmful effects includes dust, nitrogen dioxide and formaldehyde constantly. In Kryvyi Rih such substances include dust, formaldehyde and actually nitrogen dioxide constantly, and in Kamianske they are dust, nitrogen dioxide, ammonia, formaldehyde and phenol.

The maximum values of hazard index (Fig. 4) in the city of Dnipro were noted in 2016-2018. In the last years of the pre-war period the index decreased to the indicators of 2013. In the city of Kryvyi Rih the maximum of the indicator was noted in 2015 and 2019, the minimums were in 2016-2018, which is associated with a decrease in the content of nitrogen dioxide and ammonia during this period. In the city of Kamianske during the study period, a decrease in the hazard index was noted in 2014-2016 with further increasing till 2021, actually to the level of 2013.

Table 3 – Results of determining non-carcinogenic risk for the individual cities in the Dnipropetrovsk region

Pollutant	***HQ***								
	2013	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
Dnipro									
Dust	2.0	2.0	2.7	2.7	2.0	2.0	2.7	2.0	1.3
Ammonia	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Nitrogen dioxide	2.3	1.8	2.3	2.8	3.3	3.0	2.3	2.5	2.3
Nitric oxide	1.0	0.7	0.8	0.8	1.0	0.8	0.8	0.8	0.8
Carbon monoxide	1.0	0.7	0.7	1.0	0.7	1.0	0.7	0.7	0.7
Formaldehyde	3.7	4.0	3.7	4.3	4.3	5.0	3.7	5.0	4.7
Phenol	1.3	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	Kryvyi Rih								
Dust	3.3	3.3	5.3	2.7	2.7	2.7	5.3	2.7	2.7
Nitrogen dioxide	1.5	1.5	1.5	1.3	1.0	1.0	1.5	1.0	1.3
Sulfur dioxide	0.32	0.46	0.24	0.32	0.3	0.28	0.24	0.3	0.3
Nitric oxide	0.5	0.5	0.5	0.3	0.2	0.3	0.5	0.5	0.3
Carbon monoxide	0.7	0.7	0.7	2.0	0.7	0.7	0.7	0.7	0.7
Ammonia	0.8	0.8	0.5	0.5	0.3	0.14	0.5	0.3	0.3
Formaldehyde	2.7	3.0	4.0	2.7	3.0	3.7	4.0	5.3	4.7
Phenol	0.7	0.7	0.7	0.3	0.3	0.3	0.7	0.7	0.6
	Kamianske								
Dust	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.0	2.0
Nitrogen dioxide	2.0	2.0	1.8	1.8	1.8	1.8	1.8	2.0	2.0
Sulfur dioxide	-	-	-	-	0.14	0.14	0.14	0.2	0.14
Nitric oxide	0.7	0.7	0.7	0.5	0.7	0.7	0.7	0.7	0.7
Carbon monoxide	1.0	1.0	1.0	1.0	0.7	1.0	1.0	1.0	1.0
Ammonia	1.8	1.3	1.3	1.3	1.2	1.3	1.3	1.3	1.3
Formaldehyde	3.7	3.7	3.0	2.7	3.3	3.0	3.0	4.0	4.3
Phenol	2.7	2.7	2.3	2.0	2.3	2.3	2.3	2.4	2.7

For the city of Kharkiv, no cases of the plausibility of developing harmful effects were noted (Table 4) [26 – 34]. Only individual cases when the *HQ* value was equal to the limit values for carbon monoxide (2016-2017) and formaldehyde (2017) were recorded. The hazard index value underwent certain fluctuations during the study period, but it did not change significantly (Fig. 5). The minimum was noted in 2014, the maximum was in 2016.

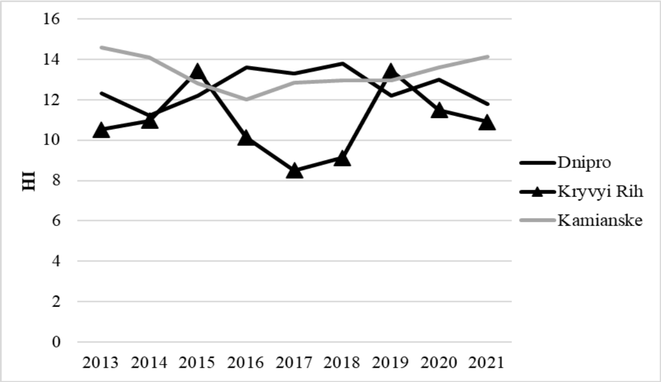


Fig. 4. Hazard index values for the Dnipropetrovsk region in 2013 – 2021.

Table 4 – Results of determining non-carcinogenic risk for the city of Kharkiv

Pollutant	***HQ***									
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
Dust	0,6	0,6	0,6	0,6	0,5	0,6	0,5	0,6	0,6	0,4
Sulfur dioxide	0,1	0,1	0,1	0,16	0,14	0,14	0,14	0,14	0,14	0,14
Nitrogen dioxide	0,6	0,6	0,17	0,2	0,5	0,7	0,5	0,7	0,7	0,7
Nitrogen oxide	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3
Carbon monoxide	0,6	0,6	0,6	0,7	1,0	1,0	0,9	0,9	0,4	0,4
Formaldehyde	0,8	0,8	0,8	0,6	1,0	0,6	0,6	0,6	0,6	1,0
Phenol	0,5	0,5	0,3	0,6	0,6	0,6	0,3	0,6	0,6	0,6
Soot	0,7	0,7	0,4	0,8	0,8	0,6	0,6	0,6	0,4	0,6

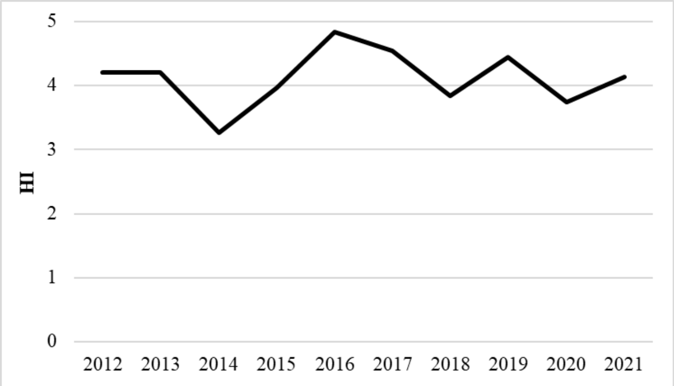


Fig. 5. Hazard index values for Kharkiv in 2012 – 2021.

In the cities of the Donetsk region, according to the official data [35 – 40], the situation varied (Table 5). Thus, in fact in all cities of the region, the probability of developing harmful effects or a limit state was noted for the content of such substances as nitrogen dioxide, formaldehyde and phenol. Also, individual cases of values of the hazard coefficient $HQ \geq 1$ were noted for the content of dust and carbon monoxide.

Table 5 – Results of determining non-carcinogenic risk for the individual cities of the Donetsk region

Pollutant	***HQ***							
	2014	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
Mariupol								
Dust	2.0	0.67	0.67	0.93	0.16	1.07	0.93	-
Ammonia	0.5	0.5	0.25	0.02	0.23	0.23	0.25	-
Nitrogen dioxide	1.0	1.0	1.0	1.25	1.63	1.5	1.25	-
Sulfur dioxide	0.28	0.24	0.2	0.24	0.26	0.3	0.4	-
Carbon monoxide	0.33	0.33	0.33	0.72	0.37	0.29	0.27	-
Formaldehyde	4.67	4.33	4.0	6.0	5.67	6.67	6.67	-
Phenol	1.0	1.0	1.0	1.33	1.67	1.67	1.0	-
Kramatorsk								
Dust	-	-	-	0.8	0.67	0.67	0.67	0.67
Nitrogen dioxide	-	-	-	1.25	0.75	1.25	1.5	1.5
Sulfur dioxide	-	-	-	0.24	0.04	0.06	0.06	0.06
Carbon monoxide	-	-	-	1.0	0.33	0.33	0.67	0.67
Formaldehyde	-	-	-	2.67	2.33	2.33	2.33	2.0
Phenol	-	-	-	1.67	2.33	1.33	1.67	1.67
Hydrogen fluoride	-	-	-	0.6	0.8	0.8	0.6	0.8
Sloviansk								
Dust	-	-	-	0.6	0.67	0.67	0.67	0.67
Nitrogen dioxide	-	-	-	2.25	1.0	1.0	1.0	1.25
Sulfur dioxide	-	-	-	0.2	0.6	0.4	0.4	0.4
Carbon monoxide	-	-	-	1.1	0.33	0.33	0.33	0.33
Formaldehyde	-	-	-	3.33	2.33	2.0	1.33	1.33
Phenol	-	-	-	1.33	2.33	1.33	1.33	1.33
Hydrogen fluoride	-	-	-	0.4	0.6	0.6	0.6	0.6

The hazard index (Fig. 6) reached its maximum value in 2019 in Mariupol. For this city this indicator increased due to an increase in the concentrations of nitrogen dioxide, formaldehyde and phenol. In the cities of Kramatorsk and Sloviansk, it has decreased in recent years.

The situation is somewhat different in the cities of the Luhansk region (Table 6) [41–50]. In the city of Lysychansk, in the vast majority of years, the content of carbon monoxide and formaldehyde could contribute to the development of harmful effects. Also, in recent years, such a dependence has been noted for dust. In the city of Sievierodonetsk, in fact, only formaldehyde concentrations contributed to the development of harmful effects, and in the city of Rubizhne they were formaldehyde and carbon monoxide. In general, the information on this region, as well as on the Donetsk region, is incomplete due to military operations that have been ongoing since 2014. Therefore, the obtained data may not fully reflect the real state of the atmospheric pollution.

In fact, the region hazard index (Fig. 7) has decreased over the study period in all cities. But it is probably a consequence of military actions and the shutdown of industrial activity in connection with this.

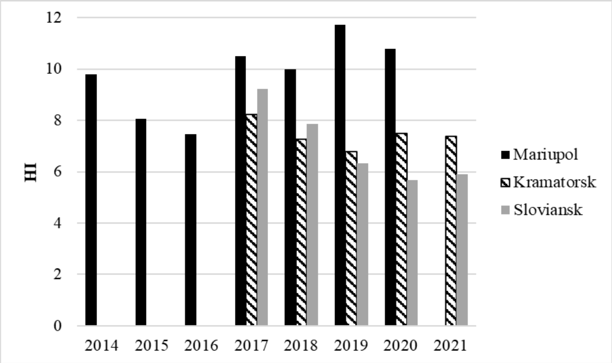


Fig. 6. Hazard index values for the Donetsk region in 2012 – 2021.

Table 6 – Results of determining non-carcinogenic risk for the individual cities of the Luhansk region

Pollutant	***HQ***									
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
Lysychansk										
Dust	0.67	0.67	-	-	0.67	0.67	0.67	1.73	1.73	1.73
Ammonia	0.75	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.33	0.33
Nitrogen dioxide	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.45	0.17	0.17
Sulfur dioxide	0.36	0.32	0.38	0.42	0.020	0.4	0.38	0.54	0.46	-
Carbon monoxide	1.33	1.33	1.33	1.33	1.33	1.33	1.33	0.2	0.93	-
Formaldehyde	4.33	4.33	4.0	4.67	4.0	3.33	3.0	1.0	1.0	1.0
Hydrogen chloride	0.3	0.3	0.3	0.3	0.3	0.3	0.3	-	-	0.3
Sievierodonetsk										
Dust	0.67	0.67	-	-	0.67	0.67	0.67	0.6	0.67	0.67
Ammonia	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.125	0.25	-
Nitrogen dioxide	1.0	0.75	0.5	0.5	0.5	0.5	0.5	0.3	1.25	1.25
Sulfur dioxide	0.4	0.4	0.36	0.36	0.38	0.38	0.36	2.1	0.67	-
Formaldehyde	4.0	3.67	3.33	3.33	3.33	3.0	3.0	0.63	2.0	-

Chlorine hydrogen	0.25	0.25	0.25	0.25	0.3	0.3	0.3	0.63	0.25	0.25
Carbon monoxide	-	-	-	-	-	-	-	-	0.33	0.33
Rubizhne										
Dust	0.67	0.67	-	-	0.67	0.67	0.67	-	0.67	0.67
Aniline	1.0	0.67	0.67	0.67	0.67	0.67	0.67	2.33	0.33	0.33
Nitrogen dioxide	1.0	0.75	0.5	0.5	0.5	0.5	0.5	0.4	1.0	1.0
Sulfur dioxide	0.4	0.4	0.3	0.38	0.38	0.38	0.36	0.48	0.64	0.64
Carbon oxide	1.67	1.67	1.67	1.67	1.67	1.67	1.67	-	1.0	-
Formaldehyde	4.0	3.67	3.33	3.0	3.33	3.0	3.0	3.33	2.33	2.33
Hydrogen chloride	0.2	0.25	0.25	0.25	0.3	0.3	0.25	0.5	0.25	0.25

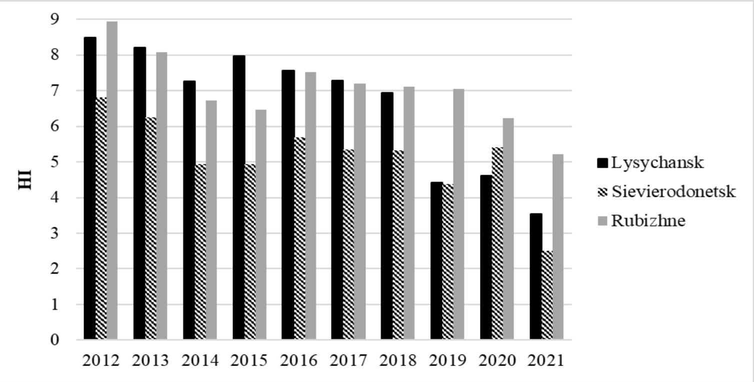


Fig. 7. Hazard index values for the Luhansk region in 2012–2021.

CONCLUSION

The paper presents the results of the assessment of non-carcinogenic risk to public health due to air pollution in the south-eastern regions of Ukraine (the Zaporizhzhya, Dnipropetrovsk, Kharkiv, Donetsk and Luhansk regions). As a result of the research, the following conclusions can be drawn:

1. The south-eastern regions are the centers of developing and functioning industry in Ukraine. The largest air polluters are enterprises of ferrous and non-ferrous metallurgy, heat and power, chemistry, mechanical engineering and food industry. In terms of emissions from the stationary sources, the Donetsk and Dnipropetrovsk regions were characterized by maximum values. The minimum indicators were noted for the Kharkiv, Zaporizhzhia and since 2014 Luhansk regions. The maximum indicators of emissions from the mobile sources were noted for the Dnipropetrovsk, Donetsk and Kharkiv regions, and the minimum was for the Luhansk region. A general tendency towards a decrease in emissions from both types of pollution sources was noted.

2. The maximum level of pollution in the pre-war period was noted in the cities of the Dnipropetrovsk region, as well as in the city of Mariupol in the Donetsk region. The minimum level of pollution was noted in the city of Kharkiv.

3. The assessment of the level of technogenic loading showed that the indicators of pollutant emissions in the study regions and the obtained indicators of the load module have the same trend. The maximum load level was noted in the Donetsk region, the minimum was in the Kharkiv region. A significant level of technogenic impact was noted in the Dnipropetrovsk region and in 2012-2013 it was in the Luhansk region.

4. The assessment of non-carcinogenic risk to human health due to air pollution showed that the list of pollutants for which there is a probability of increasing the plausibility of developing harmful effects in the different cities included nitrogen dioxide, formaldehyde, phenol, dust, ammonia, carbon monoxide. In fact, only for the city of Kharkiv, the possibility of developing harmful effects from air pollution was not noted.

The obtained results are the basis for assessing the state of the air basin in the post-war period. In fact, all studied regions are in the zone of active hostilities. Some parts of the regions are occupied, which makes it difficult to obtain reliable information about the current state of the environment as a whole, including atmospheric air.

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SPATIOTEMPORAL ANALYSIS OF HYDROCHEMICAL PARAMETERS IN THE WESTERN BUG RIVER, LVIV REGION, UKRAINE

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ABSTRACT

This study investigates the spatiotemporal dynamics of hydrochemical parameters in the Western Bug River, a transboundary watercourse in the Lviv region of Ukraine, using monitoring data collected from 2005 to 2024. The research focuses on key indicators such as biochemical oxygen demand, dissolved oxygen, total suspended solids, phosphates, ammonium, chlorides, nitrates, nitrites, and sulphates, assessed across seven observation points. Results indicate a clear gradient in water quality, with upstream rural areas showing greater stability and lower pollutant levels compared to downstream urban and industrial zones, where organic and nutrient contamination is prevalent due to anthropogenic influences such as wastewater discharges and agricultural runoff. Statistical analyses reveal significant relationships among parameters, highlighting the interconnected nature of pollution processes. However, limitations in the monitoring system, including variable sampling frequency and incomplete spatial coverage, hinder the precise identification of pollution sources and the detection of short-term fluctuations. These findings underscore the need for enhanced monitoring strategies and international cooperation between Ukraine and Poland to address transboundary water quality challenges. The study emphasizes the importance of refining data collection and analysis methods to support effective pollution control and ensure the sustainable management of this vital freshwater ecosystem.

Keywords: water quality, Western Bug River, hydrochemical analysis, correlation analysis, ecological monitoring,

INTRODUCTION

Rivers are critical components of freshwater ecosystems, providing essential resources for human populations, industry, and agriculture [1−5]. They serve as a primary source of drinking water, irrigation, and hydroelectric energy production, making their quality a crucial factor in sustainable development and environmental protection [6−10]. However, increasing anthropogenic pressures, including industrial discharge, agricultural runoff, and municipal wastewater, have led to significant changes in the hydrochemical characteristics of river systems. The assessment of hydrochemical parameters plays a vital role in understanding water quality dynamics and identifying potential threats to aquatic ecosystems and public health [11−14].

Water pollution is a growing concern worldwide, as contamination by heavy metals, nutrients, and organic substances can lead to severe ecological consequences, including eutrophication, biodiversity loss, and toxicity to aquatic organisms [15−21]. Previous studies have indicated elevated concentrations of nitrogen and phosphorus compounds, heavy metals, and organic pollutants in various river systems, necessitating continuous monitoring and evaluation [22−31]. In particular, inconsistencies in water quality monitoring data highlight the need for systematic research focused on seasonal and spatial variations of hydrochemical parameters [1], [5], [12], [32−33]. Furthermore, climate change and extreme hydrological events, such as floods and droughts, can exacerbate water quality degradation, affecting ecosystem stability and the availability of clean water resources.

The importance of hydrochemical analysis lies in its ability to provide comprehensive insights into the physicochemical state of water bodies and their response to both natural and anthropogenic stressors. By identifying pollution sources and tracking long-term trends in hydrochemical parameters, water resource managers and policymakers can develop effective measures for pollution control and sustainable water use. Given the increasing demand for high-quality freshwater and the ongoing environmental challenges, expanding research on river water quality is essential for ensuring the protection of aquatic ecosystems and human health.

This study aims to analyse the hydrochemical parameters of a selected river system, focusing on key indicators such as dissolved oxygen, biochemical oxygen demand (BOD_5), suspended solids, and nutrient concentrations (nitrogen and phosphorus compounds).

Special attention is given to assessing potential pollution sources and their contribution to water quality deterioration. By evaluating spatial and temporal trends, this research enhances the understanding of the ecological state of freshwater bodies and provides recommendations for improving water management strategies in the region.

METHODS AND EXPERIMENTAL PROCEDURES

The study area is located along the Western Bug River in the western part of Ukraine, specifically within the Lviv region, which is a key area for both environmental and socio-economic factors. The Western Bug River, one of the major rivers of the region, plays a crucial role in the local hydrological cycle and serves as an important natural resource. This river also forms part of the border between Ukraine and Poland, which adds an international aspect to the study, given the transboundary nature of water management and pollution control.

The river basin covers diverse landscapes, including rural settlements, urban areas, agricultural lands, and industrial zones. These variations result in different anthropogenic impacts on water quality, which are reflected in the hydrochemical parameters measured at various points. The study is particularly focused on understanding the spatial and temporal variations in water quality along the river, with an emphasis on human activities that influence water chemistry.

The first stage of the research involved the collection, systematization, and processing of available hydrochemical data on water quality from 2005 to 2024. These data were obtained from the State Agency of Water Resources of Ukraine, which regularly conducts water quality monitoring across the Western Bug River in the Lviv region. The focus was on key hydrochemical parameters such as Sulphates, Biochemical Oxygen Demand (BOD_5), Dissolved Oxygen (DO), and Total Suspended Solids (TSS), which are essential for assessing the health of the river ecosystem.

Water quality monitoring was conducted as part of the national water quality control programme. Regular sampling occurred at various monitoring points, providing valuable data to evaluate long-term trends in water quality and pollution levels. Sampling was done between 2 to 12 times a year, depending on the monitoring schedule and environmental conditions.

After collection, the raw data underwent preprocessing to ensure consistency and reliability. This included:

- Checking for missing or inconsistent values and applying imputation techniques if necessary.
- Standardizing measurement units and ensuring uniformity across datasets.
- Converting date formats for temporal analysis.
- Filtering out anomalous values that could distort statistical analysis.

The study primarily concentrated on analysing the levels of pollutants such as sulphates, BOD_5, DO, TSS, etc. These indicators are crucial for understanding both natural processes and the impact of anthropogenic activities, such as agriculture, industry, and wastewater discharges. The assessment of water quality was carried out by comparing the obtained values of the studied parameters with the standards specified in DSanPiN 2.2.4-171-10 “Hygienic Requirements for Drinking Water Intended for Human Consumption,” as well as in the regulatory document “On Approval of Hygienic Standards for Water Quality in Water Bodies for Drinking, Household, and Other Population Needs” and the “Methodology for the Environmental Assessment of Surface Water Quality.”

To evaluate the spatiotemporal variability of hydrochemical parameters, statistical methods were applied. Statistical methods were applied to analyse the data, including descriptive statistics (mean, range, standard deviation) to summarize the data and identify trends. Box plots were generated to visualize the distribution of each parameter over time. Additionally, correlation and regression analyses were conducted to examine the relationships between the water quality parameters.

The Pearson correlation method using the Pandas library in Python was employed to compute correlations between the parameters, helping to identify significant interdependencies.

To enhance the statistical analysis, the spatial distribution of hydrochemical parameters was examined by mapping the monitoring points using QGIS. This approach allowed for a visual representation of the sampling locations along the Western Bug River, facilitating the assessment of spatial variability in water quality.

THE RESEARCH RESULTS AND DISCUSSIONS

The Western Bug River is a key transboundary watercourse in Eastern Europe, flowing through Ukraine and Poland. It originates in western Ukraine and follows a northwestern path, forming part of the Ukrainian-Polish border before eventually joining the Vistula River. The river spans approximately 772 km, with its basin covering around 21,500 km². Major tributaries include the Horyn, Zbruch, and Styr rivers. The basin features a diverse landscape of forests, wetlands, and agricultural lands. In Ukraine, it primarily extends across the Lviv and Volyn regions.

The Western Bug plays a crucial role in local communities, serving as a source of water for drinking, irrigation, and industrial needs. Its ecosystems support a rich variety of flora and fauna, underscoring the importance of conservation efforts. The river also holds hydrological significance, influencing water quality and availability in both Ukraine and Poland. Effective management of the basin is essential for mitigating pollution, controlling flooding, and ensuring sustainable resource use. Given its transboundary nature, cooperation between the two countries is vital to maintaining the ecological health of the river and its surrounding environment [34−35].

The locations of the water sampling points are illustrated in Figure 1, providing a visual representation of the monitoring sites along the Western Bug River. A detailed description of these sampling points, including their coordinates and specific characteristics, is presented in Table 1.

Fig. 1. The study area and observation posts.

The assessment of water quality in the Western Bug River is based on a range of hydrochemical parameters that serve as indicators of pollution levels and overall ecosystem health. The key parameters analysed in this study include biochemical oxygen demand (BOD_5), dissolved oxygen (DO), total suspended solids (TSS), phosphates, ammonium, chlorides, nitrates, nitrites, and sulphates. These parameters were selected due to their ecological significance and their role in assessing the anthropogenic impact on water bodies. Their concentrations were compared with the regulatory standards and the norms set for domestic purposes water and fishery water bodies.

Table 1 − The observation points.

Observation Point	Description
P1	Western Bug River, 631 km, Litovezh village, bridge on the Novovolynsk-Chervonohrad road, border with the Republic of Poland. This point is located at the international border and is influenced by cross-border water management practices.
P2	Western Bug River, 632 km, Starhorod village, Sokal district (border between Lviv and Volyn regions). This area is characterized by agricultural land and small-scale industry, which could impact the river's water quality.
P3	Western Bug River, 637 km, Sokal town. Sokal is a larger settlement with a mix of industrial and residential areas, likely contributing to urban runoff and wastewater discharges into the river.
P4	Western Bug River, 689 km, Dobrotvir Reservoir, downstream, upper side of the water intake. This reservoir serves as a key water source, and the surrounding area is crucial for hydropower and local water supply. Water quality here can be affected by sedimentation, eutrophication, and changes in water flow.
P5	Western Bug River, 704 km, Kamianka-Buzka town. Kamianka-Buzka is a small town where agricultural runoff and untreated sewage are potential pollutants of the river.
P6	Western Bug River, 723 km, Staryi Dobrotvir village, Kamianka-Buzka district. This rural area is subject to agricultural runoff, and its impact on water quality is monitored through various chemical parameters.
P7	Western Bug River, 781 km, Busk town, Lviv region. Busk is an important urban center, with a population that contributes to wastewater discharge into the river, which can influence the water's hydrochemical characteristics.

Biochemical oxygen demand (BOD_5) is a critical indicator of organic pollution, reflecting the amount of oxygen required by microorganisms to decompose organic matter. Elevated BOD_5 levels indicate excessive organic load, often resulting from wastewater discharge, agricultural runoff, and the decomposition of organic debris. According to regulatory standards, the maximum permissible BOD_5 concentration for water bodies of fishery importance is 3 mg/dm^3 for warm-water fish and 6 mg/dm^3 for cold-water fish, while no specific limit is set for drinking water.

The box plot in Figure 2 illustrates the spatial and temporal distribution of biochemical oxygen demand (BOD_5) across the seven observation points (P1–P7) along the Western Bug River from 2005 to 2024. The median BOD_5 values range from approximately 2.5 mg/dm^3 at P1 (Litovezh village) to 4.8 mg/dm^3 at P3 (Sokal town), indicating a notable increase in organic pollution downstream. The interquartile ranges (IQR) vary significantly, with P3 showing the widest spread (2.8–6.5 mg/dm^3), suggesting greater variability and potential episodic pollution events, likely linked to urban wastewater discharges. In contrast, P1 exhibits a narrower IQR (2.0–3.2 mg/dm^3) and fewer outliers, reflecting more stable conditions near the border. Several points, particularly P3 and P5 (Kamianka-Buzka), exceed the fishery threshold of 3 mg/dm^3 for warm-water fish, highlighting areas of concern for aquatic ecosystem health.

Dissolved oxygen (DO) plays a fundamental role in sustaining aquatic life, as oxygen availability directly affects metabolic processes in aquatic organisms. The primary sources of dissolved oxygen in river ecosystems include atmospheric diffusion, photosynthesis by aquatic plants, and turbulent water flow. A decrease in DO levels is often associated with organic pollution and eutrophication, leading to oxygen depletion and potential fish kills. The minimum permissible concentration for drinking water is 4 mg/dm3, while for fishery water bodies, the required level is at least 6 mg/dm3 for warm-water fish and 7 mg/ dm3 for cold-water fish.

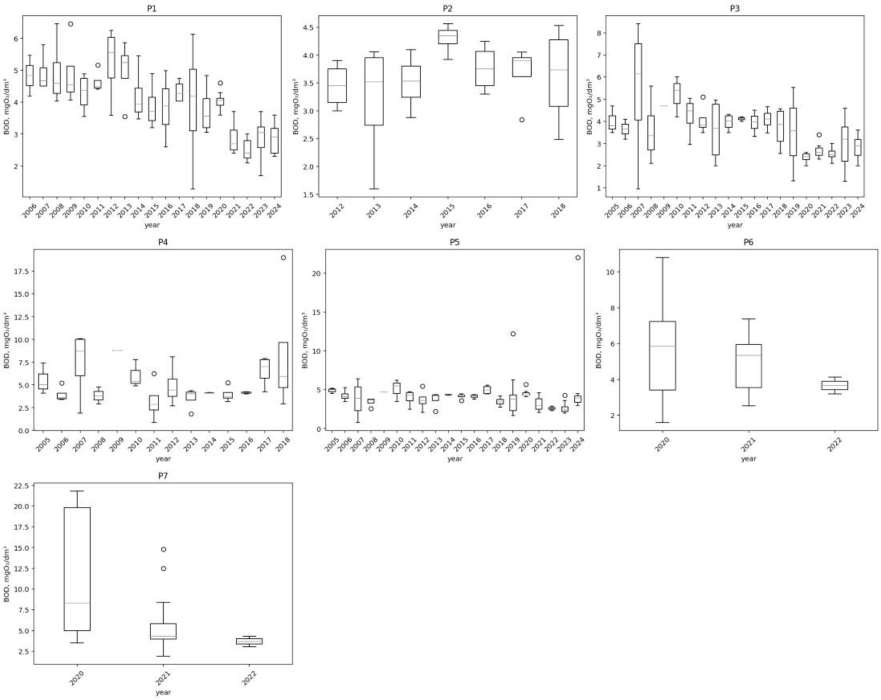

Fig. 2. Spatial and temporal distribution of observations for BOD_5.

Figure 3 presents the spatial and temporal variability of dissolved oxygen (DO) concentrations across the observation points from 2005 to 2024. Median DO levels range from 6.2 mg/ dm^3 at P3 (Sokal town) to 8.5 mg/dm^3 at P1 (Litovezh village), with a general trend of decreasing oxygen availability downstream. The IQR at P3 (5.0–7.5 mg/dm^3) indicates significant fluctuation, potentially due to organic pollution and eutrophication, while P1 shows a tighter range (7.8–9.0 mg/dm^3), reflecting better oxygenation near the river’s upper reaches. Outliers below 4 mg/dm^3, the minimum threshold for drinking water, are observed at P3 and P5 (Kamianka-Buzka), whereas P7 (Busk town) occasionally falls below the fishery limit of 6 mg/dm^3. These findings suggest that urban and industrial influences compromise oxygen levels at specific sites.

Total suspended solids (TSS) represent particulate matter present in water, which can originate from natural erosion, industrial effluents, and surface runoff. High concentrations of suspended solids reduce light penetration, hinder photosynthesis, and may serve as carriers for pollutants. Although no direct limit is established for drinking water, fishery water bodies regulations stipulate a maximum concentration of 20 mg/dm3 for warm-water fish and 10 mg/dm3 for cold-water fish.

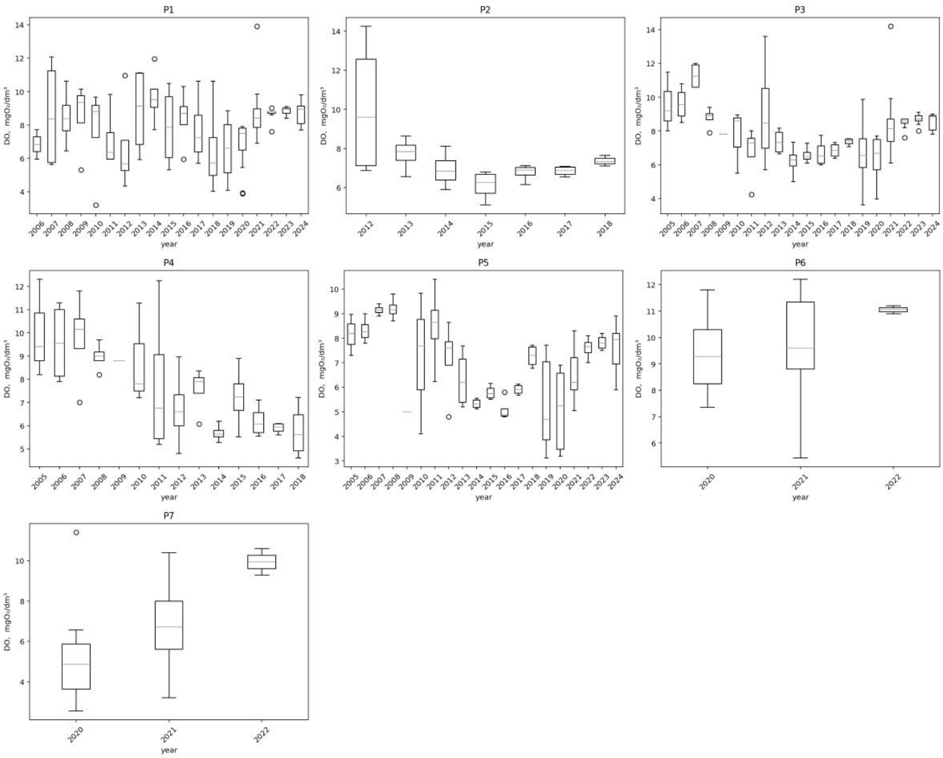

Fig. 3. Spatial and temporal distribution of observations for DO.

The box plot in Figure 4 depicts the distribution of total suspended solids (TSS) across the Western Bug River monitoring stations over the study period. Median TSS concentrations range from 8 mg/dm^3 at P1 (Litovezh village) to 18 mg/dm^3 at P4 (Dobrotvir Reservoir), with the latter showing the highest variability (IQR: 12–25 mg/dm^3). This elevated TSS at P4 likely results from sedimentation and reservoir dynamics, while P1’s lower values (IQR: 6–10 mg/dm^3) indicate minimal particulate input near the border. Multiple outliers exceeding the fishery limit of 20 mg/dm^3 for warm-water fish are observed at P3 (Sokal town) and P5 (Kamianka-Buzka), reaching up to 30 mg/dm^3, suggesting contributions from urban runoff and agricultural erosion. These spatial differences underscore the influence of land use on particulate matter loads.

Phosphates (PO_4^{3-}) are crucial for biological productivity but, in excess, contribute to eutrophication by stimulating algal blooms. The primary sources of phosphate pollution include agricultural fertilizers, domestic sewage, and detergent residues. Elevated phosphate concentrations accelerate the depletion of dissolved oxygen, leading to the deterioration of water quality and ecosystem imbalance. While phosphates are not directly regulated in drinking water standards, their concentration in fishery waters should not exceed 0.2 mg/dm3.

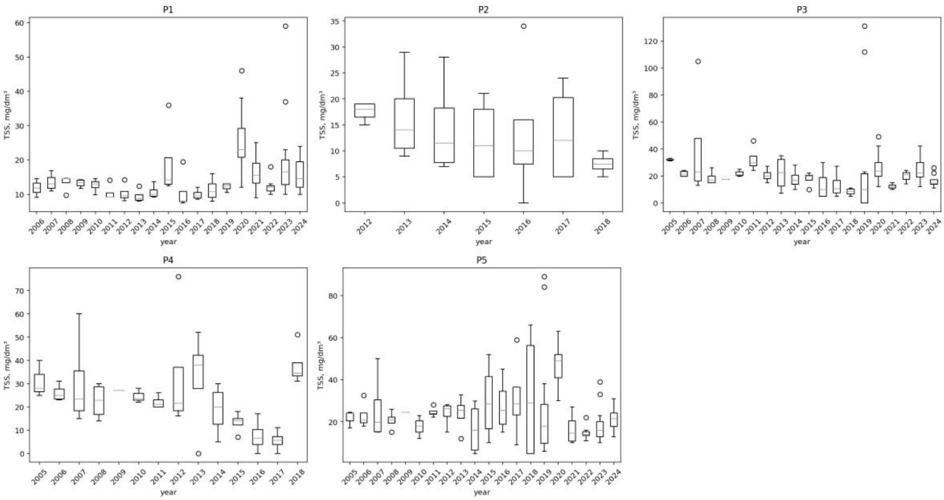

Fig. 4. Spatial and temporal of observations for TSS.

Figure 5 illustrates the spatial and temporal distribution of phosphate concentrations along the Western Bug River from 2005 to 2024. Median values range from 0.05 mg/dm^3 at P1 (Litovezh village) to 0.25 mg/dm^3 at P3 (Sokal town), with P3 exhibiting the widest IQR (0.15–0.35 mg/dm^3) and frequent outliers exceeding the fishery limit of 0.2 mg/dm^3. This suggests significant phosphate enrichment, likely from urban sewage and agricultural runoff in Sokal. In contrast, P1 and P6 (Staryi Dobrotvir) show lower medians (0.05–0.08 mg/dm^3) and narrower ranges (IQR: 0.03–0.10 mg/dm^3), indicating minimal nutrient pollution in rural upstream areas. The exceedance of regulatory thresholds at downstream sites (P3, P5, and P7) highlights the risk of eutrophication and its ecological implications.

Phosphates play a critical role in the ecological dynamics of the Western Bug River, serving as both a nutrient essential for aquatic plant growth and a potential driver of water quality degradation when present in excess. Elevated phosphate levels, primarily stemming from agricultural fertilizers and domestic sewage, are a widespread concern in river systems, as they can accelerate eutrophication, leading to algal blooms and subsequent oxygen depletion. In the context of this study, the assessment of phosphate concentrations across the observation points provides insight into the spatial influence of land use practices, particularly in areas with intensive farming and urban development. Understanding these patterns is vital for evaluating the river’s suitability for aquatic life and human use, as well as for informing strategies to mitigate nutrient pollution in this transboundary watershed.

Ammonium (NH_4^+) is another important nitrogenous compound that can indicate organic pollution and microbial activity. It originates from agricultural runoff, sewage discharge, and the decomposition of organic matter. Ammonium is particularly problematic in aquatic environments due to its potential toxicity to fish and its role in oxygen consumption during nitrification. The maximum allowable concentration in drinking water is 0.5 mg/dm^3, while for fishery waters, it should not exceed 0.5 mg/dm^3 for warm-water fish and 0.39 mg/dm^3 for cold-water fish.

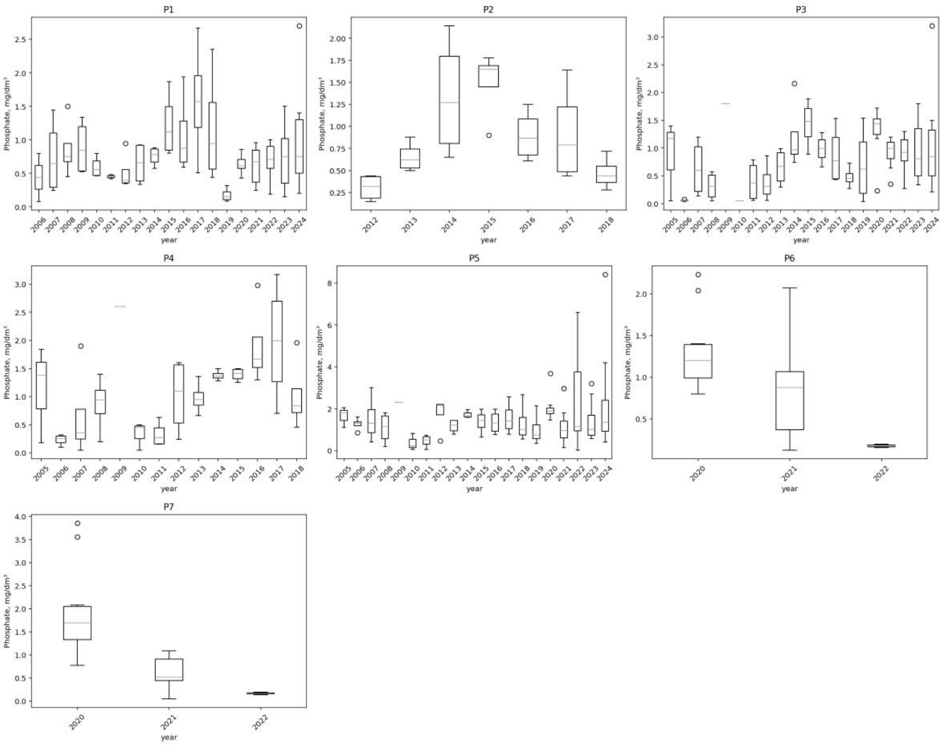

Fig. 5. Spatial and temporal of observations for phosphates.

The box plot in Figure 6 shows the spatiotemporal variability of ammonium concentrations across the observation points. Median values range from 0.10 mg/dm^3 at P1 (Litovezh village) to 0.45 mg/dm^3 at P3 (Sokal town), with P3 displaying the broadest IQR (0.30–0.60 mg/dm^3) and outliers reaching 0.80 mg/dm^3, exceeding the drinking water limit of 0.5 mg/dm^3 and the fishery threshold of 0.39 mg/dm^3 for cold-water fish. This indicates substantial organic pollution, likely from untreated sewage in urban areas. Conversely, P1 and P6 (Staryi Dobrotvir) exhibit lower medians (0.10–0.15 mg/dm^3) and tighter ranges (IQR: 0.08–0.20 mg/dm^3), reflecting less anthropogenic impact upstream. The elevated ammonium at P5 (Kamianka-Buzka) and P7 (Busk town) further suggests widespread contamination from human activities.

Ammonium is a key indicator of organic pollution in freshwater systems like the Western Bug River, often introduced through sewage discharges, agricultural runoff, and the natural decomposition of organic matter. Its presence in elevated concentrations can pose significant risks to aquatic ecosystems due to its toxicity to fish and its contribution to oxygen demand during nitrification processes. In this study, the analysis of ammonium levels across the monitoring sites sheds light on the extent of anthropogenic influence, particularly in urbanized and agriculturally intensive areas. Tracking its distribution is essential for assessing the river's ecological health and identifying priority areas for pollution control measures.

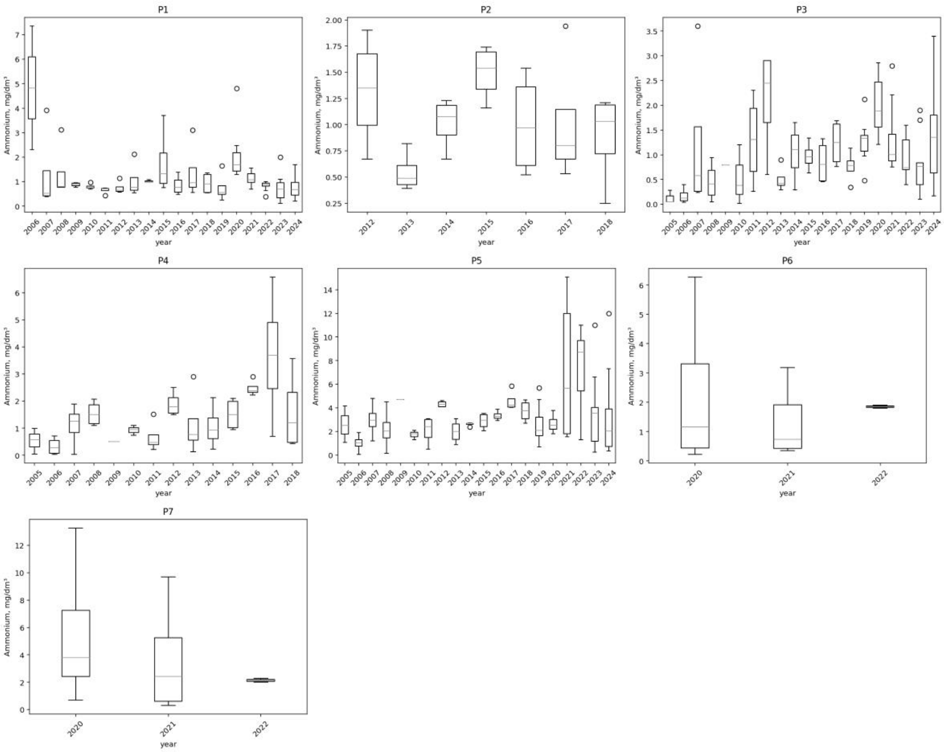

Fig. 6. Spatial and temporal of observations for ammonium.

Chlorides (Cl^-) are naturally present in water bodies but may increase due to anthropogenic influences such as road salting, industrial discharges, and wastewater effluents. High chloride levels can affect aquatic life and alter the taste and corrosiveness of drinking water. According to established standards, the permissible concentration for drinking water is 250 mg/dm^3, while for fishery waters, it should not exceed 300 mg/dm^3.

Figure 7 presents the distribution of chloride concentrations across the Western Bug River from 2005 to 2024. Median chloride levels range from 20 mg/dm^3 at P1 (Litovezh village) to 120 mg/dm^3 at P3 (Sokal town), with P3 showing the highest variability (IQR: 80–150 mg/dm^3) and outliers approaching 200 mg/dm^3. These elevated levels likely stem from urban and industrial discharges in Sokal. In contrast, P1 and P6 (Staryi Dobrotvir) exhibit lower medians (20–30 mg/dm^3) and narrower IQRs (15–40 mg/dm^3), indicative of minimal anthropogenic influence upstream. No sites exceed the drinking water limit of 250 mg/dm^3 or the fishery threshold of 300 mg/dm^3, though the increasing trend downstream (e.g., P5 and P7 with medians of 80–100 mg/dm^3) suggests a cumulative impact of human activities on chloride concentrations.

Chlorides occur naturally in river systems but can increase substantially due to human activities such as industrial discharges, road salting, and wastewater effluents, affecting water quality in the Western Bug River. While moderate chloride levels are generally benign, excessive concentrations may alter the river's taste, increase corrosiveness, and stress aquatic organisms. This study examines chloride variations across observation points to evaluate the impact of anthropogenic inputs, particularly in urban and industrial zones. Such insights are crucial for understanding the broader chemical balance of the river and ensuring its suitability for domestic and ecological purposes.

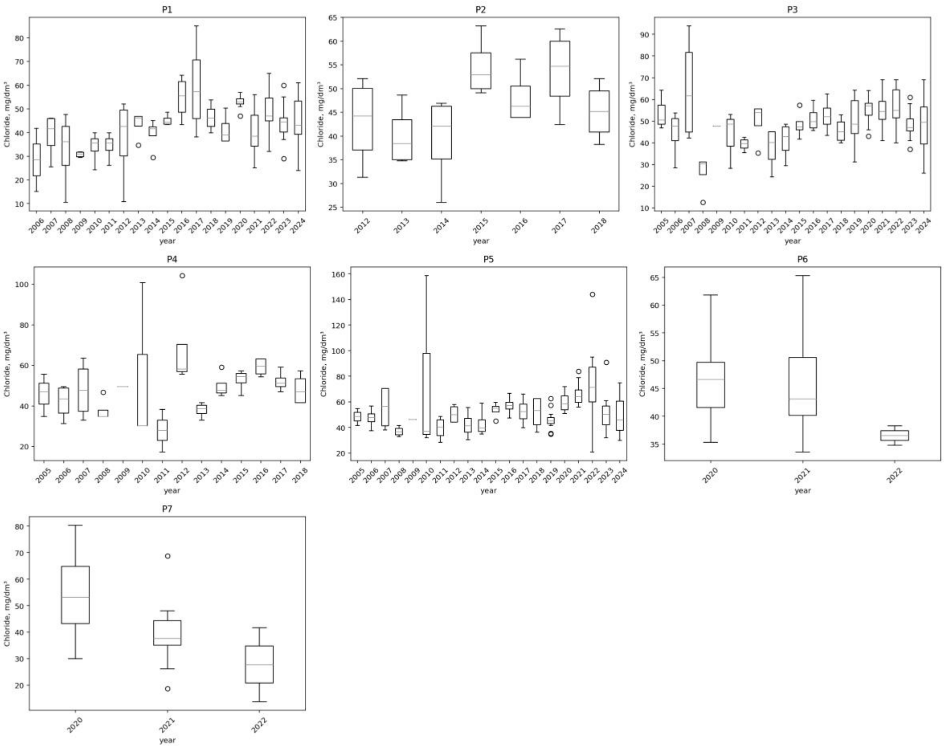

Fig. 7. Spatial and temporal of observations for chlorides.

Nitrates (NO_3^-) are essential nutrients for plant growth, but their excessive presence in water bodies leads to eutrophication and poses significant health risks, particularly through the formation of methemoglobinemia or "blue baby syndrome" in infants. Nitrate pollution primarily results from agricultural fertilizers, wastewater discharges, and atmospheric deposition. The regulatory limit for drinking water is set at 50 mg/dm^3, while for fishery waters, it should not exceed 40 mg/dm^3.

The box plot in Figure 8 depicts the spatial and temporal variability of nitrate concentrations along the Western Bug River. Median values range from 5 mg/dm3 at P1 (Litovezh village) to 25 mg/dm^3 at P5 (Kamianka-Buzka), with P5 showing a wide IQR (15–35 mg/dm^3) and outliers up to 45 mg/dm^3, approaching the drinking water limit of 50 mg/dm^3 and exceeding the fishery threshold of 40 mg/dm^3. This reflects significant agricultural runoff in the area. Upstream sites like P1 and P6 (Staryi Dobrotvir) maintain lower medians (5–10 mg/dm^3) and tighter ranges (IQR: 3–15 mg/dm^3), indicating less nitrate input. The elevated nitrate levels at P3 (Sokal town) and P7 (Busk town), with medians of 20–22 mg/dm^3, further suggest widespread nutrient pollution from anthropogenic sources across the basin.

Nitrates, vital nutrients for plant growth, become pollutants in river systems, when their concentrations rise due to agricultural fertilizers, wastewater discharges, and atmospheric deposition. Excessive nitrate levels can trigger eutrophication and pose health risks, such as methemoglobinemia in infants, making their monitoring a public health priority. This study investigates nitrate distribution along the river to assess the influence of land use, particularly in farming-intensive regions. These findings contribute to understanding nutrient dynamics and support the development of strategies to mitigate their environmental impact.

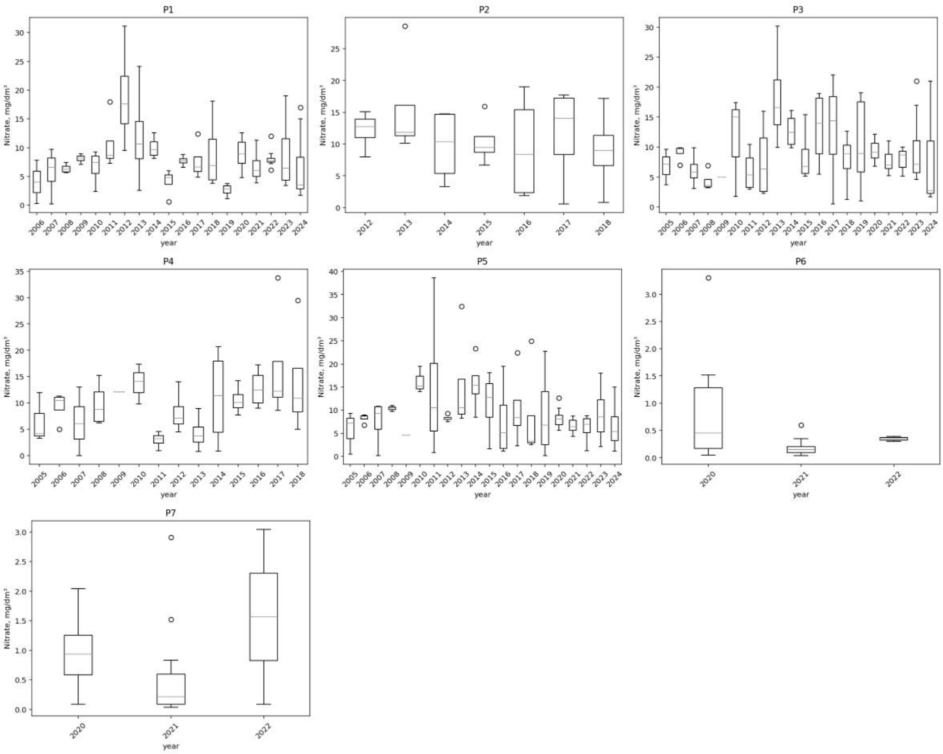

Fig. 8. Spatial and temporal of observations for nitrates.

Nitrites (NO_2^-), as intermediates in the nitrogen cycle, are highly reactive and often serve as indicators of recent contamination from sewage or industrial waste. Their accumulation in water is of concern due to their toxicity to aquatic life and potential health risks to humans. The permissible limit for drinking water is 0.5 mg/dm^3, while for fishery waters, it is significantly lower at 0.08 mg/dm^3 due to its harmful effects on fish metabolism.

Figure 9 illustrates the spatiotemporal distribution of nitrite concentrations across the observation points from 2005 to 2024. Median values range from 0.02 mg/dm^3 at P1 (Litovezh village) to 0.15 mg/dm^3 at P3 (Sokal town), with P3 exhibiting the highest variability (IQR: 0.10–0.25 mg/dm^3) and outliers reaching 0.40 mg/dm^3, approaching the drinking water limit of 0.5 mg/dm^3 and exceeding the fishery threshold of 0.08 mg/dm^3. This indicates recent contamination, likely from sewage or industrial waste in Sokal. Upstream sites (P1 and P6) show lower medians (0.02–0.05 mg/dm^3) and narrower ranges (IQR: 0.01–0.08 mg/dm^3), reflecting cleaner conditions. Elevated nitrite levels at P5 (Kamianka-Buzka) and P7 (Busk town), with medians around 0.10 mg/dm^3, underscore the pervasive influence of anthropogenic pollution downstream.

Nitrites, as reactive intermediates in the nitrogen cycle, serve as sensitive indicators of recent pollution, often linked to sewage, industrial waste, or agricultural runoff. Their accumulation is concerning due to their high toxicity to aquatic life and potential health risks to humans, even at low concentrations. This study analyzes nitrite levels across the monitoring network to detect areas of acute contamination and evaluate their spatial extent. Such data are critical for pinpointing pollution sources and safeguarding the river's ecosystem and usability as a freshwater resource.

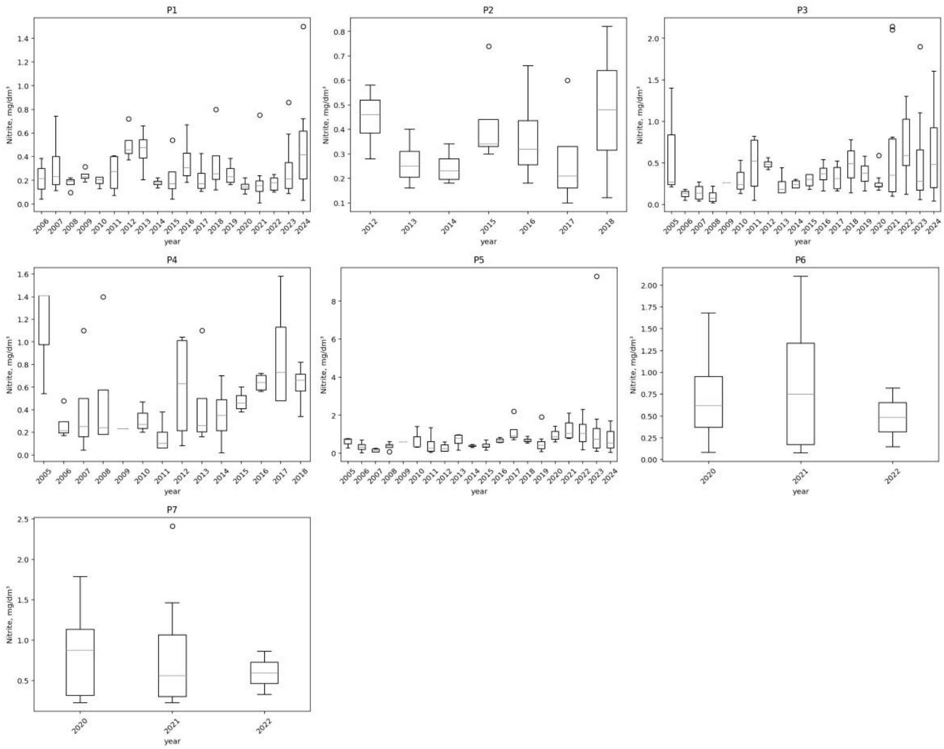

Fig. 9. Spatial and temporal of observations for nitrites.

Sulphates (SO_4^{2-}) are naturally occurring ions in water, primarily originating from geological formations, industrial processes, and mining activities. While moderate sulphate levels are not harmful, excessive concentrations can alter water taste, cause gastrointestinal discomfort in humans, and impact aquatic ecosystems. Drinking water standards set a maximum allowable sulphate concentration of 250 mg/dm^3, whereas for fishery waters, the limit is 100 mg/dm^3.

The box plot in Figure 10 shows the spatial and temporal distribution of sulphate concentrations along the Western Bug River. Median values range from 30 mg/dm^3 at P1 (Litovezh village) to 90 mg/dm^3 at P4 (Dobrotvir Reservoir), with P4 displaying the widest IQR (70–110 mg/dm^3) and outliers up to 130 mg/dm^3, exceeding the fishery limit of 100 mg/dm^3 but remaining below the drinking water threshold of 250 mg/dm^3. This suggests contributions from industrial activities or geological inputs near the reservoir. Upstream sites like P1 and P6 (Staryi Dobrotvir) exhibit lower medians (30–40 mg/dm^3) and tighter ranges (IQR: 25–50 mg/dm^3), indicating minimal sulphate pollution. The increasing trend downstream, with medians of 70–80 mg/dm^3 at P3, P5, and P7, highlights the cumulative impact of anthropogenic and natural sources on sulphate levels.

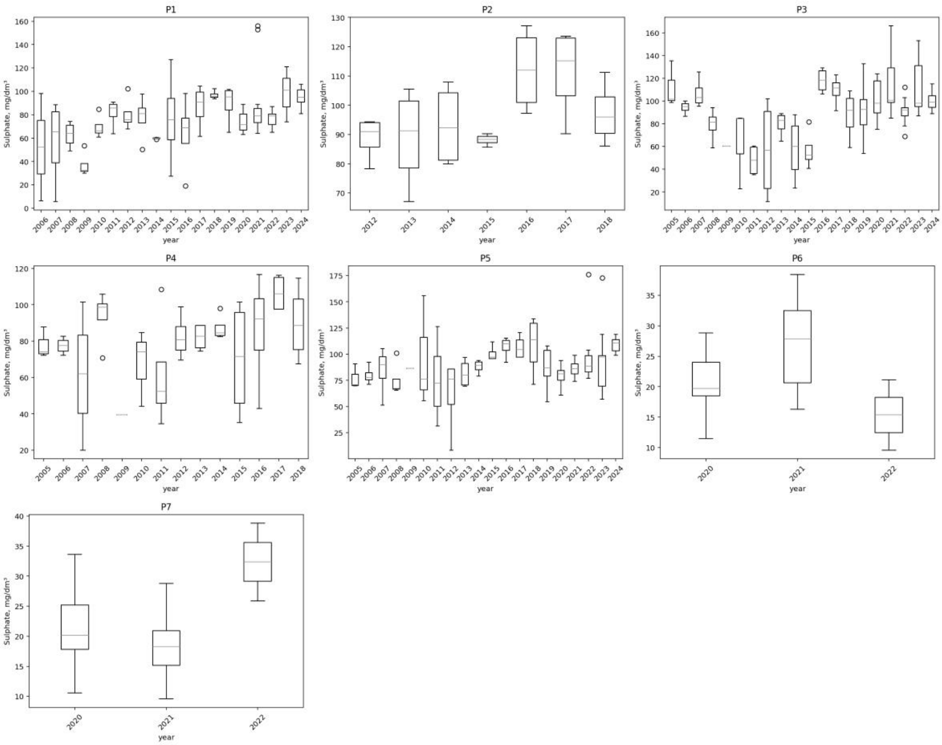

Fig 10. Spatial and temporal of observations for sulphates.

The Pearson correlation analysis shows several significant relationships between water quality parameters. The correlation matrix in Figure 11 reveals significant relationships between hydrochemical parameters across the Western Bug River observation points from 2005 to 2024, calculated using the Pearson correlation method. A strong positive correlation ($r = 0.85$) is observed between BOD_5 and ammonium, indicating that organic pollution sources, such as wastewater discharges, contribute to both parameters. Dissolved oxygen (DO) shows a strong negative correlation with BOD_5 ($r = -0.78$) and phosphates ($r = -0.65$), reflecting oxygen depletion due to organic decomposition and eutrophication. Nitrates and phosphates exhibit a moderate positive correlation ($r = 0.55$), suggesting common agricultural origins. Sulphates and chlorides also display a moderate correlation ($r = 0.60$), potentially linked to industrial discharges. These interdependencies highlight the complex interplay of natural and anthropogenic factors influencing water quality in the river basin.

The analysis of hydrochemical parameters in the Western Bug River reveals clear spatial and temporal patterns shaped by a combination of natural processes and human activities. Upstream areas consistently exhibit more stable water quality conditions with lower pollutant levels, likely due to reduced anthropogenic influence near the river's source and border regions. In contrast, downstream sites, particularly those near urban centres and industrial zones, show greater variability and evidence of contamination, reflecting the cumulative impact of pollution sources such as untreated wastewater, agricultural runoff, and industrial discharges. The diverse land use within the river basin – including rural settlements, agricultural lands, and urbanized areas – contributes to these disparities, highlighting the challenge of managing water quality across a transboundary system with varying environmental pressures.

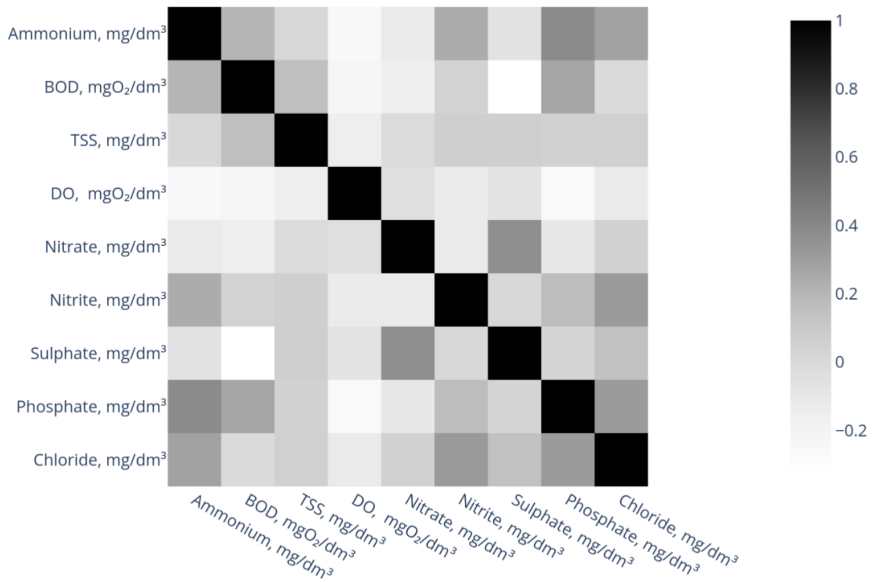

Fig. 11. Correlation matrix of the hydrochemical properties at the observed points.

Despite the comprehensive dataset spanning nearly two decades, limitations in the current monitoring system pose challenges to fully understanding and addressing water quality dynamics. The frequency of sampling, which varies across seasons and years, may not adequately capture short-term pollution events or rapid changes driven by hydrological extremes, such as floods or droughts. Additionally, potential gaps in historical records could affect the reliability of long-term trends, particularly for parameters sensitive to episodic inputs. The spatial distribution of monitoring points, while strategically placed, may not fully represent the influence of smaller tributaries or localized pollution hotspots, limiting the granularity of the assessment. These constraints underscore the difficulty of achieving a holistic picture of water quality in a complex river system influenced by both local and cross-border factors.

The statistical relationships among hydrochemical parameters further emphasize the interconnected nature of pollution processes, with organic and nutrient-related indicators showing strong associations that point to common anthropogenic origins. However, the existing monitoring framework struggles to pinpoint specific pollution sources or quantify their contributions, a critical step for effective management. The transboundary context adds another layer of complexity, as differing regulatory standards and management practices between Ukraine and Poland may hinder coordinated efforts to mitigate pollution. These findings highlight the need for enhanced monitoring strategies, including higher temporal resolution, broader spatial coverage, and integrated approaches to data analysis, to address the multifaceted challenges facing the Western Bug River and ensure its ecological integrity and usability as a freshwater resource.

CONCLUSION

This study investigates the spatiotemporal dynamics of hydrochemical parameters in the Western Bug River, a transboundary watercourse in the Lviv region of Ukraine, using monitoring data collected from 2005 to 2024.

The research focuses on key indicators such as biochemical oxygen demand, dissolved oxygen, total suspended solids, phosphates, ammonium, chlorides, nitrates, nitrites, and sulphates, assessed across seven observation points.

Results indicate a clear gradient in water quality, with upstream rural areas showing greater stability and lower pollutant levels compared to downstream urban and industrial zones, where organic and nutrient contamination is prevalent due to anthropogenic influences such as wastewater discharges and agricultural runoff.

Statistical analyses reveal significant relationships among parameters, highlighting the interconnected nature of pollution processes. However, limitations in the monitoring system, including variable sampling frequency and incomplete spatial coverage, hinder the precise identification of pollution sources and the detection of short-term fluctuations.

These findings underscore the need for enhanced monitoring strategies and international cooperation between Ukraine and Poland to address transboundary water quality challenges.

The study emphasizes the importance of refining data collection and analysis methods to support effective pollution control and ensure the sustainable management of this vital freshwater ecosystem.

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ENVIRONMENTAL AND RADIATION SAFETY OF RESERVOIRS IN THE NUCLEAR POWER PLANT AREA

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ABSTRACT

An established concentration balance is formed between the components of reservoirs of the water system adjacent to the NPP, the issues of improving the system of environmental standards for permissible levels of radionuclide contamination of freshwater reservoirs in the process of trouble-free operation of nuclear power plants, does not receive sufficient attention. The situation is complicated by the fact that water systems are connected hydrologically with the nuclear power plants technological reservoirs that are in condition of long-lasting intake of radionuclides and transfer of the latter to irrigation of agricultural crops.

In this work was solved the applied research task of developing environmental safety standards, namely, the establishment of permissible levels of radionuclide contamination of freshwater reservoirs, which are hydrologically connected with the technological reservoirs of nuclear power plants and are used to meet the irrigational consumptive use of the population.

Keywords: environmental and radiation safety, reservoirs, the nuclear power plant area, environmental standards, radionuclide contamination.

INTRODACTION

One of the types of water usage of freshwater reservoirs in the area of the Southern Nuclear Power Plant is to meet the irrigation consumptive use of the population of the adjacent territories. Due to the fact that these freshwater reservoirs are hydrologically connected with the technological reservoirs of nuclear power plants, the principles of safety of the ecological and radiation state of such a reservoir should contain non-elevation of:

– established restrictions on the flow of radionuclides to the biota of bottom sediments of a freshwater reservoir;
– restrictions on the supply of radionuclides to humans through the migration chain "nuclear power plant discharges – technological reservoirs – freshwater reservoirs – agricultural crops – humans".

Therefore, when normalizing the content of radioactive substances in the water of such a freshwater reservoir, two components should be taken into account:

– ecological - is the protection of the reservoir ecosystem from excessive pollution by not exceeding the limit on the content of radionuclides in the biota;

– hygienic - is the protection of human health by not exceeding the limit of the effective dose of human radiation.

These components fully agree with the applied technical guidance documents [5-8], according to which rationing the content of radioactive substances in irrigation water was supposed to ensure a safe ecological and radiation state and protect the environment from pollution. Subsequently, the assessment of irrigation water quality can be defined as one that is carried out in order to prevent radionuclide influence on the components of the environment (freshwater reservoir of irrigation water) and human health [2-4]. Thereupon, the permissible concentrations of radionuclides in reservoir calculated can enhance the environmental criteria for irrigation water quality in terms of radionuclide content.

The following offers the results of determining the standard values of concentrations of radioactive substances in the freshwater reservoir separately according to radiation-hygienic and environmental safety principles.

Determination of permissible concentrations of radionuclides in the freshwater reservoir according to the radiation and hygienic safety principle.

Based on certain transition coefficients k^{i}_{irr} the permissible concentrations of radionuclides in irrigation water are calculated using the proposed formula 1:

$$CC^{i}_{L} = \frac{H_L}{R^{i} \times \sum_j \left(M^{j} \times N^{j} \times k^{ij}_{irr}\right)}, \qquad (1)$$

where CC^{i}_{L} - is the permissible concentration of radionuclide *i* in irrigation water, determined according to the radiation-hygienic principle, Bq/l;
H_L - quota from the effective dose limit for irrigation water use from a reservoir near a nuclear power plant, $1 \cdot 10^{-5}$ Iw/year [10; 11];
R^{i} - dose price of radionuclide *i* when ingested through the human gastrointestinal tract, Iw/Bq [14, 15];
N^{j} - agricultural crop irrigation rate *j*, l/m^2;
M_j- consumption of food product produced from agricultural crop by adult *j*, kg / year;
i - is one of the radionuclides: ^{137}Cs,^{,134}Cs, ^{89}Sr, ^{90}Sr, ^{110m}Ag,^{108m}Ag, ^{106}Ru, ^{103}Ru, ^{58}Co, ^{60}Co, ^{54}Mn.

k^{ij}_{irr} - coefficient of transition of radionuclide *i* to agricultural crop *j* from irrigation water.

The reference values are the maximum values for 2007-2017 of food consumption by the population of the Mykolaiv region: bread – 125 kg/year, milk and dairy products – 602 kg/year, meat and meat products – 42 kg/year, potatoes – 154 kg/year, vegetables and fruits – 150 kg/year. It is assumed that the population consumes food, and livestock feeds only from irrigated land. The content of radionuclides in livestock products is calculated by the coefficients of transition of radionuclides from the daily diet of dairy cattle to milk and meat, while the volume of daily feed consumption by dairy cattle is taken according to the Mykolaiv Production Association "Elite" [9]: in winter about 29 kg, of which silage – 20 kg, mixed feed, alfalfa hay – 9 kg; in summer about 46 kg, of which alfalfa and various herbs – 40 kg, mixed feed – 6 kg.

The values of dose prices of radionuclides are taken according to international regulatory documents [14; 15].

The results of calculating the permissible concentrations of radionuclides CC^{i}_{L} in irrigation water are shown in Table 1.

Table 1 − values of permissible concentrations of radionuclides CC_L^i in irrigation water [16]

Radionuclide	Bq/l	Radionuclide	Bq/l
^{89}Sr	0.15	^{54}Mn	44
^{90}Sr	0.25	^{58}Co	20
^{134}Cs	0.70	^{60}Co	8
^{137}Cs	1.00	^{65}Zn	1.0
^{110m}Ag	6.0	^{106}Ru	38
^{3}H	387	–	–

Based on the calculation method, these permissible concentrations must ensure that the allocated quota from the effective dose limit for irrigation water use from the reservoir (10 mkIw/year) is not exceeded due to internal irradiation from a mixture of radionuclides ^{134}Cs,^{137}Cs, ^{89}Sr, ^{90}Sr, ^{106}Ru, ^{54}Mn, ^{58}Co, ^{60}Co, ^{110m}Ag, ^{3}H, that are received by human body with food produced under irrigation conditions.

Thus, these determined permissible concentrations of radionuclides in irrigation water can serve as the basis for assessing the safety of irrigation water according to the radiation and hygienic principle and to the environmental criteria for the quality of irrigation water in state regulatory documents [6].

As known, any ecosystem is able to firmly and for a long time retain the radionuclides that are received by it by active accumulation or passive sorption, and it is able to held significant amounts of radionuclides for a long time. The absence in the ecosystem of the property of relatively strong retention of previously accumulated radionuclides in any natural situation leads to: 1) violation of trophic connections between ecosystem components; 2) destruction of migration routes and absorption of food elements or their sorption, 3) degradation of the ecosystem. Namely, the ability of an ecosystem to accumulate and retain radionuclides for a long time is its fundamental property [16]. This property is provided in the ecosystem by a normally functioning biota. In addition, the biomass of the reservoir plays a significant role in the transport of radionuclides from water to bottom sediments. Radionuclides accumulated by living organisms, when they die, are firmly held in detritus and together with it settle to the bottom, transfering into bottom sediments. Thus, with the help of biota, the water of reservoirs is purified from radionuclides contamination. There is also sufficient evidence that during periods of abundant plankton flowering, the pH of water rises to 9-10 and, because of this, there is a significant decrease in the level of radionuclide contamination of reservoirs, which is a consequence of two factors – the burial of radionuclides at the bottom of the reservoir along with detritus and changes in the pH of water, which is favorable for sorption.

Taking into account these functions of the biota, it can be argued that the presence of normally functioning microflora, as well as multicellular plants and animals, are necessary conditions for the stable functioning of reservoirs as absorbers of radionuclides. Conversely, in the absence of biota in sufficient quantity and quality, the ecosystem gradually degrades.

Today, it has been established that inhibition of population growth in phytoplankton and other biosystems can be expected with an average specific activity of radionuclides in biomass of more than 370 kBq/kg [15]. This level is the approximate limit of biota pollution. Therefore, by assessing the radiation capacity of the ecosystem of reservoir, it can be used in environmental assessments of the state of the reservoirs ecosystem that ensure the functioning of the irrigation system.

Knowing the permissible activity of radionuclides in ecosystem elements, it is possible to determine the permissible amount of discharge of radionuclides into a freshwater ecosystem. The aquatic biota of a freshwater reservoir is represented by benthos of bottom sediments, plankton of algae and other aquatic plants, neuston. Planktonic algae of the studied reservoirs are represented by rdests (*Potamogeton natans*), duckweed of two species (*Lemna minor L.*, *Lemna trisulca L.*), elodea (*Elodea bifoliata H. St. John*, *Elodea callitrichoides (Rich.) Casp.*, *Elodea canadensis Michx*), a hornwort of three species (*Ceratophyllum demersum L.*, *Ceratophyllum platyacanthum Cham.*, *Ceratophyllum submersum L.*) and filamentous algae, which are represented by cladophora (*Cladophora fracta*).

That is, the flowchart of the freshwater reservoir ecosystem, which is constantly affected by radionuclides, when modeled by chamber models, can be represented as a stationary model of radionuclide transfer within the ecosystem, which is shown in Fig. 1.

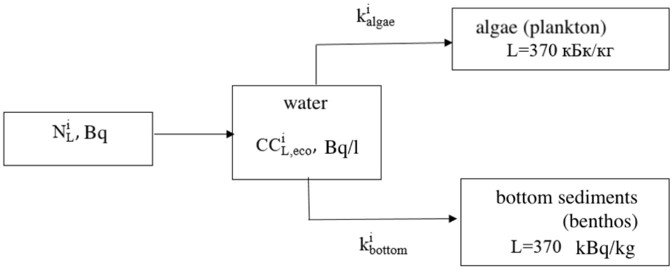

Fig. 1. Flowchart of radionuclide migration in a freshwater reservoir ecosystem.

The assessment of the permissible radionuclide discharge for the freshwater reservoir ecosystem [10] is carried out as follows:

For bottom sediments of a freshwater reservoir, the discharge (N^i_{bottom} Bq) of radionuclide *i* into the reservoir should not exceed the permissible (, $N^i_{L,bottom}$Bq):

$$N^i_{L,bottom} = L \times h \times S / (k^i_{bottom} \times F^i) \qquad (2)$$

where *L* is the limit of radionuclide content in aquatic biota – 370 kBq/kg [11],

F^i - general factor of radio capacity of the reservoir.

By another name$N^i_{L,bottom}$, it shows the maximum value of radionuclide activity *i* that the biota of bottom sediments can hold without harm to itself.

For aquatic biota in the water column, the permissible discharge of radionuclides N^i_{algae} should not exceed $N^i_{L,algae}$:

$$N^i_{L,algae} = L \times H \times S / (k^i_{algae} \times (1 - F^i)) \qquad (3)$$

Namely $N^i_{L,algae}$, it shows the maximum value of radionuclide activity i that the aquatic biota can hold without harm to itself.

Using the results of our calculations F^i_{bottom} i F^i_{algae} according to table. L. 1., L. 3 we have calculated values $N^i_{L,bottom}$, $N^i_{L,algae}$ for each radionuclide from the mixture. The calculation results are shown in The table 2 shows that for each of the studied radionuclides, the following is effectuated:

$$N^{i}_{L,bottom} < N^{i}_{L,algae} \quad (4)$$

That means, the value of the permissible discharge of radionuclides into the reservoir, which is determined by the possible impact on the state of bottom sediments, is significantly (from 10 times) lower than the value of the permissible discharge of radionuclides into the reservoir, which is determined by the possible impact on the state of aquatic biota.

The latter statement is also confirmed by calculating the ratio of estimates of permissible discharges into the reservoir using the formula (5):

$$\frac{N^{i}_{bottom}}{N^{i}_{algae}} = \frac{h*k^{i}_{bottom}*(1-F^{i})}{H*k^{i}_{bottom}*F^{i}} \quad (5)$$

From the latter formula we can see that the value of the ecological standard – the permissible discharge of radionuclides into the reservoir, which is determined by the possible impact on the state of benthos, is significantly (from 10 to 100 times) less than the value received when assessing the impact on the state of the inhabitants of the water column of the reservoir (Phyto - and zooplankton, higher plants in the water column, nekton, neuston and pleiston). Thus, as an environmental standard in general, you should choose the lowest level. that is, those values that are shown in Table 4 for this reservoir.

Taking into account the fact that for all reservoirs, the lowest value is $N^{i}_{L,bottom}$recorded for ^{137}Cs (Table 2), then it is ^{137}Cs that can be considered as an indicator radioecological state of reservoirs. Therefore, in our opinion, radioecological monitoring of the state of the freshwater reservoir, which is hydrologically connected with the technological reservoirs of nuclear power plants and in which there is a possibility of receiving a mixture of radionuclides (^{137}Cs, ^{134}Cs, ^{90}Sr, ^{54}Mn, ^{108m}Ag, ^{110m}Ag, ^{103}Ru, ^{106}Ru, ^{57}Co, ^{60}Co), can be carried out using this indicator.

Table 2 − Permissible radionuclide discharge, $N^{i}_{L,bottom}$TBq.

Reservoir	^{134}Cs, ^{137}Cs,	^{90}Sr	^{54}Mn	^{108m}Ag, ^{110m}Ag	^{103}Ru, ^{106}Ru	^{57}Co, ^{60}Co
Cooling pond	2.590	9.630	6.520	5.610	5.010	4.910
3rd OS bio-treatment pond	0.004	0.001	0.001	0.006	0.005	0.005
Oleksandrivske reservoir	36.620	149.900	10.200	6.200	54.250	48.050
Trykratske reservoir	0.034	0.137	0.010	0.080	0.070	0.050
Taborivske reservoir	$3.58 \cdot 10^{6}$	$14.07 \cdot 10^{6}$	$7.8 \cdot 10^{7}$	$27.5 \cdot 10^{7}$	$9.8 \cdot 10^{6}$	$11.0 \cdot 10^{6}$

Table 3 − Permissible radionuclide discharge, $N^{i}_{L,algae}$GBq.

Reservoir	^{134}Cs, ^{137}Cs,	^{90}Sr	^{54}Mn	^{108m}Ag, ^{110m}Ag	^{103}Ru, ^{106}Ru	^{57}Co, ^{60}Co
Cooling pond	19.780	95.720	67.580	53.450	54.01	48.53
3rd OS bio-treatment pond	0.040	0.014	0.020	0.070	0.060	0.060
Oleksandrivske reservoir	369.580	1501.900	137.010	78.060	569.050	586.050
Trykratske reservoir	0.440	13.330	0.190	0.680	0.570	0.550
Taborivske reservoir	$25.8\cdot10^{6}$	$131.07\cdot10^{6}$	$19.7\cdot10^{8}$	$10.5\cdot10^{8}$	$14.7\cdot10^{8}$	$19.7\cdot10^{8}$

Based on Formula (2), according to which it is possible to determine the standard values of permissible radionuclide discharges into a reservoir using an ecological approach, the calculation of the permissible concentration $CC^{i}_{L,eco}$ of radionuclide *i* in the freshwater reservoir can also be carried out using the formula 6:

$$CC^{i}_{L,eco}=\frac{L}{k^{i}_{bottom}} \tag{6}$$

where $CC^{i}_{L,eco}$ - is the permissible concentration of radionuclide *i* n the freshwater reservoir, determined by the radioecological principle, Bq/L.

The calculation results are in Table 4.

Table 4 − Values of permissible concentrations of radionuclides $CC^{i}_{L,eco}$ in the freshwater reservoir [1; 16].

Radionuclide	Bq/l	Radionuclide	Bq/l
^{137}Cs, ^{134}Cs	617	^{106}Ru, ^{103}Ru	870
^{89}Sr, ^{90}Sr	1396	^{58}Co, ^{60}Co	902
^{110m}Ag, ^{108m}Ag	620	^{54}Mn	1233

Analysis of the obtained results showed that the difference between the corresponding values of permissible levels of radionuclides in irrigation water, determined by radiation and hygiene (table. 1) and environmental (table. 4) principles, reaches from two to six orders of magnitude values. More stringent requirements for the content of radionuclides in the reservoir water are characterized by an approach based on human safety (radiation and hygiene principle). However, an approach based on the radioecological safety principle can be useful, for example, in assessing the state of a freshwater reservoir, the water of which is used for irrigation of industrial crops. In addition, according to the results of research done by radioecologists in ecosystems of other freshwater reservoirs [11] with higher coefficients of accumulation of radionuclides by aquatic plants, there may be a situation when more stringent requirements should be established not according to radiation-hygienic, but according to the radioecological principle of water safety of a freshwater reservoir.

In our opinion, in compliance with the radioecological principle of reservoir safety when discharging a mixture of radionuclides, the next formula should 7 be fulfilled:

$$\sum_{i=1}^{n} \frac{C_{water}^{i}}{CC_{L,eco}^{i}} < 1 \quad (7)$$

where C_{water}^{i} - is the specific activity of the radionuclide *i* in the reservoir, Bq/l;

n - is the number of radionuclides in the radionuclide mixture, n=11 (^{137}Cs, ^{134}Cs, ^{89}Sr, ^{90}Sr, ^{54}Mn, ^{108m}Ag, ^{110m}Ag, ^{103}Ru, ^{106}Ru, ^{58}Co, ^{60}Co).

CONCLUSION

A method for determining the permissible discharge of radionuclides into freshwater reservoirs based on the ecological principle is proposed. The permissible discharge of radionuclides for each of the five surveyed freshwater reservoirs was calculated. The values of permissible concentrations of ^{134}Cs,^{137}Cs, ^{89}Sr, ^{90}Sr, ^{106}Ru, ^{54}Mn, ^{58}Co, ^{60}Co, ^{110m}Ag in water were specified according to the environmental safety principle, based on compliance with the limit of radionuclide content in bottom sediments.

The lowest values of the permissible discharge of radionuclides into freshwater reservoirs for ^{137}Cs have been substantiated according to the proposal to carry out radioecological monitoring of the state of freshwater reservoirs by ^{137}Cs, as an indicator of the ecological and radiation state of the reservoir. Based on field studies of the content of ^{137}Cs in the Trykratske, Taborivske reservoirs and in irrigated agricultural crops.

The coefficients of transition of radionuclides from irrigation water to agricultural crops, which can be used in calculating of the permissible concentrations of radionuclides in irrigation water according to the radiation and hygienic safety principle, have been clarified.

A method for determining the permissible concentrations of radionuclides in the freshwater reservoir of irrigation water supply in the NPP area was developed and the values of permissible concentrations of ^{134}Cs,^{137}Cs, ^{89}Sr, ^{90}Sr, ^{106}Ru, ^{54}Mn, ^{58}Co, ^{60}Co, ^{110m}Ag, ^{3}H, were calculated. These values can serve as a basis for assessing the quality of irrigation water according to the radiation and hygienic safety principle and to supplement the existing environmental criteria for the quality of irrigation water in state technical guidance documents.

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SYSTEM OF RESEARCH METHODS FOR RADIOECOLOGICAL MONITORING OF ATMOSPHERIC AIR DURING MILITARY OPERATIONS

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ABSTRACT

The paper presents research materials on improvement of radioecological monitoring of atmospheric air in the territories exposed to the risk of nuclear accidents during military operations. The purpose of the presented studies was to analyse the methods and radiometric equipment that can be used for a full-fledged radioecological assessment of the state of atmospheric air in the territories adjacent to potentially hazardous areas - nuclear power plants - in the conditions of military operations. The dose rate values in the open area of Mykolaiv and Mykolaiv region were also analysed. It is shown that during the period of military operations in 2022-24, the effective dose rate in Mykolaiv ranged from 0.09 to 0.15 μSv/h. In general, in Mykolaiv region, the effective dose rate was in the range of 0.25-0.35 μSv/h. In the city of Mykolaiv and in the settlements of the Mykolaiv oblast during the period of military actions, the effective dose rate of atmospheric air did not exceed the limits of fluctuations in the natural radiation background. However, no other observations that are typical for radioecological monitoring have been made public.

It is shown that a full-fledged analysis of the radioecological situation caused by the spread of radioactive substances in the air is possible under conditions of comprehensive research. Such studies should be based on the results of monitoring of radioactive substances emissions into the atmosphere, monitoring of radionuclide content in the surface layer of atmospheric air, monitoring of distribution and density of local fallout, monitoring of radionuclide composition of soil, vegetation and snow. Different sampling methods are analyzed: aspiration method for radiometry of atmospheric air samples; sedimentation method for radiometry of aerosol samples and precipitation from the atmosphere.

Keywords: radioecological monitoring, atmospheric air, atmospheric precipitation, radiometry, sampling

INTRODUCTION

Radiation and environmental monitoring of atmospheric air is one of the tools for timely informing and protecting people and biota from radiation exposure. Radioactive dust contained in the air is extremely dangerous for humans [1]. Even at a low average level of its radioactivity, close to the background level, microscopic particles with a high intrinsic level of radioactivity, entering the internal organs with the bloodstream and 'settling' there, expose the surrounding tissue to local radiation, thereby causing a high probability of cancer cells development [11]. The nuclear power facilities pose a particular danger, as emergencies at nuclear power facilities are accompanied by a significant size of the affected area both in terms of area and height in the atmosphere. [5]. As it is known, on the first day of the Russian invasion in 2022, the Chornobyl NPP and the Exclusion Zone were seized by the Russian aggressor; the enemy occupied the Zaporizhzhya NPP, which was shelled with tank shells and the nuclear facility at the Kharkiv Institute of Physics and Technology was shelled, and cruise missiles were repeatedly observed flying over Ukrainian NPPs [6].

According to radiation safety scientists, radiation and environmental (radiation) monitoring of the environment is a comprehensive information and technical system of regular observations of the radiation state of the environment, processes of migration and accumulation of radionuclides, potentially hazardous phenomena, etc., which is implemented using special equipment (systems, complexes or individual devices) to assess and predict the radiation state of the environment. Radioecological monitoring of individual enterprises, especially nuclear fuel cycle enterprises and others that are sources of radioactive substances emissions into the environment, is also practiced. During the aggression of the Russian Federation against Ukraine, due to constant shelling of the territory by missiles and unmanned aerial vehicles, attention to radiation safety in Ukraine has increased [2-5], and especially near NPPs. Scientists are raising the issue of transboundary transfer of radiation exposure in probabilistic emergencies at NPPs during military operations [5, 10]. Our previous work [7] showed that monitoring of the effective/exposure dose rate of air is not sufficient. Such monitoring does not allow timely detection of radioactive substances in the air that are pure beta emitters, does not allow determining the dose load in case of local spread of contamination, etc.

The aim is to analyse the methods and equipment that can be used for a full-fledged radioecological assessment of the state of atmospheric air in the territories adjacent to potentially hazardous areas - nuclear power plants - in the conditions of military operations. Therefore, the dose rates in the open area of Mykolaiv and Mykolaiv region were also analysed.

METHODS AND EXPERIMENTAL PROCEDURES

The methods used to observe the state of the environment around nuclear power plants are used. Methods of sampling atmospheric air (aspiration), atmospheric precipitation (sedimentation), and methods of sampling soil, vegetation, and snow were used. The basic methods of radiometry and gamma spectrometry of environmental samples are used.

THE RESEARCH RESULTS AND DISCUSSIONS

Based on the results of observations of the effective dose rate in Mykolaiv at two observation sites, the average value of the effective dose rate in Mykolaiv in 2023-24 was 0.12±0.01 μSv/h. The average values of the effective dose rate of atmospheric air at the control posts ranged from 0.09 to 0.15 μSv/h. It is known that the variation of these values is due to geological features of Mykolaiv region and the presence of faults with crystalline rocks (characterised by a higher content of natural radionuclides of the uranium-radium and thorium series) coming to the surface in the centre of the region in the north.

These values almost did not differ from the monitoring data during the 'zero' background in the vicinity of the PSP in 1979-80 [7]. Thus, the highest values of effective dose rate were characteristic of areas where rocks of pink-grey granite came to the surface: these are areas along the banks of the Pivdennyi Buh River. In these places, the effective dose rate was in the range of 0.25-0.35 μSv/h. At a distance of 5-10 km away from the riverbed, the granite massifs are partially covered with sedimentary rocks, so the dose rate of gamma radiation in the open area in these places decreased to 0.10-0.11 μSv/h. This comparative analysis showed that in Mykolaiv and in the settlements of Mykolaiv oblast during the military actions, the effective dose rate of atmospheric air did not exceed the limits of fluctuations in the natural radiation background.

However, during the movement of the radioactive cloud with ruthenium-106 in autumn 2017, these natural values were not exceeded [6]. Therefore, below is an analysis of research methods that should be used in radioecological air monitoring in case of radiation hazards.

This monitoring is carried out by sampling the air in the ventilation stack, then examining it and taking appropriate measurements of the velocity and volume of air discharged to the atmosphere. The frequency of sampling and the sample volume depend on the cyclicity of the process and the concentration of radioactive substances in the exhaust air. In all cases, if they include alpha, beta and gamma emitters, continuous monitoring with automatic instruments is appropriate. Continuous monitoring of emissions before and after treatment facilities will allow the effectiveness of the latter to be assessed.

The existing methods of aerosol radiometry are based on preliminary extraction of aerosols by any method from the air and their subsequent measurement in concentrated form. For aerosol precipitation, cardboard, fibre filters (glass fibre with a fibre diameter of 2-3 μm), fabrics made of ultrafine fibres of perchlorovinyl (FPP), acetylcellulose (FPA), electrostatic precipitators and inertial precipitators are used. Sampling filters are called analytical filters and these include AFA type filters. Table 1 summarises the characteristics of the different types of analytical AFA filters used in the nuclear power industry.

The concentration of radioactive aerosols can then be determined by pumping a certain volume of air through a filter and then measuring its activity. The simplest scheme of a sampler of radioactive aerosols in air is shown in Fig. 1.

Table 1 − Characteristics of AFA analytical filters.

Filter brand	Filter material	Filter working surface, cm^2	Oil mist efficiency, %	Assignment
AFA-20	FPA-15-2,0	20	99.9	For radiometric determination of the concentration of p/a aerosols at elevated temperature (to 150^0 C)
AFA-RMP 3	FPA-15-1,7	3	99.9	Same at temperatures up to 600 C, resistant to chemically aggressive media
AFA-RCP 40	FPA-15-1,7	40	99.9	For radio spectrometric determination of p/a aerosols
AFA-XA 20	FPA-15-2,0	20	99.9	For radiochemical analysis of p/a aerosols. The filter is treated by ‘wet’ combustion, i.e. combustion with a mixture of sulphuric and nitric or acetic acids
AFA-RGP 3	FPP-15	3	99.5	For radiographic analysis
AFA-VP 20	FPA-15-1,7	18	99.9	To determine the mass concentration of aerosols
AFAC-I	FP with the addition-of pulverised coal and $AgNO_3$	3 10	99.0	For the determination of aerosols and vapour-molecular radioiodine

Compared to ashless paper filters, AFA filters have some advantages: high retention capacity, low aerodynamic resistance to air flow, high throughput up to 120 l/min), small own mass (up to 100 mg). Most of the analytical filters are not wetted by water, they are resistant to chemically aggressive media, well soluble in organic solvents (dichloroethane, acetone).

The spreading and dispersion of NPP release in the atmosphere occurs as a result of wind transport and turbulent diffusion due to the presence in the atmosphere of disorderly vortices that interact with each other and with the ground surface in a complex way. The causes of turbulence in the atmosphere are related to the interaction of wind flow with the ground surface or other obstacles in its path, as well as to the vertical lift of air due to differences in its temperature at different heights from the ground. It is well known that the local concentration of radioactive substances dispersed in the atmosphere depends on many technological and meteorological factors. For these reasons, the task of predicting the radiation situation is difficult both in terms of the physics of the phenomenon and its mathematical description. At present there are several theories of turbulent diffusion and methods of calculation of surface concentrations, the results and practical conclusions of which do not always give consistent results.

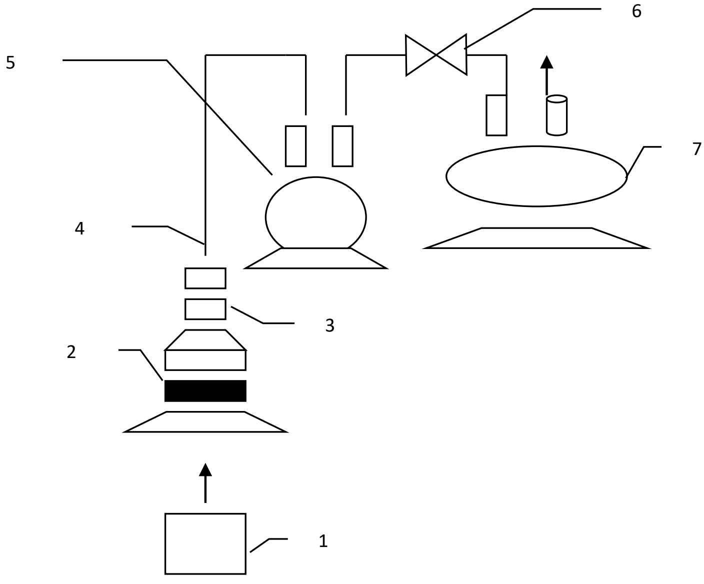

Fig. 1. Scheme of radioactive aerosol sampling with the help of air blower: 1- aerosol sampling place; 2- filter; 3 - allonge; 4 - vacuum hose; 5 - counter of pumped air volume; 6 - vacuum shut-off valve; 7 - blower.

Monitoring of the content of radioactive substances in the atmospheric air is carried out at stationary observation points located taking into account the wind rose in the prevailing directions in relation to the NPP vent stack. To determine the degree of atmospheric air contamination by radioactive aerosols, the aspiration method of sampling is used, which allows obtaining data on their concentration in a unit volume of air Bq/l. For this purpose, aspiration units are used, consisting of a fan with an electric motor; a filter holder; an air outlet designed for filtered air removal; a support for the motor and air outlet. Figure 2 shows the schematic composition of the aspiration unit.

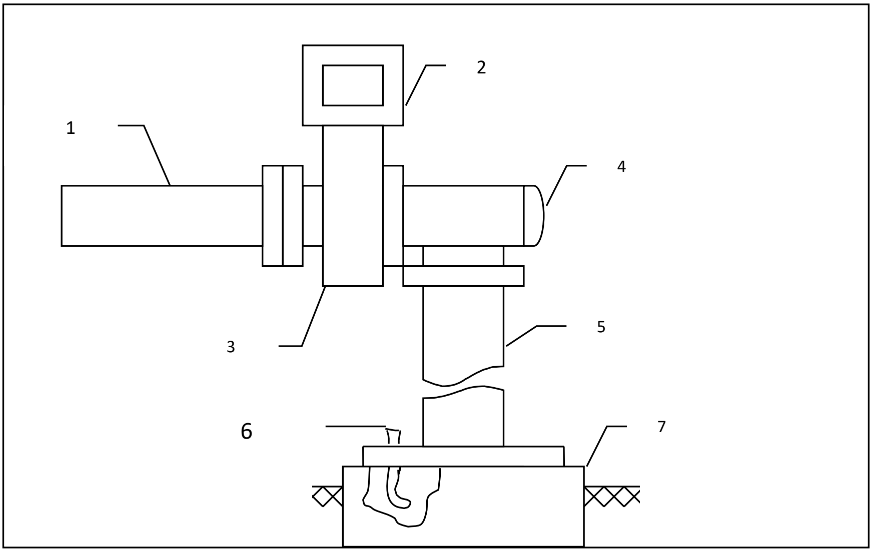

Fig. 2. Schematic diagram of aspiration installation: 1 - filter holder; 2 - air outlet; 3,4 - fan with electric motor; 5 - support for electric motor; 6 - anchor bolt; 7 - concrete base.

Sampling of aerosols is carried out by pumping air through Petryanov cloth of the FPP-15-1.5 type using aspiration units. Characteristics of filtering fabrics are given in the Table 2.

Table 2 − Characteristics of FPP filter fabrics.

Fabric grade	Approximate thickness, mm	Coefficient of slip on oil mist, %	Fabric grade	Approximate thickness, mm	Coefficient of slip on oil mist, %
FPP-15-1,5	0.2	0.100	FPP-15-6.0	0.8	0.005
FPP-15-3,5	0.4	0.010	FPP-25-3.0	0.4	0.010
FPP-15-4,0	0.6	0.050	FPP-25-6.0	0.8	0.005
FPP-15-4,5	0.6	0.005	FPA-15-6.0	0.8	0.005

The disadvantages of fibre filters are: dependence of their efficiency on aerosol dispersity, low permissible pumping speed (3-20 l/min through 1 cm^2 of the filter), necessity to make corrections for self-absorption of α- and β- particles in the filter when determining its activity. Characteristics of the most commonly used fans are given in Table 3.

To obtain reliable measurement data and acceptable measurement times, it is necessary to have a sample activity at least twice the background. If measurements are made on a counter with a background of about 20 ppm, a sample activity of at least 40 ppm is desirable. For this purpose, at an aerosol concentration (in Bq/L), the volume (in litres) of air pumped should be as follows: 10-11 – 20; 10-12 – 20·102; 10-13 – 20·103; 10-14 – 20·104; 10-15 – 20·105; 10-16– 20·106; 10-17 – 20·107 respectively.

Table 3 − Main characteristics of electric fans.

Operating characteristic	Type of electric fan				
	EV-54/25-1	EV-54/23-1	19CS-48	12CS-34	VCP-3
Capacity, m^3/h	2000	250	1900	1250	1500
Maximum differential pressure, N mmHg.	450	450	475	335	180
Power consumption, kW	4.5	0.7	0.6	2.2	1.7
Calculated area of filters, m^2	0.25	0.03	0.224	0.14	0.7
Recommended filter size, mm	670x520	-	670x520	670x390	-

The dimensions of the filter area are determined by calculation according to the formula 1:

$$S = Q \cdot K/H, \qquad (1)$$

where: S - filter area, m^2; Q - volume of sucked air, m^3/s; K - filter resistance coefficient, mm water. m/s; H - pressure drop, mm water. m/s; according to passport data air sucking through filters FPP-15 and FPA-15 at a speed of 1 cm/s is 1.5-2.0.

Monitoring the distribution and density of localized deposition. This monitoring is carried out, depending on the objectives and local conditions, by the following **sedimentation methods**:

- collection of settling aerosols and atmospheric precipitation in open vessels;

- study of snow cover;

- study of terrestrial vegetation.

The sedimentation method is a method of collecting atmospheric precipitation on collecting plates-cuvettes with a defined collection area. The sedimentation method makes it possible to determine the amount of radioactive substances falling out of the atmosphere with dust and precipitation per 1 km2 for a certain time (day, month, etc.). The efficiency of this method is 30 %.

Before considering control methods, it is necessary to explain some regularities of atmospheric phenomena and processes. Nuclear weapons testing on the ground and in the atmosphere, as well as the use of atomic energy, carried out earlier until 1980, necessitated the forecasting of emissions up to 30 km and higher. Since most nuclear explosions were airborne, almost all the explosion products (up to 99%) entered the stratosphere, and the main (up to 70%) stratospheric stock of long-lived anthropogenic radionuclides was formed. In 1967-1974, test explosions in the atmosphere were carried out by China (total power - 18 Mt), which caused an increase in the levels of atmospheric contamination with short-lived radionuclides (^{141}Ce, ^{95}Zr, ^{95}Nb et al.). The level of atmospheric contamination by long-lived radionuclides such as ^{137}Cs and ^{90}Sr, these explosions had no significant impact.

Atmospheric mixing depends on the vertical temperature gradient. With distance from the earth the temperature decreases by 6.5°C for each kilometer and so up to 11 km, further up to 32 km there is an isothermal region of the atmosphere when the temperature does not change.

Nuclear explosions in the northern hemisphere have contributed more radionuclides to the stratosphere (especially in winter) than those in the equatorial part of the globe. Radionuclides entering the stratosphere are then deposited on the Earth's surface over many years. The amount of deposition has a pronounced latitudinal character - more in the northern hemisphere than in the southern hemisphere (especially in the first years after the explosion) and a temporal character - significantly more in spring and summer than in autumn and winter.

In this method of control, monitoring points are established in the four main rhumbas (C, B, S, W) of the emission source at various distances from the source. Tentatively, at least five points should be provided in each direction. But in all cases a background monitoring point is required.

Stationary stainless-steel cuvettes with a bottom area of 0.25 m^2 and a wall height of 0.2 m are usually used to collect atmospheric deposition. The bottom of the cuvette is covered with special filter paper of FNS type. Duration of exposure of the cuvette can be from 5-10 days to 1 month depending on the task. In the absence of precipitation, only the filter paper is changed, taking precautions to avoid loss of settled dust. If rain or melt water is present in the cuvette, it should be drained into a vessel and taken to the laboratory together with the filter paper.

Monitoring of radionuclide composition of soil, vegetation and snow. Specific monitoring plots shall be selected for soil sampling and shall be located on a flat open area of open ground at a distance of at least 50-100 meters from the nearest buildings and trees. Soil sampling in meadow areas is allowed, but not in flooded areas at some distance from forest areas. It is desirable that the soil on the plots has not been ploughed for 3 years, i.e. it should be virgin. In advance, the grass cover is removed from the sampling site. Then the sample is taken by the triangle method with the side of 50 m at its corners (Fig. 4).

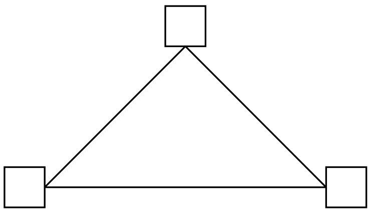

Fig. 4. Soil sampling using the triangle method.

Samples taken at the corners of the triangle and consisting of three samples are combined into one sample. Each sample is taken in a monolithic piece of 10x10x5 cm. The mass of the sample is 1.5 kg.

This is explained by the fact that radionuclides deposited on the soil move into the soil with time. Vertical movement of radionuclides along the soil profile is determined by many reasons (filtration of precipitation deep into the soil, capillary rise of moisture, diffusion of ions, mechanical transport of soil particles, activity of microorganisms, etc.) Vertical transport of radioactive contaminant in virgin soils is very slow: several millimeters per year. Therefore, radionuclides delivered to the soil are retained in the upper soil layer for a long time. On cultivated agricultural land, the radioactive contaminant is usually distributed quite uniformly within the arable layer. If one compares the penetration of radionuclides into the depth of soils of different types, it can be noted that radionuclides can penetrate to a greater depth in sandy soils than in clay and chernozem soils.

Sampling of vegetation is performed in the same place as soil. As it was mentioned earlier, in the regime of normal operation of NPPs radionuclides from the release plume get into plants by two ways - root and non-root (stem). The non-root pathway of radionuclides entering plants is usually more active than the root pathway, although it is rather slow. The fraction of radionuclides delayed by the terrestrial part penetrates into biological tissues of plants in very limited amounts, only Cs137 and Cs134 are considered radionuclides intensively assimilated by the leaf surface of plants. The root pathway of radionuclide intake into plants, i.e. radionuclide intake from soil together with nutrients is usually characterized by the radionuclide accumulation coefficient (AC) of a plant growing on soil containing radioactive substances. The accumulation factor is determined by the following formula 2:

$$\text{KH} = A_p/A_s, \qquad (2)$$

where A_p – specific activity of the radionuclide in the plant, Bk/kg; A_s – specific activity of radionuclide in soil layer, Bk/kg.

Natural peculiarities of agricultural crops determine their ability to retain radionuclides deposited from the air. According to the degree of retention they form a series: cabbage - beetroot - potato - wheat - natural grasses. For estimations it is usually assumed that for meadow grasses KN=1. Sampling of vegetation is carried out once a year, during the period of maximum vegetative development (mainly in early spring) by placing a 400 cm^2 bounding box on the grass. Grass inside the frame is cut with scissors or sickle to the ground surface at one point from three or four points on the area from 5 to 100 m^2. In cases when maximum permissible amount of iodine-131 is detected in NPP emissions, determination of iodine-131 content in vegetation is carried out using samples taken from pastures of dairy cattle. Sampling of vegetation from pastures should be carried out monthly during the whole pasture period of cattle grazing.

In the regime of normal operation of NPPs, the activity of its radionuclides accumulated by plants is generally such that the radiation impact of NPPs on plants is small and does not lead to any irreversible consequences in their organisms. Although the radiation dose to some plants turns out to be significantly higher than the human dose. If we are talking about radiation impact of radioactive pollutant coming from NPPs into terrestrial biogeocenoses, we should bear in mind that this is practically chronic contamination. For this reason, today one cannot be absolutely sure that long-term radiation exposure, although in low doses, will remain without reaction from plants. Therefore, obtaining information on the reaction of vegetation to small but long-term radiation effects is one of the important tasks of radioecology. This task is solved by organizing and conducting radiation ecological monitoring in the NPP region.

Snow sampling should generally be carried out once a year before the spring snowmelt, when snow best adsorbs radionuclides. To avoid random results, snow samples should be taken at each location only as averages. Averaging is achieved by combining five samples taken in the center and at the corners of a 10 m square over the entire depth of the snow cover (the so-called ‘envelope method’ Fig. 5).

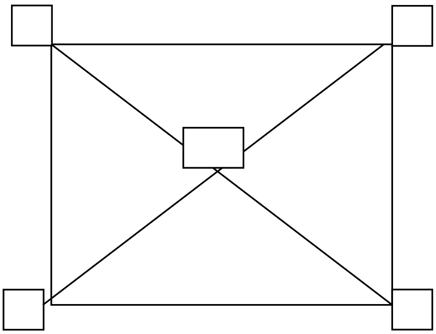

Fig. 5. Snow sampling using the ‘envelope’ method.

Radiometric method for analyzing environmental samples. All quantitative measurements of radioactivity can be expressed as a formula 3:

$$A = K \cdot N, \qquad (3)$$

where A – drug activity, Bq; N - measured value on the instrument, usually pulse count rate, imp/min, imp/s; K - conversion or calibration factor, Bq/(imp/min), Bq/(imp/s).

The main task of radiometry is to determine correctly and with a sufficient degree of accuracy in each case the value of *K*. The conversion factor K can be determined by two methods: absolute and relative.

In absolute measurements, either the detector must have the property of registering all particles emitted by the source in the 4π solid angle, or a set of corrections must be introduced to account for the fraction of particles lost outside the sensitive volume of the detector. Detectors that can measure β-radioactivity according to the first principle include 4π gas flow proportional counters, some liquid (or plastic) scintillation counters, where the sample to be measured is inserted directly into the scintillator, and face counters.

The essence of the relative method is that the activity of the measured sample is determined by comparison with a reference source identical to the given sample (in terms of layer thickness, mg/cm2, size and energy spectrum) and measured under identical conditions. According to such a source, the measuring unit is calibrated, i.e. the conversion factor K, which relates the activity of the drug to the given radiation spectrum and its count rate on this unit, is determined.

The determination of the radioactivity of β-emitter samples requires an appropriate measuring apparatus, which usually consists of a β-particle detector, a recording instrument and a power supply. This list is common whether the installation consists of separate units or is designed as a single instrument.

As detectors of β-particles, cylindrical and end-face Geiger-Muller counters, scintillating plastics and ionization chambers are usually used, and less frequently semiconductor detectors (SCDs) are used. For the needs of radiological laboratories, it is enough in principle to have a rather limited set of β-particle counters: SBM-20, STS-6, MST-17, SBT-13, SBT-15, SI-2B, SI-3B, SI-8B. This set is quite sufficient when measuring β-emitters in a wide energy range. Tables 3 and 4 show the technical characteristics of cylindrical and face Geiger-Muller counters

Table 3 − Characteristics of cylindrical counters

Counter type	Dimensions, mm		Materi al ball-boson	Counting start voltage, V		Highest load, imp/min	Prolonged-femininity plateau, B ------------ slope plateau %/V	Thickness walls, mg/cm^2
	lengt h	diamete r		min	max			
SBM-20	112,0	12	steel	280	330	10^5	80/0,125	48-40
STS-6	200	22	-«-	285	335	$6 \cdot 10^4$	-	44-60

Table 4 − Characteristics of face counters.

Counter type	Dimensions, mm		Dimensi ons, mm	Max. allowabl e load, imp/ min	Prolong ed-feminini ty plateau, B slope plateau %/V	Max. allowable load, imp/min	Thickn ess of saliva-of entran ce windo w, mg/ cm^2	Enclos ure materi al
	length	length						
SBT-13	70	40	25	380	70/0.15	10^4	3	plastic
SBT-15	40	40	25	380	80/0.3	10^4	5	-//-
SI-2Б	80	70	40	1750	150/ 0.05	10^4	5	glass
SI-3Б	90	38	18	1650	150/ 0.03	10^4	8	-//-
MST-17	100	40	17	1600	150/ 0.05	10^4	5	-//-

Absolute method for measuring the beta activity of preparations. This method is used in the absence of the necessary reference sources for the measurement of preparations by the relative method or in the case of unidentified isotopic composition of the radioactive substances contained in the sample under study. Radiometric units used for the measurement of drugs by the absolute method should measure either all β-particles produced by the decay of radionuclides or an accurately determined fraction of them. Such facilities include facilities with end or 4π counters (e.g., UMF-1500M, flow beta radiometers, KRK-1). To calculate the activity of preparations with a thin layer, it is not necessary to take into account the absorption of the studied β-radiation in the preparation material. The activity of such preparations is determined by the formula 4:

$$A_{тн} = \frac{N}{2{,}22 \cdot 10^{12} \cdot \omega \sum_{i=1}^{n} K_i \cdot p_i \cdot r_i}, \qquad (4)$$

where $A_{тн}$ – the activity of the drug, Bq, ω - coefficient taking into account the geometric factor of measurement; *Ki* - coefficient taking into account the absorption of β-radiation of the *i*-th spectrum in the layer of air and material of the counter window; pi - coefficient taking into account the backscattering of the β-spectrum from the aluminium substrate with thickness 0. 5 mm; ri - relative content of the *i*-th β-spectrum in the β-radiation of the preparation; *N* - count rate of the preparation on the radiometric unit (without background), imp/min; *n* - number of simple β-spectra (or groups of them) in the preparation.

Gamma-spectrometric methods for analyzing samples of environmental objects. In radioactive nuclides γ-junctions are characterized by emission of monoenergetic γ-quanta with known quantum yields and excited level lifetimes - half-lives. By measuring the energy and intensity of emitted γ-quanta, as well as estimating the half-life of their individual monoenergetic groups, one can unambiguously identify radionuclides in the studied sample and determine the absolute values of their activity quite accurately. These tasks are solved by γ-spectrometric methods using scintillation or semiconductor detectors.

The most widely used are semiconductor Ge-Li detectors and detectors made of extremely pure germanium. The advantage of Ge-Li detectors is high energy resolution of 4-7 keV for gamma-quanta Co^{60} with E_γ =1332 keV, due to almost complete collection of free charges formed as a result of interaction of a γ-quantum with the detector substance.

The essential disadvantage of detectors of this type, especially from the point of view of measurement of weakly active samples of external environment, is low efficiency of registration of γ-quanta due to relatively lower density of matter and small effective atomic number and limited sizes of detectors (not higher than 70 cm^3). Detectors made of very pure germanium fully meet the conditions of measurement of weakly active samples of external environment.

Gamma-spectrometric facilities consist of three main parts: a detector; a radio-technical circuit designed to amplify and generate signals; and a multichannel pulse analyzer. For short, such facilities are called γ-spectrometers. For γ-spectrometric analysis of environmental samples having, as a rule, low specific activity, detectors of DGDK type (germanium, diffusion-drift, coaxial detector) are used, which are operated at a temperature close to the temperature of liquid nitrogen (196 ˚C).

Measurement of low-activity environmental samples has a number of specific requirements, namely: low background level, the need for prolonged measurements, selection of optimal measurement geometry, usually bulk samples, and calibration of the unit when measuring bulk samples, including samples of complex configuration and large volumes.

To determine the energy of γ-radiation registered by the detector, the energy scale of the spectrometer is calibrated using the multi-source method. Its essence is that by measuring a set of emitters with known energy of γ-quanta either simultaneously or in some sequence, the dependence of the peak maximum position on the energy of the corresponding γ-radiation is found. It is convenient to calibrate the spectrometer using sources having a large number of γ-lines for which the decay patterns are well known. Such radionuclides include ^{152}Eu, ^{56}Co, ^{75}Se, as well as preparations based on ^{226}Ra and ^{232}Th in equilibrium with decay products.

CONCLUSION

During the period of military actions in 2022-24, the effective dose rate in Mykolaiv ranged from 0.09 to 0.15 μSv/h. In general, in Mykolaiv region, the effective dose rate was in the range of 0.25-0.35 μSv/h. In the city of Mykolaiv and in the settlements of the Mykolaiv oblast during the period of military actions, the effective dose rate of atmospheric air did not exceed the limits of fluctuations in the natural radiation background. However, no other observations that are typical for radioecological monitoring have been made public.

It has been shown that a full analysis of the radioecological situation caused by the spread of radioactive substances in the air is possible under conditions of comprehensive research. Such studies should be based on the results of monitoring of radioactive substances emissions into the atmosphere, monitoring of radionuclides in the surface layer of the atmospheric air, monitoring of the distribution and density of local fallout, monitoring of radionuclide composition of soil, vegetation and snow.

Different sampling methods are analyzed: aspiration method for radiometry of atmospheric air samples; sedimentation method for radiometry of aerosol samples and precipitation from the atmosphere. The filters of the AFA brand for sampling aerosols, which have a higher retention capacity and greater throughput, are highlighted. The relationship with the volume of air pumped through the filter is presented to obtain reliable data on radionuclide content in atmospheric air samples. It is shown that in order to obtain reliable data on radionuclide content in atmospheric air samples, if the activity is at the level of 10-11 Bq/l, it is necessary to pump at least 20 l. When using the sedimentation method of sampling precipitation from the atmosphere, it is important to take into account the wind rumba: at least five punters should be provided for each wind direction.

The characteristics of cylindrical and face meters for general beta radiometry are listed. The basic requirements for gamma spectrometric measurements of atmospheric air and aerosol samples are presented.

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CLIMATE MANAGEMENT TOOLS AND CRITERION-BASED EXPERT ASSESSMENT OF ENERGY, TRANSPORT, AND AGRICULTURE SECTORS IMPACT ON THE ENVIRONMENT

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ABSTRACT

To solve the problems of climate change and environmental pollution, it is necessary to introduce innovative, effective technologies and startups that align with sustainability principles. The aim of the investigation is to develop special management tools for evaluating the sustainability and eco-friendliness level of innovative projects. So, the study deals with the author's developed methodology and framework for evaluating the sustainability and eco-friendliness of innovative startups. For this purpose, T. Saaty's analytic hierarchy process was combined with geospatial analysis tools to conduct the environmental analysis.

Spatial data from the Copernicus Data Space Ecosystem were used, particularly leveraging the capabilities of the Copernicus Browser and data from the Sentinel-5P satellite mission. A series of high-resolution maps were developed for key atmospheric pollutants, including methane, sulfur dioxide, nitrogen dioxide, formaldehyde, carbon monoxide, and the UV aerosol index. These maps enabled the identification of high-emission zones across the European region. The methodology was applied to assess the authors' startup project in the sphere of bioenergy, focusing on its environmental impact and potential contributions to sustainable development. A high probability of startup compliance with eco-friendly principles was determined – 78.6 %. The proposed approach shows strong potential for broader application in key sectors such as energy, transport, and agriculture, contributing to more informed and evidence-based decisions in the transition to a greener economy.

Keywords: environmental management, climate change, green innovative projects, environmental protection, waste management

INTRODUCTION

According to the Intergovernmental Panel on Climate Change, each of the last 3 decades is characterized by a higher temperature of the Earth's surface layer compared to other decades since 1850 [1]. Globally averaged land and ocean surface temperatures for 1880-2012 show a warming result of about 0.85 °C. And this threat of climate change on the planet, according to experts, is being significantly exacerbated by ever-increasing greenhouse gas (GHG) emissions, especially those of anthropogenic origin.

According to the International Energy Agency, the agricultural, energy, and waste sectors are the most significant anthropogenic greenhouse gas emissions sources. According to the Kyoto Protocol, the main gases that cause a significant greenhouse effect are carbon dioxide CO_2; methane CH_4; nitrous oxide N_2O; hydrofluorocarbons (HFCs); perfluorocarbons (PFCs); sulfur hexafluoride SF_6, and nitrogen trifluoride NF_3. At the same time, precursor gases are carbon monoxide CO, nitrogen oxides NO_x, non-methane volatile organic compounds (NMVOCs), and sulfur dioxide SO_2.

The need to significantly reduce greenhouse gas emissions and leakages to mitigate global warming was discussed at the 2015 Paris Conference, where world leaders agreed to contribute to limiting the global temperature increase to below 2 °C by the end of the century and to take measures to limit the increase to 1.5 °C [2]. In 2021, the European Union adopted an even more ambitious program, namely the European Green Deal, to achieve climate neutrality by 2050 [3]. The key aspects of the Green Deal are clean (green & renewable) energy, climate action, sustainable industry, construction and renovation, sustainable mobility, pollution reduction, biodiversity conservation, and sustainable agricultural policies (the farm-to-table movement & strategy) [4].

In 2019, the Law of Ukraine [5] was adopted, which establishes the legal and organizational framework for monitoring, reporting, and verification of greenhouse gas emissions and is aimed at fulfilling Ukraine's obligations under international agreements, in particular, the European Union–Ukraine Association Agreement, as well as the requirements of the United Nations Framework Convention on Climate Change and the Paris Agreement.

A key aspect of this law is the adoption of a Unified register for monitoring, reporting, and verification of greenhouse gas emissions from facilities located in the territory of Ukraine. This Unified Register is actually an analog of the EU Emissions Trading System (ETS), which includes more than twelve thousand European enterprises that pollute the atmosphere with CO_2 and other greenhouse gases. The EU ETS includes five main sectors of the economy, namely:

- energy (oil refineries and coke ovens, thermal power plants with a cumulative thermal capacity of more than 20 MW, etc),

- mining industry (including production of cement, bricks, glass, ceramics)

- production and processing of ferrous metals (including production of iron and steel with a capacity of 2.5 tons per hour or more);

- pulp-and-paper industry;

- air transportation sector.

Together with the Law of Ukraine On the Principles of monitoring, reporting and verification of greenhouse gas emissions [5] and the Law of Ukraine On the National Register of Emissions and Pollutant Transfers [4], which registers emissions and pollutants (including a list of activities that lead to emissions and pollution), the Government adopted a resolution [6] – List of activities whose greenhouse gas emissions are subject to monitoring, reporting, and verification (approved by the Resolution of the Cabinet of Ministers of Ukraine on September 23, 2020, No. 880), which defines the types of activities leading to the emission of the main greenhouse gases. This list, in turn, makes it possible to accurately determine which industries are actually reducing GHG emissions in the GHG emissions trading system.

Thus, controlling and accounting for greenhouse gas emissions and leakages is reaching a new level. Our country also pays considerable attention to inventorying and monitoring sources of greenhouse gas emissions and leaks in accordance with its obligations under the United Nations Framework Convention on Climate Change. Thus, the National Inventory of Anthropogenic Greenhouse Gas Emissions by Sources and Absorption by GHG Sinks for 2024 is available at [7], and the inventory of greenhouse gas emissions was carried out following the guidelines of the Intergovernmental Panel on Climate Change [8].

So, the aim of the investigation is to develop special management tools for evaluating the sustainability and eco-friendliness level of innovative projects.

METHODS AND EXPERIMENTAL PROCEDURES

The first part of this study employed tools from the Copernicus Data Space Ecosystem (CDSE) to investigate the spatial distribution of atmospheric pollutants. CDSE facilitates seamless interaction with data, allowing its efficient discovery, visualization, and analysis. CDSE infrastructure is strategically developed to broaden and streamline the use of data produced by the European Union’s Copernicus satellite program, enabling stakeholders to construct diverse applications based on reliable, timely, and impartial data. The platform is positioned to be a principal tool for extracting actionable insights from Copernicus datasets [9].

The key tool to this investigation was the Copernicus Browser, an interactive platform within the CDSE designed to facilitate real-time access, visualization, and analysis of Earth observation data. The detailed interface of this tool customized for the research is provided in Fig. 1.

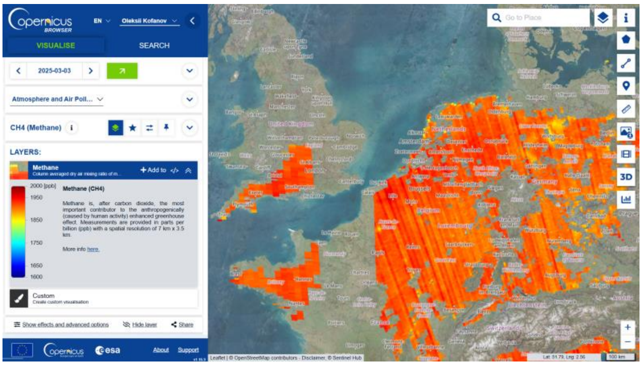


Fig. 1. The Copernicus Browser interface customized for research purposes.

The Copernicus Browser integrates data from several satellite missions, including the important one for the current study, the Sentinel-5 Precursor (Sentinel-5P) mission, which specializes in high-resolution monitoring of the atmosphere. The Copernicus Browser provided the efficient extraction of satellite imagery and air pollutant maps for the investigation. Functioning as a centralized interface, the Copernicus Data Space Ecosystem Browser enables streamlined access to and interaction with the extensive array of Earth observation and environmental datasets generated by the Copernicus Sentinel satellite missions. Built upon the capabilities of Sentinel Hub’s EO Browser, this tool allows to visualize, analyze, compare, and download a broad spectrum of satellite data. It supports various applications, including environmental surveillance, disaster response, urban development, and agricultural planning [10].

Except for the Sentinel-5P mission discussed above, several other important Copernicus initiatives exist, including the Sentinel-1 [11]. This product is equipped with radar imaging technology, which comprises two polar-orbiting satellites engineered to deliver uninterrupted, all-weather, day-and-night imagery for terrestrial and maritime surveillance. Employing C-band synthetic aperture radar, the mission capitalizes on the ability to penetrate cloud cover and operate independently of daylight conditions, thereby ensuring continuous data acquisition regardless of weather or illumination [11].

In July 2022, the European Space Agency (ESA) officially declared the termination of the Sentinel-1B satellite mission. Due to technical issues, the satellite could not transmit radar data, prompting ESA and the European Commission to conclude its operation. Sentinel-1A, however, continues to function normally. Following the loss of Sentinel-1B, the observation strategy for Sentinel-1A was revised, resulting in reduced global coverage. While certain geographic regions are no longer monitored, those that remain under observation now follow a 12-day revisit interval under the single-satellite configuration.

The Sentinel-2 mission [12] supports land monitoring through a dual-satellite configuration operating in a sun-synchronous orbit, with the satellites positioned 180 degrees apart. The mission is designed to observe dynamic changes in terrestrial environments. Its operational efficiency is enhanced by a wide swath width of 290 km and a revisit cycle of 10 days at the equator using a single satellite, which is reduced to 5 days when both satellites are active – resulting in a temporal resolution of approximately 2–3 days at mid-latitudes. Each product generated by Sentinel-2 corresponds to a tile measuring roughly 110 by 110 km in cartographic projection.

The Sentinel-3 mission [13] is primarily oriented toward measuring oceanic and terrestrial parameters, such as surface color, temperature, and topography, with high precision and reliability. These measurements are essential for advancing oceanographic forecasting systems and supporting environmental and climate-related monitoring initiatives.

The second part of this study presents the authors' methodological framework for evaluating the environmental sustainability of agricultural startups. The evaluation process is based on the analytic hierarchy process (AHP), initially developed by T. Saaty [14, 15], which facilitates structured multi-criteria decision-making by organizing complex problems into hierarchical models. Such hierarchical models include the overall objective, key criteria, and alternatives, enabling experts to assess each level through pairwise comparisons. Judgments were quantified using Saaty's nine-point scale, where 1 denotes equal importance, and 9 indicates a dominant preference. The consistency of these expert evaluations was validated using a consistency ratio, with values below 10 % considered acceptable.

To operate this framework, a custom YAML-based application was developed using the 'ahp' package in the 4.0.3 R version, executed via RStudio [16–18]. The tool enables both computation and visualization of the AHP process. The practical implementation was demonstrated using a case study based on the author's startup in agricultural waste management. Expert input, typically involving three to five participants, was used to ensure methodological robustness while avoiding inconsistency.

THE RESEARCH RESULTS AND DISCUSSIONS

Greenhouse gases differ significantly in their physical and chemical properties, lifespan, atmosphere content, and the Global Warming Potential (GWP) index. This quantitative indicator, in turn, depends on the ability of the molecules of a particular GHG to absorb infrared radiation and the time spent in the atmosphere.

It is well-known that the value of the GWP indicator is usually different for different periods. Therefore, its values are typically given for 20, 100, and 500 years. The most commonly used indicator is GWP_{100}. GWP shows how much the impact of a particular greenhouse gas on global warming is higher than that of carbon dioxide CO_2 since the latter is taken as a standard with a GWP conditionally equal to one.

For example, the GWP_{20} for the greenhouse gas methane CH_4 is estimated to be between 56 and 96 units for 20 years, which shows that during this period, the impact of methane on global warming on the planet is 56-96 times higher than that of carbon dioxide. Over time, this impact (and, accordingly, the indicator) decreases. For example, the GWP_{100} for CH_4 becomes much lower – from 21 to 40 units, while the GWP_{500} generally ranges from 6.5 to 7.6 units.

Such a significant decrease in the GWP value for the GHG methane over time is explained by its short lifespan in the atmosphere – only 12.4±1.4 years [19]. For other greenhouse gases, this period can be much longer. For example, for nitrous oxide N_2O, the lifespan in the atmosphere is 121±10 years, and its GWP_{20} reaches 264-289 units and almost does not change for 100 years (the GWP_{100} for nitrous oxide N_2O is 265–310).

GWP values are used to calculate the CO_2 equivalent (CO_2e) of other greenhouse gases. For example, if 1 ton of methane were emitted into the atmosphere, it would be equivalent to 21–40 tons of CO_2 over a century (the average is 32 tons) [20]. Similar calculations can be made for the levels of other greenhouse gases in the atmosphere.

It should be remembered that the main greenhouse gas on our planet, except water vapor, is carbon dioxide. Thus, Fig. 2 shows the trend of global CO_2 emissions from fossil fuels [21]. It is believed that more than 99 % of the carbon in the atmosphere is carbon dioxide CO_2 – its content in the atmosphere is almost 200 times higher than methane and continues to increase steadily compared to the pre-industrial era [22]. In this regard, the issue of reducing greenhouse gas emissions and leakages in industry and agriculture, waste management, etc., is extremely important and relevant, especially for our country.

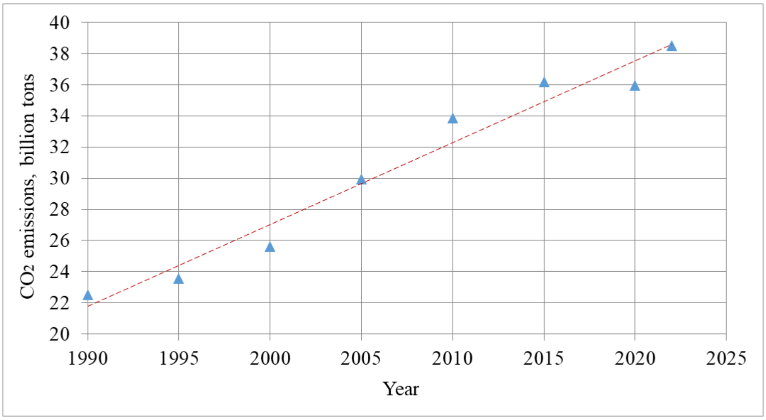


Fig. 2. Global fossil carbon dioxide emissions, billion tons.

Today, there are two main mechanisms for reducing CO_2 emissions globally. The first is the EU emissions trading system (which exists in the European Union), and the second is a tax on CO_2 emissions. Thus, the greenhouse gases ETS is a market-based incentive tool used to reduce greenhouse gas emissions based on the cap-and-trade principle.

Projects that help to reduce the impact of greenhouse gases on climate change on the planet are divided into two main types: energy efficiency measures, including increasing the share of renewable energy sources, and green technologies themselves. As for the first type, the EU created a list of facilities and industries that produce significant amounts of CO_2 and implemented a precise accounting and control system for greenhouse gas emissions.

It is known that almost 80 % of greenhouse gas emissions in the energy sector are caused by the combustion of carbon-containing fuels, including motor fuels. In this case, carbon dioxide is the main greenhouse gas emitted into the atmosphere, while methane and nitrous oxide emissions account for less than 1 %. Instead, methane accounts for about 95 % of greenhouse gas leakage during the extraction, processing, storage, transportation, and consumption of fuels [3]. Therefore, to reduce methane leakage, gas distribution network operators eliminate leaks in above-ground and underground equipment on shut-off devices (valves, taps, switches), flange and threaded connections of gas pipelines, etc.; replace metal pipelines with polyethylene pipelines; use modern seals; ensure regular and high-quality maintenance of pipelines, safety valves, filters, and other infrastructure components; and update gas consumption measurement equipment.

According to the 2021 report by the United Nations Environment Programme (UNEP) and the Climate and Clean Air Coalition on global methane emissions [23], reducing anthropogenic CH_4 emissions by just 40 % by 2030 would substantially contribute to achieving the goals of the Paris Agreement. Methane is the second most significant greenhouse gas in terms of both volume and climate impact, so such a reduction would have additional benefits, including improved public health, enhanced human development, and strengthened food security. In response, global efforts are increasingly focused on advancing technologies for greenhouse gas capture and developing systems for detecting methane leaks from pipelines and mines. These innovations enable consistent monitoring and surveillance of large geographic areas.

For example, in 2020, European Space Agency satellites under the EU's Copernicus program detected significant methane leaks from a gas pipeline supplying natural gas to Europe [3]. And this, as it turned out, is not the only such case in the world. Therefore, international experts on global climate change propose to improve the methods of assessing and reporting greenhouse gas emissions and leaks, develop new measurement systems, and conduct regular and precise monitoring studies.

The European Commission supported the launch of an international methane emissions observatory in partnership with the United Nations Environment Programme, the Climate and Clean Air Coalition, and other organizations. Therefore, in 2021, UNEP, with the support of the EU Horizon 2020 program and under the [3], established the International Methane Emissions Observatory, which covers the monitoring of CH_4 emissions from the extractive industry (oil and gas sectors) using already developed technologies and through the expanded Oil and Gas Methane Partnership initiative. In the future, the European Commission plans to expand the monitoring to the coal, agriculture, and waste sectors as soon as reliable monitoring and reporting methodologies are developed for them [24].

It is estimated [25] that 54 % of methane emissions in the energy sector are fugitive emissions in the oil and gas sector, 34 % in the coal sector, and 11 % in the residential and other end-use sectors [25]. In this context, the Copernicus Anthropogenic Carbon Dioxide Monitoring mission is planned for 2025, comprising a group of satellites, which experts believe will significantly contribute to identifying smaller sources of emissions of various types of greenhouse gases, including methane [26]. No less important is the Copernicus Data Space Ecosystem mission, which tools were used in our investigation for the climate and atmosphere studies, particularly for the visualization of the methane CH_4, sulfur dioxide SO_2, nitrogen dioxide NO_2, formaldehyde HCHO, and carbon monoxide CO distributions around the European region.

As noted earlier, the CDSE integrated platform delivers immediate and unrestricted access to extensive collections of Earth observation data from the Copernicus Sentinel satellites, encompassing both recently acquired and archival imagery alongside datasets from the Copernicus Contributing Missions [9]. The Copernicus Browser was used as the most important interactive CDSE tool for the current investigation.

There are several satellite missions providing data for the Copernicus Browser. The primary data source applied in the present study is the Copernicus Sentinel-5 Precursor (Sentinel-5P) mission [27]. The mission represents the first Copernicus initiative explicitly dedicated to atmospheric monitoring. Its primary objective is to perform high-resolution spatio-temporal measurements of atmospheric composition, which is essential for air quality assessment, ozone and UV radiation monitoring, climate change observation and forecasting. The data on carbon monoxide, nitrogen dioxide, ozone, formaldehyde, sulfur dioxide, aerosol properties, and cloud parameters is available since 2018.

In terms of the study the Sentinel-5P TROPOspheric Monitoring Instrument [28] data on three processing levels were analyzed – Level-0 (raw data), Level-1B (calibrated and geolocated radiances), and Level-2 (retrieved geophysical variables). The special focus of the study was on the Level-2 data. The sensor of this tool offers a spatial resolution of approximately 7 × 3.5 km and enabled us to determine areas of pollutants high concentration.

The first considered parameter is Level 2 methane. The analyzed dataset provides processed global observations of atmospheric methane concentrations. This product supports climate change research, facilitates identifying and quantifying emission sources, and informs environmental regulation and mitigation strategies. In Fig. 3, the methane emission across the European region is provided. The satellite image date for this and other figures displaying the pollutant distribution patterns is March 03, 2025.

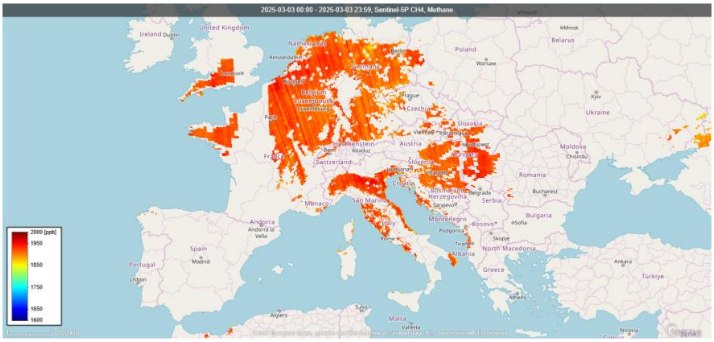


Fig. 3. The methane emission across the European region, in parts per billion (ppb).

The sulfur dioxide Level 2 data set contains comprehensive information on total column amounts and vertical distribution of such pollutant as sulfur dioxide. This includes auxiliary geolocation, cloud properties, and surface reflectance metadata. These data are crucial for analyzing not only volcanic emissions but anthropogenic pollution and their impacts on human health and atmospheric chemistry. Fig. 4 provides the sulfur dioxide distribution across the European region.

The dataset visualization shown in Fig. 5 reveals distributions of nitrogen dioxide across Europe, a short-lived pollutant closely tied to industrial and economic activities, transportation emissions, and fossil fuel combustion [28]. In turn, Fig. 6. represents information on the formaldehyde concentrations in the European atmosphere (Level 2 Sentinel-5P product), representing the behavior of biogenic emissions and secondary pollutants. While not a potent greenhouse gas compared to carbon dioxide or methane, formaldehyde plays a significant indirect role in atmospheric chemistry that contributes to climate change and air quality degradation. Auxiliary parameters such as cloud characteristics and surface reflectance also are included to the Copernicus Browser tool and enhance the accuracy and interpretability of the data.

The data on the Level 2 carbon monoxide product corresponding to the European region is highlighted in Fig. 7. It represents measurements of total column CO and vertical distribution profiles. These data are helpful in identifying fossil fuel combustion-related pollution and assessing the CO dispersion in the atmosphere. Although carbon monoxide is not a strong greenhouse gas by itself due to its relatively short atmospheric lifetime, it also plays a significant indirect role in climate change. CO is one of the precursors GHG and it affects the concentration and lifetime of methane and tropospheric ozone, which leads to warming potential increasing. In the European region, anthropogenic sources such as road traffic, industrial activity, and biomass burning contribute to CO concentrations.

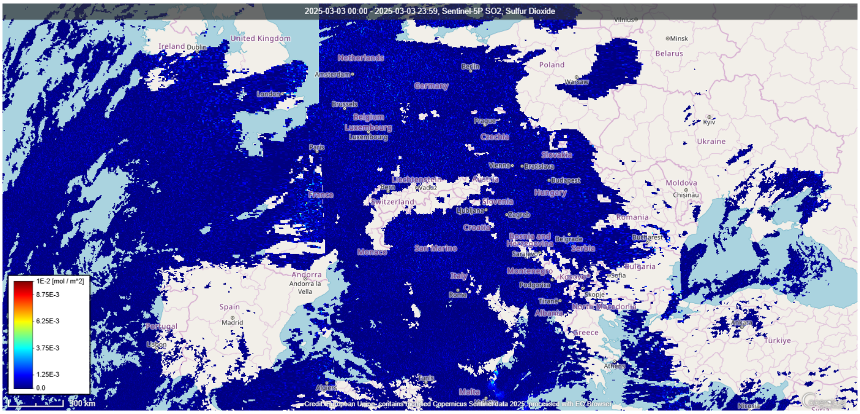


Fig. 4. The sulfur dioxide distribution across the European region,
in mol per square meter (mol/m^2).

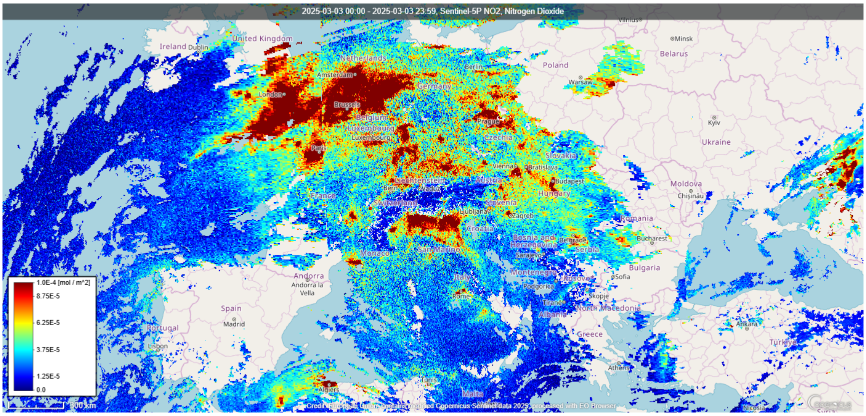


Fig. 5. The nitrogen dioxide distribution across the European region,
in mol per square meter (mol/m^2).

The aerosols are another important climate change influencer complexly impacting several important processes on Earth. Firstly, they affect climate by absorbing and scattering solar radiation, changing the Earth’s radiative balance. Secondly, finely dispersed solid particles of aerosols such as black carbon, volcanic ash, and organic carbon from biomass burning can be deposited on snow and ice, reducing surface albedo and accelerating melting. And thirdly, some aerosols act as cloud condensation nuclei, modifying cloud properties and indirectly influencing precipitation patterns and, as a result – on climate change.

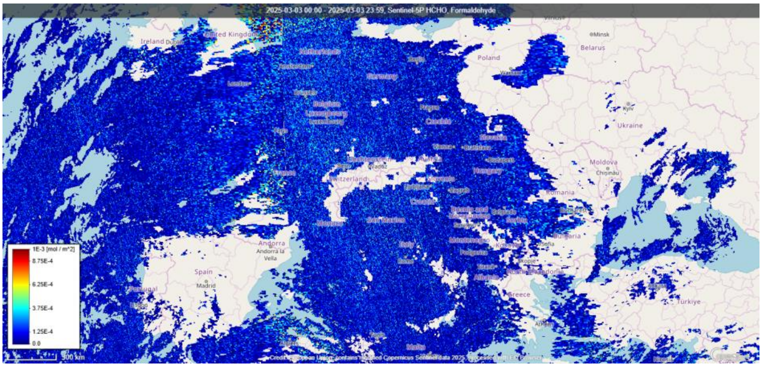


Fig. 6. The data on formaldehyde, corresponding to the European region, in mol per square meter (mol/m^2).

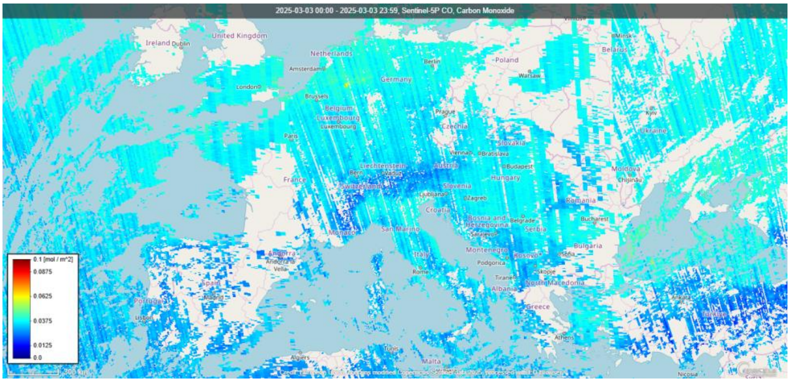
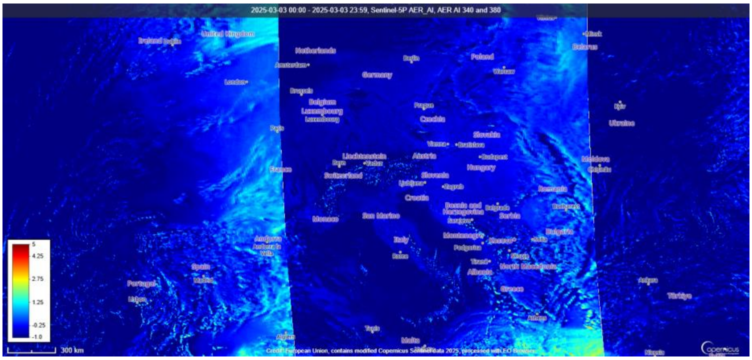


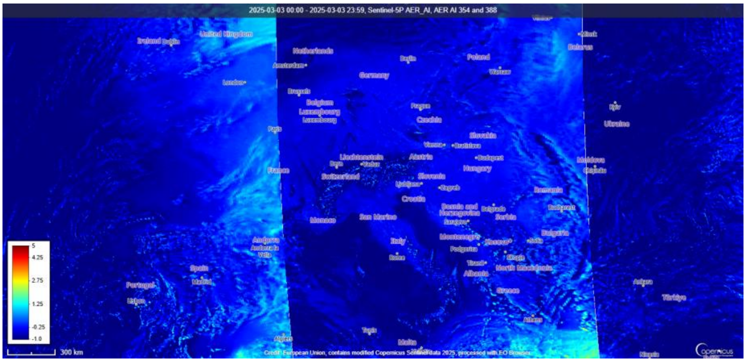
Fig. 7. The data on carbon monoxide, corresponding to the European region, in mol per square meter (mol/m^2).

The UV aerosol index (AAI) Level 2 product of the Sentinel-5P mission quantifies the presence of UV-absorbing aerosols. The AAI is derived from the differential Rayleigh scattering in the UV spectrum and is valuable for detecting episodic aerosol events and their long-range transport. The AAI is derived from the differential Rayleigh scattering in the UV spectrum and is valuable for detecting episodic aerosol events and long-range transport. The data on AAI corresponding to the European region are highlighted in Fig. 8. Positive values indicate the presence of UV-absorbing aerosol – from light blue to red in Fig. 8. In this case, the AAI was calculated for two pairs of wavelengths – 340/380 nm (Fig. 8, a) and 354/388 nm (Fig. 8, b).

In addition, military activities also have a significant impact on global climate change due to the emission of great amounts of carbon dioxide and other greenhouse gases into the atmosphere. This includes emissions caused by ammunition explosions, fires, destruction of infrastructure, fuel consumption, production of military equipment, etc. Total emissions are estimated at 51.6 million tCO_2e per year from military activities, 22.9 million tCO_2e per year from fires, and 17.2 million tCO_2e per year from the destruction of energy infrastructure [29]. The urgent need for post-war reconstruction of the country leads to the conclusion that the construction and property sector will play a major role in ensuring the United Nations climate goals of climate neutrality up to 2050.



a)



b)

Fig. 8. The data on the UV aerosol index, corresponding to the European region: the wavelengths of a) 340/380 nm and b) 354/388 nm.

For example, the #BuildingToCOP26 [30] initiative created the Consortium for zero emissions and a sustainable environment, including the UN's Race to Zero, the World Resources Institute, the World Business Council for Sustainable Development, and other leading industry associations. It is planned to halve greenhouse gas emissions in the construction sector by 2030 and make the built environment a major provider of solutions to combat the climate crisis.

Different national and multinational groups monitor emissions and leakages of the main greenhouse gases; some are government-affiliated, while others are as a rule university-based. The most comprehensive global monitoring program is conducted by the US National Oceanic and Atmospheric Administration, whose activities, for example, in the area of carbon dioxide inventory, are directly coordinated with national programs in Australia, Canada, China, Japan, New Zealand, South Africa, and many other countries.

Among the European Union's programs, the most well-known are Carbo-Europe and System of Satellite Radio Monitoring and Geolocation of Satellite Communication Earth Stations (GEOmon), the French Network for Measurement of the Greenhouse Effect of Atmospheric Compounds (RAMCES), which also covers India and Africa. However, these programs are not always fully funded and are subject to significant cuts. Through the Global Atmosphere Service program, the World Meteorological Organization supports monitoring carbon dioxide and methane emissions into the atmosphere, which is part of the Global Climate Observing System.

Ukraine has been fulfilling its commitments to reduce its total greenhouse gas emissions that can be seen by analyzing the data [31] (Fig. 9). The country has the Law of Ukraine ‘On the Basic Principles (Strategy) of the State Environmental Policy of Ukraine for the Period up to

2030’, the Government has adopted the ‘Strategy of the National Environmental Policy of Ukraine until 2030’ and the ‘National Transport Strategy of Ukraine for the period up to 2030’, the Action Plan until 2025, etc. which set out the main goals to reduce environmental pollution and greenhouse gas emissions, use natural resources more efficiently. The country's accession to the Partnership for the Implementation of Article 6 of the Paris Agreement, launched by the Ministry of the Environment of Japan at the 27th UN Climate Change Conference, was approved [32]. This will allow our country to significantly reduce greenhouse gas emissions (Fig. 9) and facilitate additional funding and investment for its post-war green recovery [33].

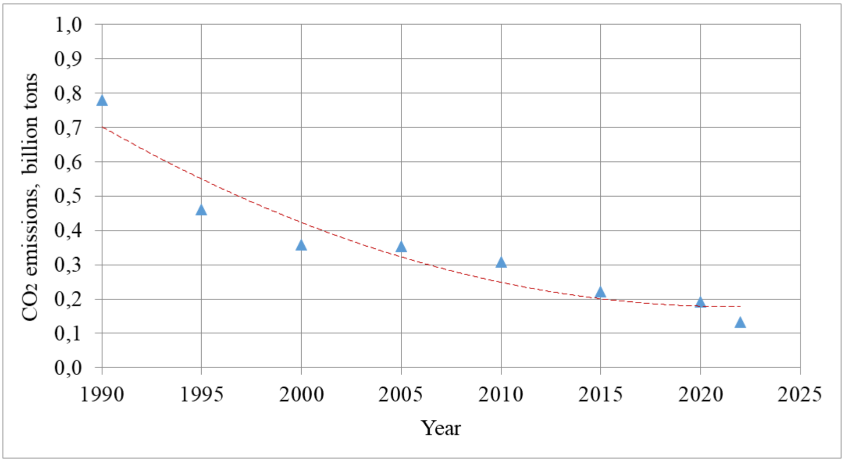


Fig. 9. Fossil carbon dioxide emissions in Ukraine, billion tons.

Thus, introducing innovative environmentally friendly and safe technologies and projects in Ukraine will be particularly important in the post-war period, requiring scientifically based solutions, strategies, and plans for sustainable economic development of communities. The theoretical basis for the development and implementation of economic and environmental incentives is the assessment of the environmental sustainability of the territory of our country and the creation of criteria for assessing the degree of environmental friendliness (greenness) of proposed technical and technological solutions and projects. Energy efficiency reform is important for Ukraine not only from the point of view of environmental protection or rational use of natural resources but also to ensure national, energy, and environmental security.

The introduction of energy-efficient, environmentally friendly technologies, especially in the transport and energy sectors, aligns with sustainable and green development goals and provides an opportunity to use renewable energy sources and improve the energy efficiency of both production and residential development at the end-user level. This goal can only be achieved by introducing the latest waste recycling technologies, using recycled materials, energy-saving measures, greenhouse gas capture and disposal, etc. The marketing component is also important.

As one of the main components of the business management system, marketing involves a series of analytical, strategic, and organizational measures based on a marketing mix - product, price, placement, and promotion policies based on the results of comprehensive market research and the study of consumer behavior. Thus, green marketing, which presents the innovative green energy projects, alternative fuels, etc., is the basis for successfully promoting green products in the market.

It is well-known that the role of marketing activities for a company increases significantly during a crisis. When justifying a strategy, it is necessary to conduct a thorough analysis and evaluation and make the right choice of priorities in marketing activities. The interrelationship of goals and strategies, their temporal coherence, subordination, etc., should be considered. Today, to retain existing customers, attract new ones, and find new marketing techniques to influence them, national companies must introduce green and organic production, promote the improvement of existing technologies, and create new environmentally friendly ones based on the concepts of sustainable development and circular economy, as well as minimize environmental risks to human health and the environment, including as a result of climate change on the planet.

So, taking into account the importance of the sustainability for the customers, a methodological framework for evaluating the environmental performance of innovative projects (startups) in the energy, transport, and agriculture sectors was developed based on the authors' criterion-driven expert assessment approach. The evaluation was based on the analytic hierarchy process introduced by T. Saaty. It enables systematic analysis of complex decision-making scenarios by structuring them into a multi-level hierarchy of criteria and alternatives. The approach was applied and validated using the case of an innovative startup focused on converting agricultural and food industry waste into eco-friendly biodiesel, using a sustainable process that avoids highly toxic inputs. In particular, the production technology incorporates a homogeneous catalyst enhanced with lipophilic surfactants to improve process efficiency and does not use methanol in the production process [34].

The methodology's core is a hierarchical system of evaluation criteria to determine how much the startup aligns with circular economy principles and sustainable development goals, minimizing its environmental impact, including GHG emissions. The highest tier of the hierarchy represents the overall objective, which is assessed through three principal criteria: compliance with EU environmental and sustainability standards, integration of circular economy principles into the business model, and resource-use efficiency. The criteria structure used in the hierarchy reflects insights from the authors' earlier research on sustainability, environmental safety, and decarbonization, particularly [35–37].

Each principal criterion was further divided into sub-criteria. The first criterion examined regulatory compliance and promotion of sustainability through international certifications, the use of advanced technologies such as artificial intelligence and automation, and engagement in socially responsible and biodiversity-preserving activities. The second evaluated the incorporation of sustainable agricultural practices, the adoption of '3R' (Reduce, Reuse, Recycle) principles, the mitigation of environmental pollution, and efforts to reduce greenhouse gas emissions and carbon footprint. The third focused on minimizing health and environmental risks, implementing zero-waste production strategies, and utilizing renewable energy sources. These criteria are explained in more detail in [38].

At the lowest hierarchical level, two decision alternatives are presented: the startup aligns with sustainability and circular economy principles and thus contributes to environmental goals, or the startup does not meet these criteria. The selection of the optimal alternative is based on the AHP-derived weighted scoring provided by qualified experts.

A custom-built YAML-based program was developed to perform the AHP computations and visualize the results. This program utilizes the 'ahp' package in R (version 4.0.3) within the RStudio environment, enabling the structured processing of expert opinions. Three domain experts were engaged in the evaluation process, following appropriate methodological training to ensure consistent and informed judgments. The results of the expert evaluation of the above-mentioned startup are illustrated in Fig. 10.

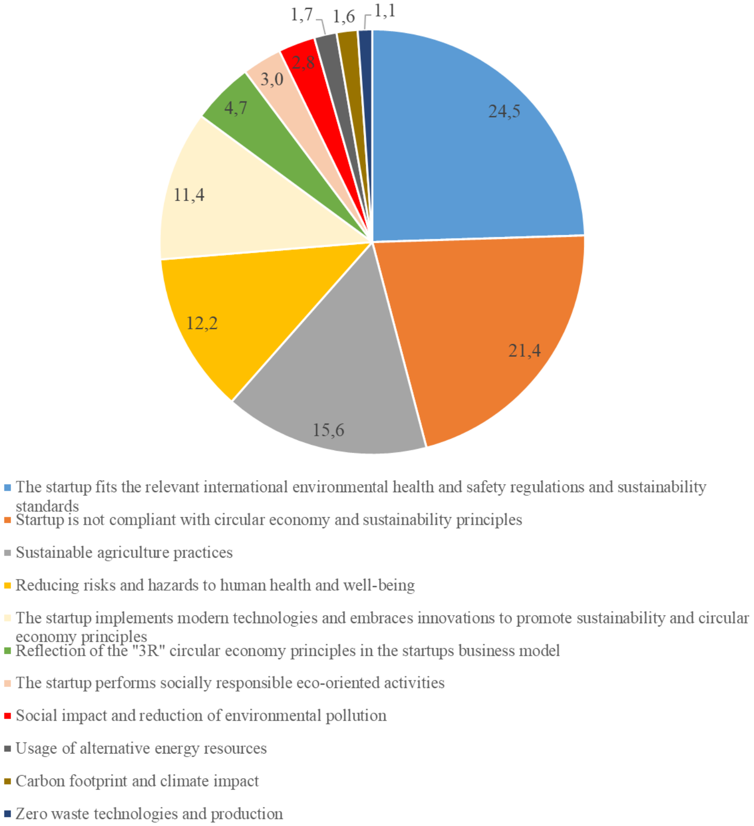


Fig. 10. The results of the expert evaluation of the innovative startup project, by criteria in percent.

According to the developed methodology and provided expert evaluations, it was determined that the startup adhered to the circular economy and sustainability principles. That is to say, our startup was recognized as environmentally responsible because the ‘Yes’ alternative receives a score higher than 75.0 %. As shown in Fig. 10, the evaluated innovative project achieved a total score of 78.6 %. Disaggregating this result, criterion related to the compliance with the European Union environmental standards and sustainability principles, contributes 38.9 %; criterion related to the business model compliance with the circular economy & sustainability principles accounts for 24.7 %; and criterion dedicated to the resource usage rationality contributes 15.0 %. Data on all sub-criteria is presented in Fig. 10. The consistency ratio across all judgments remained below the acceptable threshold of 10 %, indicating high reliability and internal coherence in the expert evaluations.

CONCLUSION

So, climate change on the planet has become a reality. The warming of the Earth's climate system is no longer in doubt, either among experts or ordinary citizens. Since the 1950s, many abnormal and even extreme climatic situations have been recorded. It is documented not only the key GHGs concentration increasing on a global scale but also the world ocean warming, a rise in its acidity due to the intensified absorption of carbon dioxide, and a reduction in both the extent and thickness of snow and ice cover. Scientists attribute all these consequences to natural phenomena (volcanic eruptions, meteorite impacts, earthquakes, etc.), as well as to a significant intensification of anthropogenic activities, including the considerable use of fossil fuels. Thus, emissions from various economic sectors, such as energy production, industrial processes, agriculture and land use, waste, etc., are meaningful influencers of global climate change.

Mitigating climate change requires substantial efforts by countries and their governments, businesses, citizens, etc. to reduce emissions and leakage of dangerous greenhouse gases significantly. This can be achieved through various economic incentives, as well as by improving the energy efficiency of production facilities and the rational use of natural resources, implementing the concepts of circular (green) economy and sustainable development. Since nearly 80 % of greenhouse gas emissions, mainly carbon dioxide, are emitted from the combustion of carbon-based fuels, including transportation fuels, the world is increasingly implementing zero-carbon technologies, intensifying combustion processes in internal combustion engines, and making a transition to renewable energy sources.

To support the climate change mitigation strategies, satellite technologies and Earth observation tools are increasingly utilized. In this context, the present study employed the Copernicus Data Space Ecosystem to analyze spatial patterns of key atmospheric pollutants across the European region. Using data from the Sentinel-5P satellite mission, the high-resolution maps for methane, sulfur dioxide, nitrogen dioxide, formaldehyde, carbon monoxide, and the UV aerosol index were developed. As a result, methane emissions maps were used to detect high-emission zones with potential climate risks; SO_2 and NO_2 maps revealed areas with significant industrial and transport-related emissions, while HCHO visualizations contributed to assessing secondary pollutants and biogenic sources. At the same time, the CO map was used to identify fossil fuel combustion-related pollution, and the aerosol index data highlighted aerosol transport patterns and places with the presence of UV-absorbing particles.

Thus, green innovative projects, being actively implemented, require an effective tool to assess their sustainability and eco-friendliness. So, the methodology and framework for determining the degree of environmental friendliness of innovative startups was developed in the study. It is based on the T. Saaty's analytic hierarchy process and a criterion-based expert evaluation approach. This methodology was tested on the authors' bioenergy startup project aimed at reducing waste from the food and woodworking industries, agriculture, etc., through their recycling.

The key element of the framework is the hierarchical structure based on three main criteria – compliance with EU environmental and sustainability standards, circular economy integration, and rational resource use. The implementation of the developed algorithm confirmed that the authors' startup aligns with sustainability and circular economy principles. Expert evaluations indicate a 78.6 % probability that the project is environmentally responsible, exceeding the 75 % threshold. The reliability of these findings is supported by a consistency ratio being below the threshold of 10 %. The developed methodology demonstrates strong potential for broader application in assessing the sustainability performance of innovative projects in the energy, transport, and agriculture sectors.

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OPPORTUNITIES FOR THE UKRAINIAN CONSTRUCTION BUSINESS IN THE EUROPEAN GREEN COURSE

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ABSTRACT

In the context of the European Green Course the integration of Environmental, Social, and Governance standards into the practices of Ukrainian companies represents both a challenge and an opportunity. For Ukrainian construction companies, especially amid post-war reconstruction and European Union integration efforts, aligning with these standards is crucial not only for enhancing competitiveness but also for accessing international funding and markets. This analysis examines the key components of Environmental, Social, and Governance standards and assesses how Ukrainian construction companies can implement these practices to meet European requirements and drive sustainable development. For calculation and measuring Greenhouse Gas emissions used the principles, requirements and guidance provided by the Greenhouse Gas Protocol Corporate Standard, Global Reporting Initiative 305, and International Organization for Standardization 14064-1:2018. In the European Sustainability Reporting Standards, the undertakings analyze climate-related transition risks, that ensue from the transition to a low-carbon and climate-resilient economy. They typically include policy risks, legal risks, technology risks, market risks and reputational risks, that can arise from related transition events. Efforts to mitigate and adapt to climate change can produce opportunities for undertakings, such as through resource efficiency and cost savings, the adoption and utilization of low-emissions energy sources, the development of new products and services, and building resilience along the supply chain. The transition to green construction is not just a necessity for Ukraine's post-war recovery but also a strategic move toward long-term economic growth and European integration.

Keywords: green course, climate change, green building, resources efficiency, ESG.

INTRODUCTION

The European Green Course (EGC) was officially presented by the European Commission in December 2019 and approved in 2020. This is the European Union's (EU) comprehensive strategy initiate the set of policy initiatives to achieve climate neutrality by 2050 in the key sectors. For the construction industry, EGC define such aims as prioritizing sustainability on the building renovation, developing innovation, energy efficiency, circular economy, and conservation biodiversity.

The idea of introducing stricter rules for corporate reporting for undertakings arose as part of the EGC. As a result, the European Commission launched work on the Corporate Sustainability

Reporting Directive (CSRD) in April 2021. The directive aims to improve the availability and quality of sustainability information for investors and stakeholders, and to ensure the integration of environmental, social and governance (ESG) criteria into companies' business strategies. The European Parliament and the Council of the EU reached a political agreement on the CSRD in June 2022, and the directive was formally adopted in December 2022, but it will be implemented gradually.

The comprehensive EU strategy encompasses also includes the Corporate Sustainability Due Diligence Directive (CSDDD). This directive requires companies to take environmental and social responsibility, complementing the transparency focus. CSRD and CSDDD, while distinct, are closely interrelated and complementary, playing an important role in promoting a sustainable economy. These directives remove the possibility for companies to selectively disclose sustainability information, requiring comprehensive reporting on all relevant aspects.

The European Sustainability Reporting Standards (ESRS) were adopted in July 2023. The following mandatory corporate sustainability reporting deadlines were established: 1) from 1 January 2024 for large undertakings which are public-interest entities; 2) from 1 January 2025 for large companies; 3) from 1 January 2026 for small and medium-sized companies; 4) from 1 January 2028 for companies outside the EU that have branches/subsidiaries. The first reports under the new standards have already been submitted in 2025 based on data for 2024. However, additional transition periods are provided for medium-sized enterprises and non-European companies until 2026-2029.

In October 2024, Ukrainian government adopted the Strategy for the Introduction of Sustainable Development Reporting for Ukrainian Enterprises. The Strategy provides synchronization with the requirements of the CSRD, CSDDD, ESRS, and with additional audit and control procedures that will contribute to the transparent management, social responsibility, and environmental sustainability. In 2025 the Ministry of Finance of Ukraine has published a draft of amendments to the Law of Ukraine "On Accounting and Financial Reporting in Ukraine", which is related to the introduction of the ESRS and enters into force on 1 January 2026. To implement this, an operational plan has already been developed, which provide the introduction of mandatory sustainable development reporting from 2026 for large Ukrainian enterprises with an average number of employees of more than 500 people, and in subsequent years, medium and small companies should join the reporting.

The EU, in cooperation with the Ukrainian government, has developed the Ukraine Facility, aimed at supporting Ukraine's economic and social recovery after the Russian aggression, with a particular emphasis on sustainable development. This program includes financial and technical resources to restore infrastructure, modernize the energy sector and stimulate investment in renewable energy sources. The Ukraine Facility will help construction businesses direct investments to projects that take into account environmental, social and governance factors. The program supports the development of green energy and the implementation of innovations in the field of energy efficiency, in particular projects to reduce greenhouse gas emissions and switch to renewable energy sources. Attention is also focused on social aspects - such as improving the quality of life of citizens, social inclusion and creating new jobs. The implementation of this strategy is critically important for Ukraine in the context of European integration and global challenges related to war and climate change. For the Ukrainian construction business, the implementation of sustainability reporting opens an opportunity and is a challenge in same time. The first companies to provide sustainability reporting faced already a number of methodological problems. Therefore, the purpose of this study is to analyse the opportunities of the Ukrainian construction business on the way the European Green Course, and make an overview of the climate change content of ESRS with the methodology for their implementation.

METHODS AND EXPERIMENTAL PROCEDURES

General overview of ESRS content

European Sustainability Reporting Standards (ESRS) cover the following sustainability topics and sub-topics reporting areas:

1) General information – ESRS 1 General principles; ESRS 2 General, strategy, governance and materiality assessment.

2) Environmental information – ESRS E1 Climate change; ESRS E2 Pollution; ESRS E3 Water and marine resources; ESRS E4 Biodiversity and ecosystems; ESRS E5 Resource use and circular economy.

3) Social information – ESRS S1 Own workforce; ESRS S2 Workers in the value chain; ESRS S3 End users / consumers; ESRS S4 Affected communities.

4) Governance information – ESRS G1 Governance, risk management, internal control; ESRS G2 Business conduct.

To measure relative ESG performance, research analysts gather more than 630 raw ESG data points per company from public resources such as annual reports, company websites, NGO websites, stock exchange filings, and CSR reports etc. This raw data is then rolled up into 186 comparable measures, which are then grouped into 10 categories, including resource use, emissions, innovation, workforce, human rights, community, product responsibility, management, shareholders, and CSR strategy. These 10 categories (themes) are classified into one of three pillars: environmental, social, and corporate governance. The category scores are reformulated into three pillar scores and the final ESG score is a relative sum of the category weights. A percentile rank scoring methodology produces a score between 0 and 100, as well as letter grades from A+ to D- [10].

Analyses of climate change information in ESRS

ESRS E1 "Climate change" shows the nature, type and extent of the undertaking's material risks and opportunities arising from the undertaking's impacts and dependencies on climate change, and how the undertaking manages them. The first disclosure requirement in Environmental ESRS information is about climate change affects in terms of material positive and negative actual and potential impacts. It is help to understand the financial effects on the undertaking over the short-, medium- and long-term time horizons of risks and opportunities arising from the undertaking's impacts and dependencies on climate change. The undertaking shall describe the process to identify and assess climate-related impacts, risks and opportunities. When disclosing the information required, the undertaking shall explain how it has used climate-related scenario analysis to inform the identification and assessment of physical and transition risks and opportunities over the short-, medium- and long-term time horizons. The information shall include an explanation of the decarbonisation levers identified, and key actions planned, including changes in the undertaking's product and service portfolio and its adoption of new technologies. The undertaking shall indicate whether and how its policies address the following areas: climate change mitigation, climate change adaptation, energy efficiency, renewable energy deployment, and other.

Emission reductions may result from energy efficiency, electrification, suppliers' decarbonisation, electricity mix decarbonisation, sustainable products development or changes within the undertaking's own operation and value chain. Aggregated types of mitigation actions must fit with undertakings' specific actions, however removals and avoided emissions are not counted as emission reductions. The most difficulties arise when calculating emissions by Scope 1, 2, 3.

GHG emissions calculation methods

Greenhouse Gases (GHG) are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of terrestrial radiation emitted by the Earth's surface, the atmosphere itself and by clouds, which causes the greenhouse effect. Water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3) are the primary GHGs in the Earth's atmosphere. Moreover, there are a number of entirely human-made GHGs in the atmosphere, such as the halocarbons and other chlorine- and bromine-containing substances, dealt with under the Montreal Protocol. Besides CO_2, N_2O and CH_4, the Kyoto Protocol deals with the GHGs sulphur hexafluoride (SF_6), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs).

While preparing the information for reporting GHG emissions the undertaking shall consider the principles, requirements and guidance provided by the GHG Protocol Corporate Standard, and GRI 305, and also the requirements stipulated by ISO 14064-1:2018. It is need to disclose the methodologies and emissions factors used to calculate or measure GHG emissions, and provide a reference or link to any calculation tools used.

The disclosure on GHG emissions shall include in metric tonnes of CO_2eq, which is the universal unit of measurement to indicate the global warming potential (GWP) of each greenhouse gas. GWP is a factor describing the radiative forcing impact and degree of harm to the atmosphere of one unit of a given GHG relative to one unit of CO_2. It is used to evaluate releasing different greenhouse gases on a common basis.

Scope 1 are direct GHG emissions from sources owned or controlled by the undertaking, in particular, objects and vehicles on the company's balance.

Scope 2 is indirect emissions from the generation of purchased or acquired electricity, steam, heat, or cooling consumed by the undertaking. Scope 2 are a consequence of the operations of the undertaking but occur at sources owned or controlled by another company. Purchased or acquired energy is brought into the undertaking's facility from a third party. It reflects circumstances where a company may not directly purchase electricity, e.g. a tenant in a building. The total Scope 2 GHG emissions makes a distinction of measured using the location-based method and the market-based method. The total energy consumption expresses in MWh and the net revenue in monetary units.

The origin of energy is also assessed, depending on the use of renewable and non-renewable resources for its production. Renewable energy is energy taken from sources that are inexhaustible, as such covers wind, solar (solar thermal and solar photovoltaic) and geothermal energy, ambient energy, tide, wave and other ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas, and biogas. Fossil fuels such as oil, natural gas, and coal are examples of non-renewable resources.

Scope 3 are all indirect GHG emissions (not included in scope 2) that occur in the value chain of the company, including both upstream and downstream emissions. Scope 3 category is one of the 15 types of Scope 3 emissions identified by the GHG Protocol Corporate Standard and detailed by the GHG Protocol Corporate Value Chain. For many undertakings, Scope 3 GHG emissions may be the main component of the GHG inventory. Their calculation is based on a combination of methods and primary and secondary data ranging from precise figures (supplier-specific or sites-specific methods) to extrapolated figures (average-data or spend-based methods).

Total GHG emissions is to provide an overall understanding of the undertaking's GHG emissions and whether they occur from its own operations or the value chain. The disclosure of total GHG emissions shall be the sum of Scope 1, 2 and 3 GHG emissions.

The GHG intensity ratio calculate by the following formula:

[$Total\ GHG\ emissions\ (t\ CO_2eq)$] / [$Net\ revenue\ (Monetary\ unit)$]

The intensity ratio defines an organization's energy consumption in the context of an organization-specific metric calculates using the following formula:

[$Total\ energy\ consumption\ from\ activities\ in\ high\ climate\ impact\ sectors\ (MWh)$] / [$Net\ revenue\ from\ activities\ in\ high\ climate\ impact\ sectors\ (Monetary\ unit)$]

The share calculates by using the following formula:

[GHG emissions in (t CO_2eq) from EU ETS installations +national ETS installations + nonEU ETS installations] / Scope 1 GHG emissions (t CO_2eq)

The total GHG emissions calculate by the following formulas:

Total GHG emissions$_{location-based}$ (t CO2eq) = Gross Scope 1 + Gross Scope 2$_{location-based}$ +Gross Scope 3

Total GHG emissions $_{market-based}$ (t CO2eq) = Gross Scope 1 + Gross Scope 2 $_{market-based}$+Gross Scope 3

The undertaking may disaggregate its Scope 1, 2 and 3 GHG emissions by country, operating segments, economic activity, subsidiary, GHG category (CO2, CH4, N2O, HFCs, PFCs, SF6, NF3, and other GHG considered by the undertaking) or source type (stationary combustion, mobile combustion, process emissions and fugitive emissions) as appropriate.

The undertaking discloses information about its GHG emissions in gross Scope 1, 2, 3 and calculate total GHG emissions to provide an understanding of the direct impacts of the undertaking on climate change. This disclosure is a prerequisite for measuring progress towards reducing GHG emissions in accordance with the undertaking's climate-related targets and EU policy goals [4].

THE RESEARCH RESULTS AND DISCUSSIONS

The use of ESG indicators ensures transparency, objectivity and measurability of company performance. More than 90% of S&P500 companies now publish ESG reports in some forms, as do approximately 70% of Russell 1000 companies. In a number of jurisdictions, reporting ESG elements is either mandatory or under active consideration. ESG links to cash flow in five important ways: (1) facilitating top-line growth, (2) reducing costs, (3) minimizing regulatory and legal interventions, (4) increasing employee productivity, and (5) optimizing investment and capital expenditures [5]. A major part of ESG growth has been driven by the environmental component of ESG and responses to climate change [7]. More than 5,000 businesses have made net-zero commitments as part of the United Nations' "Race to Zero" campaign.

Background for sustainable reporting among Ukrainian businesses

Based on the International Finance Corporation (IFC) report "ESG in Ukraine: New Opportunities for Business" and the research of the Centre for Economic Recovery, about 40% of Ukrainian companies already integrate some aspects of ESG into their operations, and more than 60% of executives consider the implementation of ESG standards important for the successful future of business [6].

In January-February 2025 Green Transition Office requested the research for understanding the status of implementation of ESG practices in Ukrainian business. Weighted sample had over 420 completed questionnaires, representing the economy of Ukraine by industry, region, and size of enterprises throughout the country [9].

Only a small proportion of Ukrainian companies (15%) indicate that they understand well what sustainable business is, 33% have a general idea without details, 22% heard something, and 30% hearing about it for the first time (Fig. 1-a). At the same time, the majority of surveyed enterprises consider their business to be sustainable: 32% - definitely, 45% - probably, 17% - don`t sure in sustainability their business, 6% - definitely sure about negative impact their activity to environmental (Fig. 1-b).

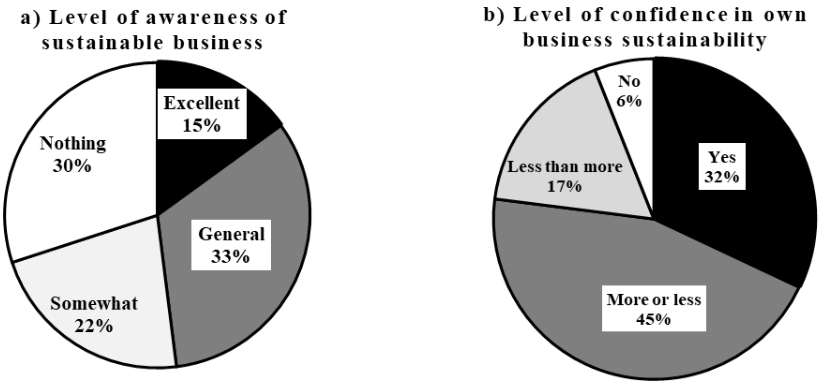

Fig. 1. Level of awareness and confidence about sustainable business in Ukraine.

The level of awareness of specific sustainable development standards is approximately equally low among respondents: the popularity of various sustainable reporting standards doesn't differ significantly: IFRS (International Financial Reporting standards) - 9%, ESRS - 8%, UN Global Compact - 8%, GRI (Global Reporting Initiative) - 7%. It is indicative that there is a tendency to forget the GRI standards, which were previously the most recognizable. However, despite the low awareness, the majority of companies (both among those who know about ESG and among those who don't) express a rather positive attitude towards the implementation of ESG standards in Ukraine (Fig. 2).

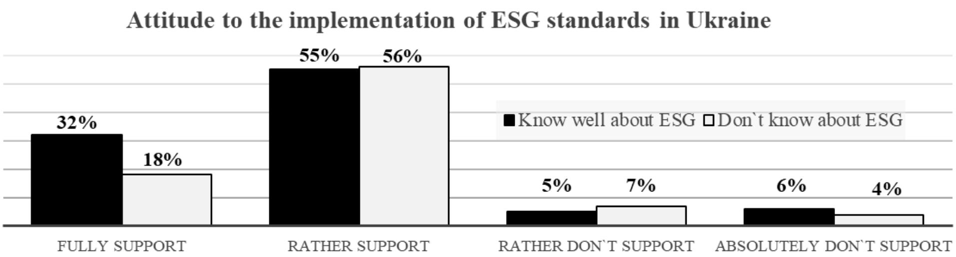

Fig. 2. Comparison the attitude to the implementation of ESG in depending of knowledges about it.

The majority of companies surveyed indicated that, given the appropriate regulatory guidance, they would be ready to implement ESG standards within a year. Most of companies (77%) consider the lack of qualified personnel and insufficient qualifications of existing employees as a problem, and 89% believe that training existing employees will improve their readiness to implement ESG. 72% believe that hiring new employees with strong ESG competencies will improve their readiness to implement sustainable reporting. This result indicates that there is significant potential for implementing sustainable development practices in Ukraine.

Construction and property sector has a key role in delivering the EGD given the significant economic, environmental and social impacts and benefits associated with construction products, buildings and infrastructure assets across their lifecycle. On professionals working in the buildings industry, there is an expectation and responsibility to take actions to reduce these impacts. Also, in the construction sector ESG factors are crucial for determining the overall value and potential of a real estate object, which helps investors receive more information for decision-making and risk assessment.

Climate-related risks and opportunities

Climate-related transition risks arise from the transition to a low-carbon and climate-resilient economy. They typically include policy risks, legal risks, technology risks, market risks and reputational risks, that can arise from related transition events. Climate-related opportunities refer to the potential positive effects related to climate change on the undertaking. Efforts to mitigate and adapt to climate change also can produce opportunities for undertakings, such as through resource efficiency and cost savings, the adoption and utilization of low-emissions energy sources, the development of new products and services, and building resilience along the supply chain.

According Task Force on Climate-Related Financial Disclosures (TCFD) classification, climate-related transition events are affected policy and legal, technology, market, reputation (Fig. 3). Political and legislative changes may cause increasing pricing of GHG emissions, enhanced emissions-reporting obligations, mandates on and regulation of existing products, production processes and services, exposure to litigation. Technological development contributes to investment in new technologies with substitution of existing products and services with lower emissions options. Market development provides changing customer behaviors in conditions uncertainty in market signals and increased cost of raw materials. The company's reputation affects by shifts in consumer preferences, stigmatization of sector, increased stakeholder concern and their negative feedback.

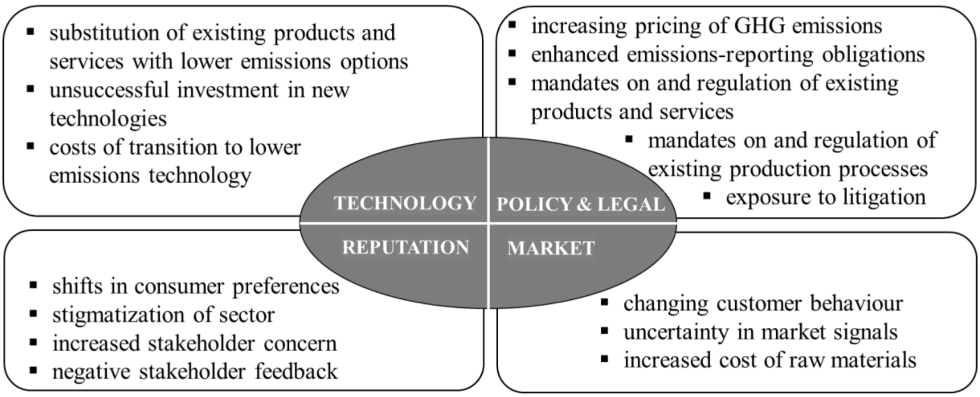

Fig. 3. Examples of climate-related transition events based on TCFD classification

The undertaking needs to identify climate-related hazards over the short-, medium- and long-term time horizons and screened whether its assets and business activities may be exposed to these hazards. The identification of climate-related hazards and the assessment of exposure and sensitivity are informed by high emissions climate scenarios or relevant regional climate projections. It is need taking into consideration the likelihood, magnitude and duration of the hazards as well as the geospatial coordinates specific to the undertaking's locations and supply chains. Identified hazards should be agreed to the expected lifetime of its assets, strategic planning horizons and capital allocation plans. It is necessary to screened its activities and plans in order to identify actual and potential future GHG emission sources in own operations and along the value chain.

When conducting climate scenario analysis, the undertaking may consider the following guidance: TCFD Technical Supplement on “The Use of Scenario Analysis in Disclosure of Climate-Related Risks and Opportunities” (2017); TCFD “Guidance on Scenario Analysis for Non-Financial Companies” (2020); ISO 14091:2021 “Adaptation to climate change — Guidelines on vulnerability, impacts and risk assessment”; any other recognised industry standards; and EU, national, regional and local regulations.

Climate-related opportunities will vary depending on the region, market, and industry where the undertaking operates. For example, the company has saved $2.2 billion since introducing its “pollution prevention pays” (3Ps) program, preventing pollution up front by reformulating products, improving manufacturing processes, redesigning equipment, and recycling and reusing waste from production [1]. Another enterprise, a major water utility, achieved cost savings of almost $180 million per year thanks to lean initiatives aimed at improving preventive maintenance, refining spare-part inventory management, and tackling energy consumption and recovery from sludge [5]. Numerous studies demonstrate that firms conducting ESG practices increase firm performance, the stability [10]. ESG create long-term financial and social returns, such as management quality, corporate culture, and innovative capability [3].

Investments opportunities

The Global Sustainable Investment Review (GSIR) reports that at the start of 2020, global sustainable investment reached US$35.3 trillion in five major markets – the United States, Canada, Japan, Australasia, and Europe, where the U.S. and Europe represent more than 80% of global sustainable investing assets [10]. In 2024, the largest investor network on responsible investment PRI (Principles for Responsible Investment) has over 5,300 signatories, of which 750 are asset owners from over 80 countries representing approximately US$128 trillion [3]. Asset owners are likelier than investment managers to take a longer-term approach to identifying climate-related risks and opportunities and to use climate scenario analysis (58% vs 29%) [2]. A survey of over 300 fund managers, of whom only 23% self-identified as “socially responsible investors,” found that over 70% viewed ESG as a tool to identify investment opportunities as well as to manage risk [8].

ESG-oriented investing has experienced a meteoric rise, 72% of institutional investors implemented ESG factors [8]. Global sustainable investment now tops $30 trillion—up 68% since 2014 and tenfold since 2004 [5]. Implementing a trading strategy of buying stock with high socially responsible ratings and selling stocks with low socially responsible ratings, they show that this strategy earns an abnormal return of 8.7% per year [10].

The rising profile of ESG has also been also plainly evident in investments, even while the rate of new investments has recently been falling. Inflows into sustainable funds, for example, rose from $5 billion in 2018 to more than $50 billion in 2020, then to nearly $70 billion in 2021, and in 2022 global sustainable assets was about $2.5 trillion. These funds gained $87 billion of net new money in the first quarter of 2022, followed by $33 billion in the second quarter [7]. Midway in 2024, global investments in exchange-traded ESG funds amounted to $5.4 billion, according to Bloomberg [6]. Potential financial effects impact on the undertaking’s future position, performance and cash flow arising from material sustainability matters.

Recommendation for Ukrainian construction companies

Analysis of current market trends allows us to recommend the following areas of development for Ukrainian construction companies: EU regulatory compliance, green certification, transparency and accountability, leveraging international funding, partnerships stakeholder engagement, workforce training, innovation and digitalization technology, sustainable smart cities and infrastructure, indoor environmental quality, energy- and resource efficiency, sustainable construction materials, circular economy and recycling waste management.

EU regulatory compliance. Ukrainian construction undertakings must overcome challenges such as compliance with EU regulations. Aligning with EU standards not only facilitates market entry into Europe but also helps Ukrainian companies attract green financing and establish partnerships with European business.

Green certification. Ukrainian building companies recommended to implement green certification, such as BREEAM, DGNB, WELL, and EU Taxonomy-aligned industry standards to enhance competitiveness and attract European investors. Buildings must be designed to withstand the impacts of climate change, including extreme weather events and other hazards Current realities require equipment climate-resilient design elements, such as flood and fire defences with green infrastructure.

Transparency and accountability. Strong corporate governance practices, including transparency, accountability, clear reporting, ethical conduct, and risk management, are integral to current business compliance. Implementing robust internal controls, regular ESG reporting, and third-party audits in Ukraine can improve transparency and enhance credibility in the international arena.

Leveraging international funding. Leveraging international funds, grants, and low-interest loans dedicated to sustainable projects can alleviate financial constraints development of the construction market of Ukraine. Ukraine's recovery plans include funding for green projects and construction solutions under the slogan "build back better".

Stakeholder partnerships engagement. Inclusive decision-making processes, effective stakeholder communication, and long-term strategic planning are key to sustainable governance. By fostering a culture of accountability and engaging with diverse stakeholder groups, Ukrainian firms can ensure that their governance models support long-term environmental and social objectives. Collaboration with governmental bodies help update national construction standards and integrate ESG benchmarks aligned with EU requirements. Collaborating with European construction firms and technology providers can help Ukrainian companies adopt best practices and expand their business in public-private partnerships (PPPs). The range of stakeholders should also be expanded through close cooperation with local communities, academic institutions, and industry-related international organizations.

Workforce training. There is a need for enhanced training, development and certifications programs to upskill the workforce in sustainable construction practices and digital technologies. Workers are also increasingly prioritizing factors such as belonging and inclusion as they choose whether to remain with their company or join a competing employer.

Innovation and digitalization technology. Digital tools like Building Information Modeling (BIM) improve efficiency, reduce costs, and help comply with EU sustainability standards for digitalization and innovation in construction. Prefabrication and 3D printing enhance speed, reduce waste, and improve quality in large-scale construction projects. According to green reconstruction and large-scale sustainable urban development in Ukraine need provides an opportunity to rebuild using modern, energy-efficient, eco-friendly materials.

Sustainable smart cities and infrastructure. Ukraine can integrate smart cities and smart grid technologies, sustainable infrastructure renewable energy, and eco-friendly urban planning principles in its reconstruction efforts. Ukrainian companies can contribute to the development of smart energy management solutions for buildings. Focusing on affordable reconstruction and inclusive design can promote social equity, a critical factor in the post-war rebuilding process. By adopting transparent labour policies, ensuring workplace safety, and engaging local communities, Ukrainian construction companies can build trust and support sustainable urban development.

Indoor environmental quality (IEQ). High standards for health, safety, and indoor environmental quality are essential for occupant health and comfort, including proper ventilation, low-emission materials, and effective lighting and acoustics. In Ukraine enhancing indoor air quality and overall comfort through modern construction practices can address public health concerns, particularly in densely populated urban areas.

Energy- and resource efficiency. European standards emphasize energy-efficient building design, the reduction of greenhouse gas emissions, and the use of renewable energy. The EU's commitment to renovating inefficient buildings presents an opportunity for Ukrainian firms specializing in insulation, retrofitting, and HVAC systems. Ukrainian business is increasingly investing in modern insulation, high-efficiency HVAC systems, and renewable energy installations to align with EU targets. In particular, there are a number of state programs for financing energy efficiency in buildings, installing solar panels and geothermal systems. Implementing renewable energy systems in residential and commercial buildings aligns with EU sustainability goals.

Sustainable construction materials. The EGC promotes the use of sustainable, recyclable, and low-impact construction materials while emphasizing the reduction of construction waste. This action can reduce environmental impacts and improve long-term sustainability. Ukraine can develop and manufacture eco-friendly materials that comply with EU standards such as low-carbon concrete, recycled insulation, and sustainable timber.

Circular economy and recycling waste management. Ukraine needs to establish sustainable materials and waste management adoption of circular economy principles, such as reusing construction materials and minimizing waste during demolition and reconstruction. Implementing circular economy principles, such as reusing construction waste and promoting modular construction, can reduce costs and improve sustainability.

Ukraine's construction sector has a unique opportunity to align with the EGC and position itself as a key player in the green transition. Ukrainian companies may face challenges in meeting EU standards due to outdated technologies and regulatory frameworks that differ from those in Europe. Ukrainian construction firms must overcome challenges such as compliance with EU regulations, investment barriers, and technology gaps. Ukrainian regulations should harmonize with the EU's energy performance, emissions reduction, and circular economy policies. Collaboration with EU partners, engaging in joint ventures and knowledge-sharing with European construction firms can accelerate modernization. Social sustainability requires responsible labour practices, community involvement, and stakeholder engagement throughout the construction process.

By embracing sustainable practices, digital innovation, and EU standards, Ukrainian firms can access new markets, attract investments, and contribute to the country's resilient and environmentally friendly reconstruction. The transition to green construction is not just a necessity for Ukraine's post-war recovery but also a strategic move toward long-term economic growth and European integration.

Discussion

After Russia invaded Ukraine, the U.S. media brought to light that a number of ESG funds hold stakes in Russian assets ranging from state-backed energy companies to government bonds. Indeed, ESG has been criticized by those who think it does not do enough "good for the world" and instead is "just capitalism at its slickest: ingenious marketing in the service of profits" [8]. On March 5 2025 Donald Trump, in his speech to a joint session of Congress, announced the USA withdrawal from the Paris Climate Agreement, calling it a "green scam". These are very dangerous trends that are destroying the global system for confronting the dangers of climate change.

On 26 February 2024, the European Commission presented the Omnibus simplification package. According to the new proposals, the criteria for mandatory reporting are significantly changed - now the requirements will apply only to companies with more than 1,000 employees, which will lead to a reduction in the number of enterprises subject to regulation by 80%. In addition, the deadlines for introducing reporting for the second and third waves of companies are postponed by two years. Among other important changes note the complete abolition of industry standards and the abolition of sanctions in the amount of 5% of turnover, which were previously provided for violation of the requirements [9].

The corporate sustainability standards aren`t only beneficial for the EU, but also a critical important tool to support Ukraine's recovery, development and integration into the European economy. A strong EU framework sends a clear signal to international companies that responsible behaviours is expected and valued. This predictability and commitment to ethical standards will make Ukraine a more attractive destination for responsible foreign investment, which is crucial for our economic recovery and long-term development.

In times of war and post-war reconstruction, the risks of exploitation of labour and resources increase. A robust social criterion of ESG can act as a safeguard against unethical business practices in Ukraine, ensuring that companies operating in or sourcing from Ukraine respect human rights, labour standards, and environmental protection. Social components of ESG have been gaining prominence. The social-related shareholder proposals rose 37% percent in the 2024 proxy season compared with the previous year [7]. This is vital to protecting Ukraine's workers and resources and building a sustainable and just society.

Ukraine aspires to become a full member of the EU and shares its values, including human rights, sustainable development, and the rule of law. European countries have consistently demonstrated their unwavering support for Ukraine's sovereignty, resilience, and European path. The commitment to a strong and effective Sustainability Reporting Standards is a logical extension of this support. By ensuring that companies operating in the EU adhere to high standards of due diligence, European governments can contribute to a more stable and ethical business environment for Ukraine as it shapes its own future.

It is expected that in the next 3-5 years Ukraine will significantly increase CO_2 prices. This will happen for several reasons: either through the introduction of the Carbon Border Adjustment Mechanism (CBAM), or through an increase in the CO2 emission tax, or through the creation of a greenhouse gas emissions trading system, at least 20-30 EUR/t CO_2-eq. in Ukraine, while the current ETS price is 80 EUR/t CO_2 [6].

Meanwhile, the European Commission plans to postpone the main set of requirements of the Sustainable Reporting Directives until 2030, as there is currently no consensus among member states. Against this background, Ukraine can become a flagship of sustainable reporting, because the war convinced us of the importance of tracking supply chains. ESG reporting for Ukraine during the war is a matter of survival. The new legislative initiative brings Ukraine's European integration closer and promotes the development of companies. Businesses that demonstrate specific commitments to sustainable development will become undisputed leaders in their industries in the next 30 years and will gain access to investment capital. On the other hand, companies that do not take care of compliance with international standards in a timely manner risk losing their business in the medium term.

As Ukraine seeks to rebuild and strengthen its economy, alignment with EU standards is paramount. This promotes responsible business conduct and fair competition, creating a level playing field that benefits Ukrainian businesses seeking to integrate into the EU market. ESG standards encourage responsible supply chains and can help Ukrainian companies attract sustainable investment from European partners who increasingly value due diligence and ethical practices. This is particularly important for Ukraine's reconstruction efforts, ensuring that they are conducted in a transparent and accountable manner.

The integration of ESG standards into the construction practices of Ukrainian companies represents both a challenge and an opportunity. By aligning environmental, social, and governance practices with European standards, Ukrainian construction businesses can not only contribute to sustainable urban development but also secure a competitive advantage in the European market. This transformation is critical for meeting the objectives of the European Green Course, supporting post-war reconstruction, and fostering long-term economic growth and societal well-being in Ukraine.

CONCLUSION

For integration to the EGC Ukrainian enterprises need embracing sustainable practices and EU standards which supporting post-war reconstruction, and fostering long-term economic growth and societal well-being in Ukraine. In the context of the EGC the integration of ESG standards into the practices of Ukrainian companies represents both a challenge and an opportunity. Ukraine's construction sector has a unique opportunity take position a key player in the green transition by implementation green building technologies and ESG practices, which allowed access to new markets, attract investments, and contribute to the country's resilient and environmentally friendly reconstruction. The study of the readiness of Ukrainian businesses for ESG standards indicate the trends of significant potential for implementing sustainable development practices in Ukraine. Only a small proportion of Ukrainian companies indicate that they understand well what sustainable business is, but at the same time, the majority of surveyed enterprises consider their business as sustainable. Despite the low awareness, the majority of companies express a positive attitude towards the implementation of ESG standards in Ukraine and with the appropriate regulatory guidance, they would be ready to implement ESG standards within a year. The EGC and implementation of ESG standards offers significant benefits for Ukraine in several key areas: supporting Ukraine's economic recovery and EU integration, attracting responsible and long-term investment, preventing exploitation and ensuring ethical business practices in Ukraine, alignment with European values and support Ukraine's European integration aspirations. Analysis of current market trends allows us to recommend the following areas of development for Ukrainian construction companies: EU regulatory compliance, green certification, transparency and accountability, leveraging international funding, partnerships stakeholder engagement, workforce training, innovation and digitalization technology, sustainable smart cities and infrastructure, indoor environmental quality, energy- and resource efficiency, sustainable construction materials, circular economy and recycling waste management.

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ECO-FRIENDLY WATER DISINFECTION USING HIGH-VOLTAGE ELECTRIC DISCHARGE

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ABSTRACT

Water disinfection is a crucial step necessary for its use in human activities. The study explores applying plasma technology based on an electric discharge known as "high-voltage liquid breakdown" to achieve a bactericidal effect. It has been experimentally established that cavitation is the key factor among the factors arising during the high-voltage breakdown of the interelectrode gap in a liquid and affecting bacterial survival. The combined use of oxidizers and high-voltage electric discharge in a liquid in cavitation mode ensures effective and sustainable water disinfection. Moreover, the doses of oxidizer required to achieve a bactericidal effect are reduced by 10 times compared to existing standards, and the energy consumption for electric discharge treatment, enhanced by small doses of oxidizer, is reduced by 6 times compared to using only electric discharge. Additionally, the combined use of high-voltage electric discharge in cavitation mode with oxidizers significantly reduces the time required for water disinfection.

An analysis of the physical and chemical phenomena associated with electrical discharges has been conducted, focusing on the key factors that influence the inactivation of microorganisms. The study experimentally demonstrates the similarity between cavitation processes in water systems induced by underwater electric discharges and those caused by ultrasound. The characteristic features of electrical discharge in the cavitation mode, which enable effective water disinfection with significantly reduced amounts of active chlorine, are identified and prioritized.

The inactivation of microorganisms is enhanced primarily by the generation of chemically active particles from the water itself, driven by the combined effects of electro-discharge cavitation across the entire treated volume, as well as localized shock waves, acoustic flows, and ultraviolet radiation near cavitating bubbles.

The main advantages of electric discharge cavitation over ultrasonic methods include a broader range of high-frequency acoustic radiation inherent to electric discharges, higher intensity and power of cavitation processes, and the potential to significantly increase the volume of disinfected liquid. This research provides a deeper understanding and improved prediction of the bactericidal effects of high-voltage underwater electrical discharges.

Keywords: water disinfection; plasma-based technologies; underwater electrical discharges; cavitation; liquid activation.

INTRODUCTION

The growth of the global population, coupled with increasing demand for both drinking and industrial water, as well as the negative impact of human activities on the environment, has made freshwater one of the most critical and sought-after resources of the 21st century. Over 1 billion people currently face a chronic shortage of clean freshwater. According to projections, by 2025, this issue will become even more severe in half of the world's countries, and by the end of the century, two-thirds of the global population could find themselves in a dire situation due to a lack of drinking water. The U.S. Environmental Protection Agency estimates that nearly 35% of deaths in developing countries are linked to the use of contaminated water [1]. The pollution of rivers and streams by chemical and harmful biological agents remains one of the most pressing environmental challenges. Contaminated water entering natural water bodies triggers a chain of devastating consequences. The need to treat domestic wastewater before discharge is evident, with the primary goal being to prevent unacceptable harm to the environment. Modern wastewater treatment methods must aim for a desired level of disinfection and demonstrate long-term effectiveness. The ultimate objective of wastewater treatment is the efficient management of water resources in a way that is both economically and environmentally sustainable.

Despite the vast number of studies dedicated to the issue of water treatment, the relevance of research in this field remains high. Contemporary authors [2-6] explore various methods of water disinfection, highlighting their key advantages and disadvantages. Significant attention is given to both traditional methods of removing heterogeneous impurities of biological origin (such as chlorination, ozonation, and ultraviolet treatment) and unconventional approaches (including plasma and membrane technologies, among others). According to current perspectives [7-9], the primary mechanisms for inactivating microorganisms include: the rupture of cell walls; modification (alteration) of cell permeability; changes in the nature of protoplasm (e.g., disruption of colloidal structure); induction of abnormal redox processes; and alterations in the structure of nucleic acids, which hinder protein synthesis within the cell.

A breakthrough in water treatment over the past few decades has been the development of membrane technologies, including microfiltration, nanofiltration, ultrafiltration, and reverse osmosis. These technologies are based on the concept of a physical barrier and are undisputed leaders in the quality removal of colloids and organic compounds with higher molecular weights. The extremely low residual toxicity, due to the absence of by-product formation during treatment, gives membrane technologies significant advantages for replenishing groundwater sources and reusing water for drinking purposes compared to other methods. As early as 1991, pilot tests of a microfiltration system using hydrophilic membranes (pore size 0.2 μm) [10] demonstrated the ability to remove suspended solids, algae, and bacteria from water. Following these, similar experiments were conducted with ultrafiltration membranes (pore size 0.01 μm) [11] and reverse osmosis systems. The use of ultrafiltration reduced the concentration of heterogeneous biological contaminants by 2–3 orders of magnitude, and complete removal of E. coli, streptococci, salmonella, clostridia, and enteroviruses was demonstrated across various effluents, with performance heavily dependent on the fouling state of the membrane. A flow rate of around 50 $dm^3/h \cdot m^2$ is now commonly accepted as the nominal standard for both ultrafiltration and microfiltration. The use of reverse osmosis membranes enables the production of very high-quality water, such as that required for food applications [12]. However, due to lower productivity and the high equipment cost, this method's primary niche remains desalination. Nevertheless, membrane-based disinfection is now successfully combined with intensive biological treatment in membrane bioreactors [13], where membrane technology serves as the final element in full-cycle wastewater treatment systems. Thus, by the beginning of the 21st century, it became evident that membrane technology is the most advanced method of water purification. The compact size of the systems, relatively simple maintenance, and the high quality of water produced through membrane filtration have allowed this cutting-edge technology to replace traditional treatment processes [14]. Despite these advantages, membrane technologies have not yet gained widespread adoption as a standalone solution for large-scale water treatment. This is primarily due to significant fluctuations in performance caused by membrane fouling. For example, changes in wastewater quality can quickly foul membranes, reducing their permeability severely [15; 16], which is unacceptable for large-scale water treatment. To this day, membrane technologies remain an extremely effective but expensive component in the water treatment cycle, primarily used for fine polishing. Extensive research is needed to clarify the relationship between the nature and extent of membrane fouling and operational conditions, enabling a more informed selection of membrane properties, configuration, pre-treatment methods, and cleaning conditions.

To this day, water disinfection using various chlorine-based agents (liquid chlorine, electrolyzed chlorine, sodium hypochlorite, chlorine dioxide, inorganic chloramines) remains one of the oldest and yet most widely used methods for treating domestic wastewater and preparing water from natural sources for safe human use. Alongside its clear advantages—such as the relative simplicity of the systems, consistently high productivity, strong disinfecting capability, and prolonged bactericidal effect—this technology has an inherent drawback: the formation of highly toxic and carcinogenic compounds when reacting with organic impurities (e.g., trihalomethanes) [17-19]. Often, the doses of chlorine used in water treatment exceed permissible levels by tens of times [20; 21]. For instance, hyperchlorination is employed to reduce contamination by the hepatitis *A* virus. Nevertheless, due to its relative simplicity, the depth of technical solutions developed for its implementation, and its high adaptability for large-scale treatment, chlorination remains the leading method for disinfecting water consumed by large human populations.

To reduce the number of chemical reagents required for wastewater disinfection, chlorination is often combined with ozonation, another well-established and advanced method for disinfecting water and air. According to modern understanding, the mechanism of ozonation disinfection is based on ozone's ability to inactivate enzymes present in animal and plant organisms, although this perspective still awaits definitive confirmation [22-25]. A significant advantage of ozonation is the compactness of the systems, ease of operation, and the absence of reagent storage requirements. In addition to disinfection, ozonation also deodorizes water and breaks down organic compounds responsible for its color. However, ozonation is most often used as part of a combined water disinfection method, as ozone itself is toxic, and excessive ozonation can lead to environmental pollution. Undoubtedly, such issues can be mitigated through complex technical measures, such as ozone recovery, chemisorption and adsorption of excess ozone and harmful by-products using porous materials, and catalytic decomposition [26-28]. However, the emphasis on preventive environmental protection measures often renders these efforts impractical.

Low-dose ozonation is often combined with water disinfection using ultraviolet (UV) radiation. UV radiation as a water disinfection tool has several undeniable advantages, particularly the fact that the physical and chemical properties of the treated water remain unchanged, and the bactericidal effect is observed for all types of bacteria, including spore-forming ones. Currently, the most widely supported hypothesis is that UV rays act on the protein colloids in the cytoplasm of bacterial cells, leading to structural damage and cell death [29-32]. However, a significant drawback of both UV irradiation and ozonation is the lack of residual bactericidal effect. This is why these methods are typically combined with chemical disinfection by introducing chemical disinfectants in doses that are justified from both ecological and economic perspectives.

Among the physical methods of water disinfection, ultrasonic treatment is also known. While there is no unified theory explaining the mechanism of the bactericidal action of ultrasound, most researchers believe that the primary effect is the mechanical destruction of bacteria due to ultrasonic cavitation. The effectiveness of ultrasonic treatment depends on the shape of the microorganisms, the strength and chemical composition of their cell walls, the age of the culture, and the intensity and frequency of the ultrasound [33-35]. By adjusting the duration and frequency of the ultrasound, it is possible to target almost all types of microorganisms. In the field of ultrasonic waves, both gram-positive and gram-negative bacteria, aerobic and anaerobic bacteria, rod-shaped, coccal, and other forms are disintegrated. Ultrasound affects both vegetative and spore forms [36-38]. Unlike ultraviolet radiation, the effectiveness of ultrasonic disinfection does not depend on the turbidity (up to 50 mg/L) or color of the water, making this method suitable for disinfecting water that has undergone poor pre-treatment. Currently, the main limiting factor for adapting ultrasonic methods to treat large volumes of water is the limited power of ultrasonic sources. This limitation arises because increasing the power and intensity of the ultrasound leads to the rapid destruction of the acoustic vibration source components due to cavitation.

Plasma technologies currently hold a significant place among the tools for water purification from harmful and hazardous micro-pollutants [2] and are being applied in the treatment of domestic wastewater [39-41], recycling of industrial effluents [42-45], and upgrading natural water from surface sources to potable standards [46-49]. The key instrument in these technologies is non-equilibrium plasma—an ionized gas composed of electrons, ions, and neutral particles, where the average energy of electrons is lower than the characteristic ionization potential of atoms (<10 eV), along with the phenomena that arise when matter transitions into this state.

It is known that electric discharge in gases and liquids is not only one of the relatively simple methods for creating plasma states of matter but also comes in several forms: glow discharge, spark discharge, arc discharge, and corona discharge; each of them can be further subdivided. The implementation of any type of discharge leads to plasma-chemical and plasma-physical processes of varying intensity, which play a significant role in addressing water purification challenges. Due to the differing mechanisms of action on pollutants depending on the specific type of discharge, researchers have yet to establish a unified perspective on the mechanism of water disinfection under the influence of electric discharge.

Acknowledging the predominant use of chlorination for wastewater disinfection today and the slow adoption of newer water treatment methods, it is essential to leverage a key advantage of chlorination—its prolonged action against pathogenic microorganisms. By combining it with other disinfection methods, the harmful environmental impact of chlorination can be significantly reduced.

One of the options for solving this problem may be a method that includes a complex action on water by a high-voltage electric discharge simultaneously with chlorination, and the **goal** is to significantly reduce the concentration of the chemical reagents required in this case compared to traditional chlorination and minimize the energy of the high-voltage discharge required to achieve the disinfection effect. To understand the mechanism of water disinfection with such a complex action, it is necessary to identify the factors inherent in the electric discharge in the liquid in the cavitation mode, and causing the occurrence of a synergistic effect with the simultaneous effect of an electric discharge and chemical reagents on the treated water.

The hypothesis under consideration is that the primary factor affecting target objects (bacteria) is the presence of oxidizing particles generated in the liquid as a result of sonolysis throughout the volume of the discharge chamber. In this case, we assume that the cause of sonolysis is cavitation, which can be induced under certain conditions by an electric discharge. The most well-known consequence of high-voltage breakdown in liquids is the formation of shock waves. However, when shock waves act on objects smaller than the width of the wavefront (such as bacteria), these objects simply experience quasi-static, omnidirectional compression. Therefore, the direct role of shock waves in liquids in affecting small objects should not be overestimated.

Let us examine the essence of high-voltage breakdown in liquids. When a voltage above a critical threshold is applied to a pair of electrodes immersed in a liquid (a weak electrolyte), breakdown occurs — a plasma channel forms, through which electric current flows. However, before the discharge channel forms in the electrode gap, sometime elapses, known as the statistical delay time. During this period, an electric current begins to flow in the discharge gap—ionization processes in the liquid are initiated, and a plasma formation starts to develop in the form of streamers moving from the anode to the cathode. This is followed by the formation stage of the discharge. As the streamer branches develop, some slow down and disappear, while only one reaches the counter-electrode. The formation stage is characterized by a gradual increase in current and a slight voltage drop. Importantly, during this stage, energy is lost, which is expended on heating the liquid and forming vapor bubbles. The delay and formation stages together last from a few microseconds to hundreds of microseconds and are collectively referred to as the "pre-breakdown stage." The pre-breakdown stage concludes with the formation of a highly conductive electric discharge channel (breakdown) - the electric current sharply increases, and the voltage drops. Energy stored in the capacitor bank rapidly flows into the formed plasma channel of the electric discharge. The material in the discharge channel heats up to temperatures of 20 000…40 000 K, and the pressure rises to 300…1 000 MPa. Under this pressure, the discharge channel expands, and its walls acquire high velocities (typically much higher than the speed of sound in the liquid). The stage of active energy conversion in the discharge channel lasts from tens to hundreds of microseconds. Then, the accelerated motion of the channel walls stops, and they continue to move more slowly, forming a vapor-gas cavity. After reaching equilibrium, the cavity collapses to its minimum size, re-expands, and continues to oscillate with decreasing amplitude and period. During the brief moments when the cavity collapses to its minimum size, secondary compression waves form in the liquid. This stage, which lasts several milliseconds after the discharge channel ceases to exist, is crucial for creating cavitation throughout the chamber volume. The reason is that multiple cavitation ruptures in the liquid can only occur on cavitation nuclei after the excitation of negative (tensile) pressure in the liquid. Thus, a necessary condition for cavitation development throughout the chamber is the presence of cavitation nuclei (bubbles), and cavitation strongly depends on the initial amount of gas phase in the liquid. In ordinary water, cavitation nuclei are relatively few, so to induce cavitation throughout the volume, it is necessary to ensure their formation before tensile stresses are excited in the liquid. The phenomena occurring during the pre-breakdown stage can be used as a means to create multiple cavitation nuclei in electric discharge reactors. If a regime of liquid breakdown is established that promotes active gas formation during the pre-breakdown stage, all cavitation nuclei will compress and expand in sync with the main vapor-gas cavity. Post-discharge cavitation processes are then observed over a period ranging from milliseconds to hundreds of milliseconds throughout the discharge chamber volume. Conditions for the mass formation of cavitation nuclei can be created: a relatively long voltage pulse facilitates gas formation due to boiling and electrolysis. At the same time, the condition of breakdown in the discharge gap is mandatory for the occurrence of electric discharge cavitation. Liquid breakdown generates compression and rarefaction waves from the primary vapor-gas cavity, and the shock wave disrupts the gas phase formed during the pre-breakdown stage, creating a cloud of microscopic bubbles. As a result, conditions are created for cavitation to occur around each cavitation nucleus. An important conclusion at the research planning stage is that the occurrence of powerful electric discharge cavitation requires both significant gas formation during the discharge formation stage and high-voltage breakdown of the liquid.

METHODS AND EXPERIMENTAL PROCEDURES.

The study on the potential reduction of chlorine agent concentration during the integrated disinfection of water using electric discharge was conducted with a laboratory setup (Fig. 1).

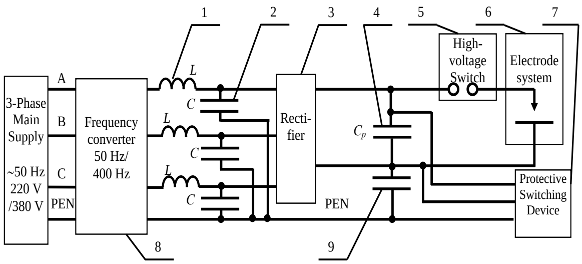

Fig. 1. Laboratory setup [50].

The high-voltage pulse current generator was connected to the industrial three-phase main supply. The generator contains three identical inductors 1, three identical high-voltage capacitors 2, the three-phase high-voltage rectifier 3, the capacitive energy storage device 4, the high-voltage switch 5, the working chamber and electrode system 6, and the protection system 7. The high-voltage pulse current generator was equipped with the three-phase frequency converter 8 and the dividing capacitor 9. The laboratory setup provided a working voltage (U) ranging from 15 to 25 kV, while the capacitance of the capacitor bank (C) varied from 0.1 to 1 μF. The energy stored in the capacitor bank for a single pulse was adjusted by changing both the voltage and the capacitance. Such a wide range of energy adjustments was necessary to identify the optimal combination of electrical parameters for achieving a discharge regime characterized by significant gas formation during the pre-breakdown stage and a mandatory liquid breakdown—a specific cavitation mode. The discharge frequency was varied between 1 and 5 Hz, as the desired effect of volumetric cavitation during the electric discharge occurs within milliseconds after the liquid breakdown.

The cylindrical working chambers, with volumes of 1, 2, and 3 dm^3, were made of fluoroplastic. The primary electrode system, of the "point-to-plane" type, was constructed from a titanium alloy. The pointed electrode had a diameter of 4 mm, and the interelectrode gap was adjustable from 10 to 30 mm, as the positioning and dimensional relationship between the working chamber and the electrode system are critical for achieving the cavitation discharge mode. The use of titanium as the primary material for the electrodes helped avoid intense electro-erosion and eliminated the influence of additional contaminants that could affect oxidative processes in the water. To specifically study the impact of electrode erosion on water disinfection, electrodes made of steel, brass, and aluminum of the same design were also used.

The acoustic spectra of pressure pulses from electric discharges were recorded using the same laboratory setup as the source of the discharges. The spectra were captured by generating underwater electric discharges in a large-volume pool. A Neptune Solar Limited Model D/140/H Underwater Sonic Detector was positioned at a depth of 1 m from the axis of the horizontal discharge gap of the electrode system. The electrode system was placed in a pool with a depth of 2.5 m, ensuring a distance of at least 1.5 m from the pool walls and 1 m from the free water surface. This arrangement prevented reflections from the free surface from distorting the acoustic field pattern.

As mentioned earlier, one of the key conditions for generating powerful cavitation during an electric discharge is the presence of a large number of gas bubbles in the liquid. It is well-known that water can boil at temperatures below 100°C when the pressure is lower than standard atmospheric pressure. For example, at an altitude of about 5000 m (where the pressure is approximately 0.5 atm), water boils at 80°C. In this study, an attempt was made to enhance the formation of cavitation bubble nuclei by reducing the external pressure. To achieve this, the working chamber was placed in a hermetically sealed container, from which air was evacuated using a vacuum pump.

Bacteriological testing was conducted in the laboratory of the Ingulets Water Treatment Facilities, operated by the "Mykolaivvodokanal" enterprise. Since the concentration of *Escherichia coli (E. coli)* is the primary sanitary indicator microorganism, the bactericidal effect was studied using this test subject. Water for treatment was collected from the discharge water masses of the Ingulets treatment facilities, where the initial concentration of *E.coli* ranged from $1{\cdot}10^4$ to $1{\cdot}10^6$ CFU/dm³, depending on the time of water sampling. To avoid additional contamination of the water after treatment, all glassware used was pre-treated thermally at 433K for 2 hours, and containers for collecting samples treated with electric discharge were sterilized by flaming. The determination of *E.coli* was performed using the membrane filtration method. This method involves concentrating bacteria from a specific volume of the analyzed water onto a filter, cultivating colonies at 310 ± 5K on Endo medium, and counting the number of colony-forming units (CFU) per 1 dm³ of water.

For the indirect quantitative determination of the intensity of oxidant formation during the electric discharge treatment of water, the iodometric titration method was used, adapted for studying the effects of electric discharge processes in water [51]. This method is based on the oxidation of *KI* solutions, which is accompanied by the release of I_2. The iodine content can then be quantified by titration 1:

$$2I^- + [Ox] \rightarrow [Red] + I_2 \qquad (1)$$

where [*Ox*] – oxidizing particle; [*Red*] – reduced form of oxidizing particle.

The released iodine is titrated with a sodium thiosulfate solution until the blue color of the solution, formed when starch is used as an indicator, disappears. The process is described by the following reaction equation:

$$I_2 + 2Na_2S_2O_3 \rightarrow 2NaI + Na_2S_2O_4$$

The blue color, which appears due to the formation of the starch-iodine complex, fades as the iodine is consumed during the titration. This method allows for the precise determination of the iodine concentration, which is directly related to the number of oxidants generated during the electric discharge treatment of water.

The described processes in the system occur without the participation of hydrogen ions, which allows iodometric determinations to be carried out over a wide range of solution acidity (pH = 2 … 10). The concentration of active chlorine (chlorine radicals, hypochlorite ions, hypochlorous acid, etc.) [Cl^*] (mg/dm³) is calculated using the formula 2:

$$[Cl^*] = \frac{(a \cdot b)k \cdot 0{,}01 \cdot 35{,}45 \cdot 1000}{V} = \frac{(a \cdot b)k \cdot 354{,}5}{V} \qquad (2)$$

where *a* – is the volume of 0.01 N sodium thiosulfate solution used for titrating the sample, mL;

b - is the volume of 0.01 N sodium thiosulfate solution used for titration in the blank determination, mL;

k - is the correction factor to adjust the concentration of the sodium thiosulfate solution to exactly 0.01 N;

V- is the volume of the analyzed sample, mL;

35,45 - is the atomic weight of chlorine;

0,01 - is the normality of the sodium thiosulfate solution.

This formula allows for the accurate determination of active chlorine content in the sample, taking into account the titration results.

THE RESEARCH RESULTS AND DISCUSSIONS.

Experimental research.

The bactericidal effect of the specific energy of the electric discharge introduced into the volume of disinfected water **without** the addition of any chemical oxidizing agents is illustrated in Fig. 2.

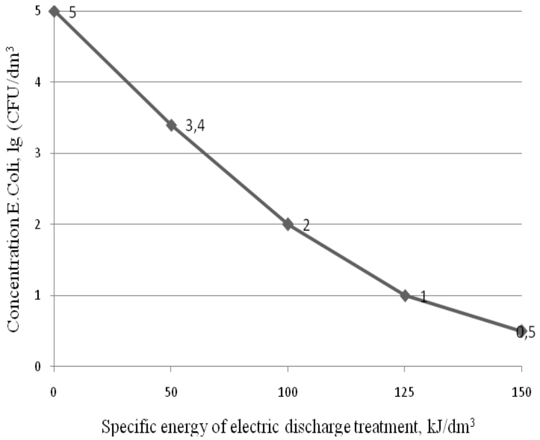

Fig. 2. The dependence of *E. coli* concentration on the specific energy of electric discharge treatment **without** chemical reagents.

It is evident that as the specific energy increases, the concentration of bacteria decreases. At an initial *E.coli* concentration of $1{\cdot}10^5$ CFU/dm^3 and a specific energy of E_{sp} = 150 kJ/dm^3 (41 kWh/m^3), a significant but not 100% bactericidal effect is observed. However, at such specific energy consumption levels, the practical application of electric discharge systems becomes impractical. Therefore, the core philosophy of our research was based on identifying a synergistic effect between chemical and electric discharge treatment methods.

The data on the bactericidal effect of **sequential** treatment of water by electric discharge and chlorination are presented in Fig. 3 and 4. By Scheme 1, water was first treated with an electric discharge, reducing the specific energy of treatment to 50 kJ/dm^3 (approximately 13 kWh/m^3). Then the treated water was chlorinated to achieve the epidemiological safety standards for drinking water in terms of *E.coli* ([Cl^*] = 5 mg/L – two times less, than accepted, with a total exposure time of 2 hours), as shown in Fig. 3. As expected, no *E.Coli* observed after such a treatment.

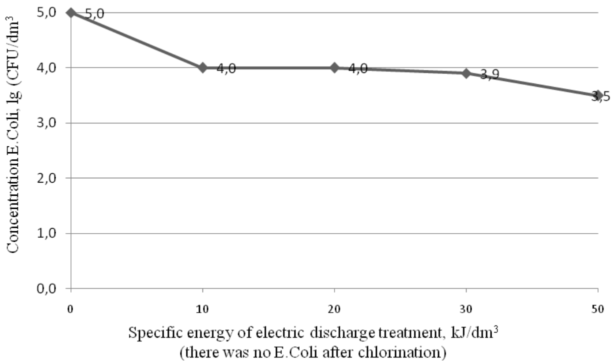

Fig. 3. The dependence of *E.coli* concentration on the specific energy of electric discharge treatment during sequential electrodischarge-chemical treatment (Scheme 1: electric discharge followed by chlorination with [Cl^*] = 5 mg/l)

In Scheme 2, water that had been pre-chlorinated (with an exposure time of 10 minutes) was subjected to electric discharge treatment for 20 seconds at a specific energy of 50 kJ/dm³. In this case, the concentration of active chlorine was reduced to [Cl^*] = 1 mg/l. The corresponding data are presented in Fig. 4.

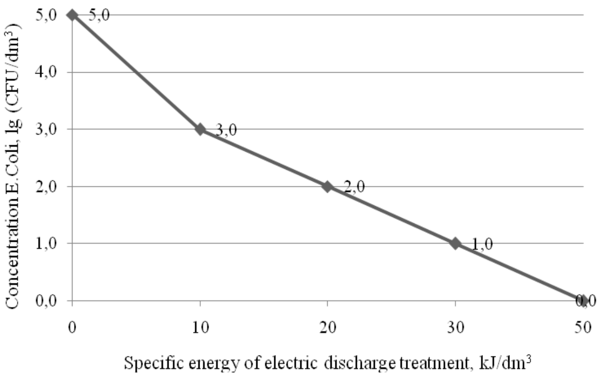

Fig. 4. The dependence of *E.coli* concentration on the specific energy of electric discharge treatment during sequential electro-discharge-chemical treatment (Scheme 2: chlorination with [Cl^*] = 1 mg/L followed by electric discharge).

In both schemes, an important advantage of the chlorination method was preserved — its prolonged action. While in the first treatment scheme, this could be attributed to the excess of active chlorine in the treated water, the second scheme, with a five times lower concentration of active chlorine, also yielded water that remained sterile even after settling for 48 hours post-treatment.

The next stage of the research focused on further reducing energy consumption and decreasing the concentration of the chlorine agent by **combining** electric discharge and chemical treatment.

The preliminary chlorination stage was eliminated, and electric discharge treatment was initiated immediately after adding the chlorine agent at concentrations of [Cl^*] = 1, 0.8, 0.6, 0.4, and 0.2 mg/L. During the treatment, water samples were collected at intervals corresponding to 5 kJ/dm³ of input energy. The initial concentration of *E.coli* was $1 \cdot 10^6$ CFU/dm³, the results are presented in Fig. 5.

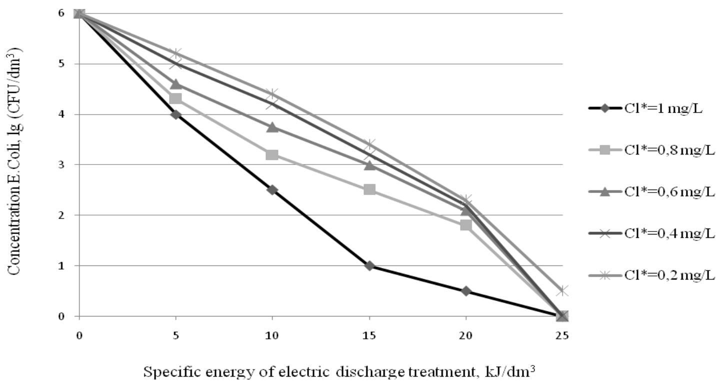

Fig. 5. The dependence of *E.coli* concentration on the specific energy of electric discharge treatment during **combined** electro-discharge-chemical treatment.

As evidenced by the presented data, the addition of a chlorine agent in amounts of 0.4 mg/L or more, combined with simultaneous electric discharge treatment, results in a strong bactericidal effect. After introducing a specific energy of 25 kJ/dm³ into the aqueous solution containing the chlorine agent via electric discharge, no colony-forming units (CFU) of *E.coli* were observed in the samples. This treatment also retains its prolonged action — after settling for 48 hours post-treatment, water samples with [Cl^*] concentrations of 1, 0.8, 0.6, and 0.4 mg/L remained sterile. In contrast, the sample with [Cl^*] = 0.2 mg/L showed an increase in CFU from 3 to 200 over the same period. Thus, the **combined** treatment of contaminated water using chlorination and electric discharge demonstrates a synergistic effect: the bactericidal action of this combination is more potent than that of either method applied separately, while significantly reducing the required energy and chemical reagents.

Given that the target of treatment is relatively small (the size of E. coli ranges from 0.4–0.8 to 1–3 μm), it was hypothesized that the mechanisms affecting the bacteria operate at the molecular level. This implies that factors such as shock waves, magnetic fields, and electric fields (considering the wavelength of their impact) can be neglected. Therefore, the likely sources of intensification of redox processes, in this case, could be: photolysis (UV and visible parts of the electric discharge spectrum), electrolysis (pulsed electric current), sonolysis (an ultrasonic component of the electric discharge spectrum), and volumetric cavitation caused by powerful hydroacoustic flows.

Further, using *KI* as an indicator of redox processes in tap water during electric discharge treatment, an assessment was conducted to evaluate the contribution of the aforementioned factors under the experimentally determined conditions of effective combined disinfection.

1) When only the light component of the discharge was applied to the *KI* solution (a transparent polyethylene container with 2 g/L *KI* was placed in the discharge chamber), no formation of I_2 was observed. This indicates the absence of a photocatalytic reaction $H_2O \rightarrow OH^* + H^*$,

followed by the oxidation of *I* by the reactions: $KI + OH^* \rightarrow I^* + KOH; 2I^* \rightarrow I_2 \downarrow$. Under these conditions, no bactericidal effect was observed, as the intensity of the light flux and the wavelength range of UV radiation generated by the electric discharge in water are not lethal to bacteria.

2) When treating an aqueous solution containing 2 g/L *NaCl*, unlike *KI* solutions, no Cl_2 is released. It is known, that in conventional electrolysis of an aqueous solution of table salt, the primary reaction at the anode is the decomposition of chloride ions with the release of gaseous chlorine: $2Cl^- - 2e \rightarrow Cl_2 \uparrow$. This observation allows us to conclude that pulsed electrolysis is not the cause of the observed formation of I_2 during the electric discharge treatment of an aqueous *KI* solution.

3) Treatment of *KI* solutions with ultrasound at a frequency of 22 kHz and an intensity of about 0.5 W/cm² leads to a slow accumulation of I_2 (a blue color appears in the *KI* + starch system). In [52], it was shown that during ultrasonic treatment of solutions, the primary factor of sonochemical action is the process of cavitation bubble collapse. Clearly, under the influence of ultrasound, the intensity of cavitation is not high, and accordingly, the process of I_2 accumulation is slow.

Thus, it can be assumed that during the electric discharge treatment of aqueous solutions, the primary factor influencing the formation of oxidizing particles is volumetric cavitation.

To test this hypothesis, the effect of simultaneous electric discharge treatment and chlorination on the disinfection process under reduced pressure (relative to atmospheric pressure) was studied. As previously shown [53–55], under these conditions, powerful volumetric cavitation occurs in the electric discharge reactor. Water treatment with an initial *E.coli* concentration of $1 \cdot 10^6$ CFU/dm³ was carried out at reduced pressures of 0.8, 0.6, and $0.4 \cdot 10^5$ MPa. The operating voltage was 18 kV, the capacitor bank capacitance was 0.25 μF, the pulse frequency was 1 Hz, the [Cl^*] concentration was 0.3 mg/L, the treatment time was 6 seconds, and the specific energy input into the liquid was only 5 kJ/dm³. In all experiments with reduced pressure, a 100% bactericidal effect was observed after treatment, and the water met the drinking water standards in terms of *E.coli* content. This confirms, that the primary disinfection factor in the electric discharge treatment process, is volumetric cavitation.

Some researchers attribute the bactericidal effect of water treatment by electric discharge to electrode erosion, which is inevitable in such processes [56, 57]. The destruction of electrodes during the passage of high discharge currents leads to the appearance of metal ions in the liquid, some of which exhibit oligodynamic effects. Water containing small amounts of positively charged metal ions (e.g., copper and silver) becomes a lethal environment for microorganisms. Studies on the survival of *E.coli* bacteria in water treated with so-called diaphragm electric discharges confirmed the oligodynamic effect of electrode materials [58, 59]. Experiments were conducted to determine the dependence of electrode erosion on various electrical parameters [60]. It is evident that the energy released in the electrode gap significantly influences electrode erosion. The concentration of iron, aluminum, and copper in water increases proportionally with the increase in input energy, with the erosion of a brass electrode, for example, being approximately twice as high as that of a steel electrode under the same energy density.

More important for our study was the investigation of the dependence of the amount of oxidants formed during electric discharge on the electrode material. When performing electric discharges with a working voltage of 25 kV, an energy storage capacitance of 0.25 μF, a pulse frequency of 1 Hz, a treatment time of 20–30 seconds, and a specific energy of 150 kJ/dm³ in distilled water, it was found that the yield of oxidants, detectable by the iodometric method, weakly depends on the electrode material and increases with the density of the input energy. Conducting similar treatment with the same electrical parameters on contaminated water with an initial *E.coli* concentration of $1 \cdot 10^4$ CFU/dm³ and a specific input energy of 25 kJ/dm³, **without** adding chemical reagents, demonstrated greater disinfection efficiency for electrode systems made of aluminum and brass (Fig. 6).

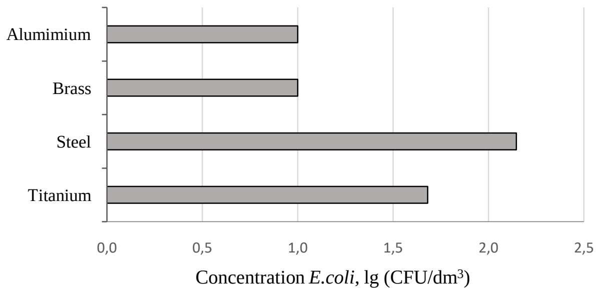

Fig. 6. Bactericidal effectiveness of various electrode materials during electric discharge treatment at fixed electrical treatment parameters.

Nevertheless, considering the high electro-erosive properties of copper and aluminum, which lead to rapid electrode wear and poorly controlled contamination of the treated water with erosion byproducts (whose permissible concentration limits can be quickly exceeded during treatment), titanium electrodes are preferable for the practical application of the electric discharge cavitation method.

The mechanism of the bactericidal action of electric discharge is of great interest. To date, the question of the influence of numerous factors present during electric discharge in water on microorganisms remains open and is discussed at the level of hypotheses [61 – 63]. The obvious factors characteristic of underwater electric discharge that affect biological objects include: ultraviolet and thermal radiation, primary pressure waves and secondary acoustic waves, volumetric nonlinear cavitation, and the acoustic radiation it generates. On the other hand, three of the five causes of microorganism inactivation listed in the introduction are the result of the interaction between the cell and chemically active particles. Therefore, it is necessary to create conditions for the formation of such particles in the medium treated by electric discharge. The occurrence of chemical reactions in sound fields is associated not only with the collapse of cavitation bubbles but also with their ability to undergo resonant periodic pulsations [64].

Gas bubbles suspended in a liquid medium undergo periodic compression and expansion, i.e., pulsation at a specific frequency. The natural oscillation frequency f of such a bubble, in the case of small amplitudes, is given by: $f = \frac{1}{2\pi R_{max}}\sqrt{\frac{3\gamma p_0}{\rho}\left(p_0 + \frac{2\sigma}{r}\right)}$, where r – bubble radius at a given stage of compression, p_0 – external pressure, R_{max} – maximum bubble radius, γ - the ratio of the heat capacities of a gas filling a bubble at constant pressure and volume, σ – surface tension of a liquid, ρ – density of liquid. Since the term $2\sigma/r$ is extremely small compared to the initial pressure p_0, the formula simplifies to: $f = \frac{1}{2\pi R_{max}}\sqrt{\frac{3\gamma p_0}{\rho}}$. This simplified form is commonly used to describe the natural oscillation frequency of a gas bubble in a liquid under small amplitude conditions, neglecting the influence of surface tension due to its minimal contribution.

At an external pressure of 0.1 MPa, the natural frequency of an air bubble in water is given by f=0.328/ R_{max} (kHz), where R_{max} is the maximum radius of the bubble. This means that, under other equal conditions, the natural oscillation frequency of a gas bubble is determined by its radius. The amplitude and energy of the pulsations of gas bubbles in an acoustically excited liquid are maximized when the natural frequency of the pulsating bubble matches the frequency of the sound field in the liquid (resonance). Importantly, bubbles of such resonant sizes are responsible for initiating chemical processes in the acoustic field.

Experimental studies [65] have shown that up to 60% of the bubbles in the cavitation region of an electric discharge reactor have characteristic maximum diameters ranging from 0.2 to 2 mm, with their resonant frequencies falling within the range of 15–35 kHz. The remaining bubbles in the cavitation region have maximum diameters ranging from 0.1 to 0.05 mm, with resonant frequencies in the range of 70–125 kHz. Thus, it is necessary to generate acoustic waves in the working medium with the specified frequencies to achieve powerful cavitation. In [66], the presence of frequencies in the range of 15–35 kHz in the acoustic emission spectrum of an underwater electric discharge has already been demonstrated, and these frequencies were shown to have sufficient intensity. However, the range of 70–125 kHz in the acoustic emission spectrum of electric discharge has not been studied, even though the influence of a large number of bubbles resonating in this frequency range could have a decisive impact on the intensity of cavitation and related processes.

Thus, one of the objectives of studying the mechanism of water disinfection by electric discharge and chlorination at a tenfold reduced dose was to prove the generation of acoustic emission in the range of 70–125 kHz by electric discharges in water. It was necessary to identify the conditions for generating such discharges that ensure the presence of frequencies in this high-frequency ultrasonic range in the acoustic emission spectrum. It is known that the acoustic emission shifts to the high-frequency region of the spectrum when the leading edge of the pressure pulse, generated by the rapidly expanding channel of the electric discharge, is shortened. From the physical principles of the theory of underwater electric explosions, it is known that to obtain pressure pulses with a short leading edge, it is necessary to generate a current pulse in which the leading-edge duration is 1.2–1.5 times shorter than the duration of the pulse itself.

In these studies, the same laboratory setup was used (Fig. 1). It provided a working voltage (U) ranging from 15 to 25 kV, the capacitance of the capacitor bank (C) varied from 0.1 to 1 μF, the inductance of the discharge circuit varied from 1 to 3 μH, and the length of the uninsulated part of the electrode was also adjusted. The characteristics of the discharge current of underwater electric discharges were determined for various parameters of the discharge circuit and varying lengths of the uninsulated tip of the anode electrode in the discharge gap. Table 2 presents data on the characteristics of the obtained current pulses in several typical modes of electric discharge in water.

Table 2 − Amplitude-time characteristics of the generated current pulses (energy in a single pulse: 250 J, capacitance of the capacitor bank: 0.25 μF)

Number of Mode	**Length of non-insulated part of anode, mm**	**Discharge circuit inductance, μH**	**Current pulse period, μs**	**Duration of the leading edge of the current pulse, μs**	**Current pulse amplitude, kA**
1	4	1.2	5.4	1.35	16
2	10	1.2	6.5	1.62	12
3	10	2.6	9.0	1.8	14

It is evident that by adjusting the length of the uninsulated part of the anode electrode and the inductance of the discharge circuit, the duration of the leading edge of the current pulse can be varied. In certain modes (e.g., Mode 3), the current pulse becomes significantly asymmetric, with a very short leading edge compared to the total pulse duration. Importantly, the peak current amplitude in this case is lower than that of the current pulse in Mode 1, which was achieved with the shortest possible uninsulated part of the anode electrode.

Analysis of the obtained acoustic emission spectra (Fig. 7) confirmed that modes enabling short leading edges of current pulses also produce very short leading edges (2.0 µs for Mode 1, 2.78 µs for Mode 2, and 3.2 µs for Mode 3) of acoustic pulses. This results in a significant expansion of the frequency range of acoustic emission from underwater electric discharges into the ultrasonic range, up to 120 kHz, compared to the frequencies previously detected and described in [66].

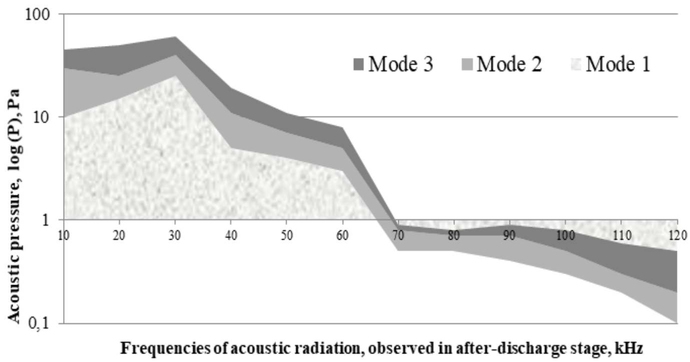

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Fig. 7. Acoustic radiation of the underwater electric discharge (post-discharge stage) in cavitation mode.

It should be acknowledged that the sound pressure levels of acoustic emission from electric discharges in water in the range of 70 to 125 kHz are significantly lower than those in the range of 15 to 35 kHz [66]. Specifically, for the modes studied, the sound pressure levels in the 70–125 kHz range are as follows: Mode 1 - $5 \cdot 10^{-1}$ … $2 \cdot 10^{-1}$ Pa, Mode 2 - $3 \cdot 10^{-1}$ … $1 \cdot 10^{-1}$ Pa, Mode 3 - $1 \cdot 10^{-2}$ … $1 \cdot 10^{-3}$ Pa. Naturally, this results in reduced displacements, velocities, and accelerations of the particles in the medium irradiated by these high-frequency acoustic pulses. Returning to Table 2, we conclude that the intensity of the high-frequency part of the acoustic emission spectrum from electric discharges in water is highly dependent on changes in the inductance of the discharge circuit and the length of the uninsulated part of the anode electrode protruding into the discharge gap.

Thus, the obtained experimental results confirm the emergence and identify the conditions for the occurrence of an ultrasonic component in the range of 75 to 125 kHz in the acoustic emission of underwater electric discharges. They also demonstrate that during underwater electric discharges, conditions can be created for the resonant excitation of bubbles with diameters smaller than 0.1 mm, which constitute a significant portion of the gas phase in the treated water. Consequently, the ultrasonic component of the acoustic emission from electric discharges in water lies in the range of 20 to 125 kHz, and there is an extended possibility of activating gas or vapor bubbles in the working medium of the electric discharge, analogous to irradiating such a medium with ultrasound.

Theoretical research

Physical phenomena accompanying electric discharge cavitation.

When acoustic waves of high intensity propagate in the medium, nonlinear effects occur that depend on the amplitude of the wave - second-order effects. These include, for example, acoustic currents (together with the acoustic turbulence they cause) and pulsations of gas bubbles. Pulsations induce some concomitant phenomena: flotation effect, rectified diffusion, and local shock waves. In addition, second-order phenomena are ponderomotor forces, surface effects, radiation pressure, and cavitation. Cavitation is accompanied by both the flotation effect and rectified diffusion, as well as microfluid streams, microflows, and local shock waves.

Acoustic currents are stationary vortex flows of fluid that occur in an inhomogeneous acoustic field, both in free space and near obstacles of various kinds. In addition, the occurrence of acoustic currents is also possible in the vicinity of pulsating and oscillating bodies. The reason for the occurrence of various acoustic flows is the same – irreversible losses of energy and momentum of the acoustic wave in the medium. If you cross an acoustic wave with an imaginary plane, then from the side the energy density of an incident wave is greater than that of the same volume behind the plane, on the side of the passing wave. In this regard, a force will act on the plane, tending to move it away from the source of acoustic vibrations. This force, which is equal to the energy density gradient and is directed towards the propagation of the wave, causes the medium to move. Energy losses in the medium, which cause acoustic flows, can occur both in the entire volume occupied by the acoustic field and in part of the volume. Acoustic currents are more intense and their speed is greater the greater the loss of acoustic energy in the medium. It does not matter whether the loss mechanism is related to the viscosity of the medium or due to the inhomogeneity of the medium (suspended particles, gas bubbles, cavitation region); The only thing that matters is the irreversibility of the loss of energy and momentum of the acoustic wave [67]. Currents arising in an acoustic field are usually divided into three groups: flows in an inhomogeneous space of limited volume; currents originating outside the acoustic boundary layer; and currents that occur in a viscous boundary layer near obstacles.

Ponderomotor forces include: the Bjerkenss force, the Stokes force, associated with the change in viscosity; the force associated with the distortion of the waveform; and the force generated by the interaction of a pulsating bubble with an acoustic field. The transition from acoustic oscillations with a small amplitude to oscillations with a large amplitude, in which the continuity of the fluid is broken and cavitation bubbles appear in it, is due to a qualitative change in the oscillatory process in the liquid. These changes are because the presence of cavitation bubbles changes the properties of the medium and its characteristics become nonlinear [68]. In addition, with developed cavitation, there is a process of periodic propagation of the hydrodynamic rupture in the form of a wavefront of collapsing bubbles. Note that gas bubbles, unlike cavitation bubbles, exist in a liquid even in the absence of acoustic vibrations. The equation describing the pulsation of a cavitation bubble in an acoustic field is a second-order differential equation and cannot be solved in general by analytical methods, taking into account the compressibility of the fluid, this equation was obtained by Herring and is written as follows (formula 3):

$$R\left(1-\frac{2U}{c_0}\right)\frac{d^2R}{dt^2}+\frac{3}{2}\left(1-\frac{4}{3}\frac{U}{c_0}\right)\left(\frac{dR}{dt}\right)^2-\int_{P\infty 0}^{P(R)}\frac{dP}{\rho}-\frac{R}{\rho}\frac{U}{c_0}\left(1-\frac{U}{c_0}-\frac{U^2}{c_0^2}\right)\frac{dP(R)}{dR}=0, \quad (3)$$

where U – bubble velocity, R – bubble radius, c_0 – local velocity of acoustic bubble oscillation.

Member $\int_{P\infty}^{P(R)} \frac{dP}{\rho} = h$ is an enthalpy on the surface of the vesicle, in which P_∞ – pressure in the medium at infinity (in the special case, hydrostatic pressure), and $P(R)$ – pressure on the surface of the bubble cavity. If use the Nolting–Nepayras equation and the equation of state of water [69], are recorded as $P = A(\rho/\rho_0)^n - B$, where A, B, and n – constants for water (A = 3,001·10^8 Pa, B=3·10^8 Pa, n=7), ρ and ρ_0 – density of the fluid at the present moment and the moment of determination of the constants A and B, the enthalpy on the surface of the cavitating bubble can be expressed as follows (formula 4):

$$h = \frac{n}{n-1}\frac{A^{1/n}}{\rho_0}\left[\left(\rho_0 + \frac{2\sigma}{R_0}\right)\left(\frac{R_0}{R}\right)^{3\gamma} - \frac{2\sigma}{R} + B\right]^{\frac{n-1}{n}} - \left(P_0 - P_m \sin \omega t + B\right)^{\frac{n-1}{n}}, \quad (4)$$

where σ – surface tension of fluid; γ – polytropic indicator, which determines the state of the gas in the cavity; ω – cyclic frequency of acoustic vibrations.

The local velocity of the acoustic oscillation c_0 in formula (1) can be represented as follows (formula 5):

$$c_0 = \sqrt{c^2 + (n-1)h}, \quad (5)$$

where c – velocity of acoustic vibrations in the fluid as a whole.

From the above expression, it can be seen that the local velocity is a function of the enthalpy of the bubble surface. Equation (1) is solved by numerical integration methods under certain initial conditions and using equations (2) and (3). The solution of the equations for various initial conditions showed that the oscillations of the cavitation bubble are not harmonic. This is manifested in the fact that the growth time of the bubble is four to five times longer than the time it closes, and there are modes where the closing time is only one-tenth of the growth time. It also follows from the calculations that the radii of bubbles of sub-resonance size increase with an increase in acoustic intensity and at the same time the time of closure increases. From the solution of equation (1), an important conclusion was obtained about the possibility of controlling the bubble closing time by changing the external pressure. The closing time is dramatically reduced if the bubble closes in the initial pressure wave of the subsequent liquid breakdown. In the case of high external pressure, the velocity of bubble closure varies for two reasons. Firstly, the mass of the liquid attached to the bubble decreases and the pressure inside the cavity is maintained, which contributes to an increase in the velocity of the bubble walls in the closure phase, secondly, the closure phase changes relative to the period of acoustic oscillations, which in turn leads to an increase in the effective pressure acting on the cavitation cavity in the compression phase.

The movement of bubbles in the liquid as a result of interaction with each other is erratic. At the same time, since each bubble has a drain at the interface, the movement of the bubbles to the interface is unidirectional. This pattern of motion can be described by the equation of diffusion kinetics with a source in the volume of the fluid and a runoff at its boundary (formula 6):

$$\frac{\partial C}{\partial t} + (\vec{U}\nabla)\cdot C = D\Delta C + Q_w, \quad (6)$$

where C – concentration of cavitation bubbles, D – a coefficient similar to the diffusion coefficient, and Q_w– cavitation bubble source power.

When acoustic waves propagate, short wavelengths are formed at the "soft" interface between two media (liquid-gas, for example). These surface waves are also called "capillary waves" because their parameters depend on the surface tension of the liquid. The length of such waves can be determined from the equation: $\lambda = \sqrt[3]{8\pi\sigma / \rho f^2}$. Capillary oscillations at the interface are stable as long as their frequency is half the frequency of the acoustic vibrations that cause them. Acoustic currents that occur at the surface of pulsating bubbles are a source *of acoustic turbulence*. The occurrence of acoustic turbulence here is associated with the inhomogeneity of the field, where high transverse and longitudinal gradients of high pressure are formed. The flow is also turbulent at the interface between the direct and the reverse acoustic flow, as the phenomenon is observed in a limited volume.

According to the theory of isotropic turbulence, when vortices reach the "internal" scale, the properties of the medium become isotropic, that is, independent of the direction of acoustic flows. The frequency of pulsations also becomes independent of the scale of the currents, which in this case will be constant and equal to the highest value. In an acoustic field, the internal scale of turbulence is defined as follows (formula 7) [70]:

$$\lambda_0 = \frac{b^{3/4}}{\rho^{3/4}\varepsilon^{1/4}} = \sqrt[4]{\frac{b^3\lambda_n}{u^3\rho^3}}, \qquad (7)$$

where b – a constant that takes into account, in addition to viscous energy losses, also losses inherent in an oscillating medium; λ_n – acoustic flux scale; u – velocity of fluid in acoustic flow; $\varepsilon = u^3/\lambda_n$; the constant b is often referred to as acoustic viscosity, and it can be calculated by the formula 8 [70]:

$$b = \frac{4\eta}{3} + \frac{\gamma' - 1}{c_p}\chi + \eta', \qquad (8)$$

where η − shear viscosity; γ' – modulus of bulk elasticity of fluid at atmospheric pressure related to its internal pressure; c_p – heat capacity of liquid at constant pressure; χ – thermal conductivity coefficient; η' – bulk viscosity of fluid.

The internal scale of water turbulence in real conditions is within the range of $5\cdot10^{-5}\ldots1\cdot10^{-4}$ m.

In the presence of long-lived (pulsating) bubbles in the liquid, *a flotation effect* emerges in the acoustic field. Around each bubble, small particles suspended in the liquid are concentrated. To elucidate the mechanism of this phenomenon in [71] a solitary pulsating spherical bubble was considered, the expansion time of which is longer than the collapse time. In the frequency range $1\cdot10^{-4}\ldots1\cdot10^{5}$ Hz with a bubble size of up to $1\cdot10^{-5}$ m, the authors consider water to be an incompressible liquid. The velocity field that creates a pulsating bubble in a fluid using the equation of continuity in spherical coordinates and the symmetry of the problem can be represented as (formula 9):

$$divU_r = \frac{1}{r^2}\frac{d}{dr}\left(\vec{r}^{\,2}\vec{V}_r\right) = 0, \qquad (9)$$

where r – bubble radius.

Particles in a liquid are thought to be suspended and spherical. Falling into the vicinity of a pulsating bubble, such a particle finds itself in its velocity field. However, since the radius of friction and inertial forces are different, there is a boundary radius beyond which the bubble does not trap the particle. As the particle moves away from the bubble (beyond the capture radius), its velocity first increases and then drops to zero. As the particle moves toward the bubble, its velocity gradually increases. As the size of the particles decreases or their density decreases, the effective capture radius decreases, so that for particles smaller than the limit of the capture radius, the gripping radius is smaller than the radius of the pulsating bubble. In this case, only the Stokes force will act on the particle, removing the particles from the bubble. In this way, very small particles are repelled by a pulsating bubble. However, it should not be thought that small particles are blocked from reaching the surface of the bubble. Forming strong aggregates that are not destroyed by alternating flows, such particles can also be trapped by the bubble.

The term "*rectified diffusion*" refers to the transfer of the mass of a gas from a liquid to a bubble as a result of its oscillations in an acoustic field [72]. The mechanism of this process can be represented as follows. When the bubble is compressed, the concentration of gas in it increases, and at some point begins to exceed the concentration of gas in the surrounding liquid, at which point the gas begins to diffuse from the bubble into the liquid. When the bubble expands, the reverse process occurs, a diffusion flow occurs in the opposite direction. The phenomenon of unilateral diffusion is explained by the fact that when the bubble expands, the surface through which the diffusion occurs is much larger than during compression, so the flow of gas directed into the bubble is much greater than the flow in the opposite direction. As the frequency of oscillations increases, the density of the diffusion flux under the action of microflows decreases, while the density of the flux, which is due to the pulsations of the bubble, increases.

Cavitation bubbles are also a source *of microflows* in the acoustic field. If the bubble retains its spherical shape when oscillating, a so-called vortex-free motion occurs, where the velocity potential satisfies Laplace's equation [73]. The value of this velocity is in the range of $2\cdot10^{-4}$... $6\cdot10^{-3}$ m/s.

One of the properties of cavitation bubbles is the generation of intense *local shock waves*. Shock waves are pressure pulses propagating in a medium at a speed greater than the speed of acoustic waves. When a cavitation bubble pops due to a sudden stop of the entire mass of fluid involved in the motion, pressure builds up at the point of collapse and a pressure pulse is generated that propagates through the fluid [73]. To calculate the pressure of the resulting shock waves, it is customary to use the equation of fluid motion in a potential approximation as a starting point: $\frac{\partial^2\psi}{\partial t^2} = a^2\nabla^2\psi - \frac{\partial(\nabla\psi)^2}{\partial t}$, where ψ − speed potential, *a* – velocity of sound in the perturbed fluid. Despite the rapid decrease in pressure in the shock wave as it moves away from the point of origin, it is very powerful at the distance of the initial radius of the bubble. It is also possible to estimate the pressure that develops when a cavitation bubble collapses using an empirical formula [74]: $p_{\max} = \frac{p_g^4}{81p_h^3}$, where p_g – is the pressure acting in the medium at the beginning of the collapse, and *pH* is the pressure determined by the presence of gas residues in the bubbles. The magnitude of the pressure when the cavitation bubble is closed increases very strongly nonlinearly as the radius of the cavitation nucleus decreases. This can be expressed in terms of the gas content parameter: $\delta = \frac{p_0 + 2\sigma R_0}{p_0}\left(\frac{R_0}{R_{\max}}\right)^3$. Some cavitation parameters obtained experimentally in the paper [74] are shown in Table 3. It can be seen that true shock waves are generated in the course of electric discharge cavitation processes.

Table 3 – Typical parameters of electric discharge cavitation.

Initial bubble radius, R_0, cm	**Maximum bubble radius, R_{max}, cm**	**Minimum bubble radius R_{min}, cm**	**Gas content, δ**	**Pressure developed when the bubble collapses p_{max}, Pa**	**Ratio of the sound speed in the medium to the velocity of the leading edge of the microcavitation wave**
$1\cdot10^{-3}$	$2.9\cdot10^{-3}$	$5.8\cdot10^{-5}$	$4.8\cdot10^{-2}$	$7.4\cdot10^{3}$	4.5
$5\cdot10^{-4}$	$2.6\cdot10^{-3}$	$2.5\cdot10^{-5}$	$1.0\cdot10^{-2}$	$1.9\cdot10^{4}$	6.2
$1\cdot10^{-4}$	$2.3\cdot10^{-3}$	$0.9\cdot10^{-6}$	$2.1\cdot10^{-4}$	$2.8\cdot10^{7}$	13.3

The time of the cavitation bubble slamming shut ultimately determines the duration of the leading edge of the micro cavitation waves: $\tau = FR_{\max}\sqrt{\frac{\rho}{p_{\max}}}$, where F is coefficient for water, it is close to unity. The characteristic value of the leading edge duration of micro cavitation shock waves ranges from $0.5\cdot10^{-7}$ to $0.5\cdot10^{-8}$ s.

When the micro cavitation bubbles shut, high-velocity *microjets of* liquid are produced. The above model of the cavitation bubble slamming assumes that it is perfectly sphericity. In real conditions, the sphericity of the bubble is broken when it is at the liquid-solid interface if the plane of the solid surface is significantly larger than the size of the bubble (for example, the walls of an electric discharge reactor). Slamming the extremely distorted cavitation bubble (hemispherical, when the base rests on a solid surface), if compressibility, viscosity, and surface tension are neglected, can be described by the differential equation of the form presented in the paper [75]: $\nabla^2 \cdot \Phi(r,\Theta,t) = 0$, where Φ – scalar potential function.

The solution of this equation shows that when the current radius approaches zero, the shape changes according to a very complex law. The deformation of the bubble is so great that its walls hit a solid surface before the radius reaches zero. At the same time, the speed of microjets can reach several hundred meters per second.

All of the second-order effects described above that accompany a high-voltage electrical breakdown of a liquid are also characteristic of ultrasonic fluid treatment. These two ways of influencing a substance are united by cavitation, as well as macro- and microflows. All the second-order effects that accompany cavitation have a strong impact on water treatment processes, especially in terms of disinfection. In addition, chemical reactions also take place directly in the cavitation bubbles. At the same time, high-voltage electrical breakdown is characterized by phenomena that affect chemical reactions: ultraviolet radiation and a strong electric field.

Given a constant gas content in the bubble and the pressure of the surrounding liquid, the minimum radius of the cavitation bubble is determined by the formula: $R_{\min} = R_{\max}\left(\frac{p}{(\gamma-1)p_0}\right)^{\frac{1}{3(\gamma-1)}}$. At the same time, the pressure will be expressed by the formula: $p = p_{\max}\left(\frac{R_{\max}}{R_{\min}}\right)^{3\gamma}$, where $p_{\max}$ – gas pressure in a bubble at maximum radius, p_0 – hydrostatic pressure, γ – ratio of heat capacities of gas in a bubble at constant pressure and volume. With the adiabatic nature of the bubble closure, the temperature in it is: $T_{max} = T_0\left(\frac{(\gamma-1)p_0}{p}\right)^{3(\gamma-1)}$, where T_0 – initial fluid temperature. For example, when R_{min}=0.1R_{max}, p_0=10^5 Pa, γ=3/4, T_0=300 K the pressure of the gas in the bubble at the moment it reaches its maximum radius will be p=3.3·10^3 Pa. Substituting these values into the equations above, we get that when the bubble is closed, the pressure reaches p_{max}=3·10^7 Pa, and the temperature T_{max}=3000 K. Such high temperatures, which occur in a gas-filled cavity of a small volume, create conditions for the appearance of electric charges, luminescence, dissociated and ionized molecules, as well as atoms and free radicals.

In general, the chemical reactions in aqueous solutions that are initiated in a liquid by an electric discharge in the cavitation mode are well explained by the theory of free radicals. Molecules of water and gas dissolved in it undergo the following transformations in aqueous solutions under the influence of cavitation:

$$H_2O, N_2, O_2 \xrightarrow{\text{cavitation}} H\cdot, OH\cdot, H_2O_2, N_2^+, O_2^+$$

The yield of chemical reaction products formed is strongly influenced by the mixing of the liquid, which is automatically provided by the first-order effects of liquid decomposition (hydraulic flows). For example, hydrogen peroxide is emitted 10 times less in the absence of hydraulic flow than in the presence of it. The authors of [76] explain this by the enrichment of the liquid with air during mixing and the reduction of the concentration resistance. If solutes and micro-objects are present in the liquid, they react with excited gas molecules or formed radicals.

Second-order electrical discharge effects can play an important role in providing chemical action, with volumetric cavitation playing a very important role. According to several researchers [77], when cavitation occurs in a liquid medium, chemical bonds are broken and, as a result, ions and free radicals appear near the cavitation pocket. These reactive particles can react with substances located at the gas-vapor cavity-liquid interface. According to the authors [78, 79], the bubble collapses at an increasing rate. At the same time, the temperature of the gas in the bubble is constantly increasing and, from a certain point, the collapse of the bubble occurs under adiabatic conditions. Under certain assumptions, the authors have derived an equation that makes it possible to calculate the temperature inside a cavitating bubble at any stage of its compression under adiabatic conditions: $T_0 r_0^{3(\gamma-1)} = Tr^{3(\gamma-1)}$, where r_0 – maximum bubble radius, r – bubble's radius at a given compression stage, T_0 – gas temperature at the beginning of bubble compression, T – temperature at the moment of compression. According to the authors' calculations, for a certain ratio of the maximum radius of the bubble and the value of γ for the gas filling the bubble, the temperature in the compressed bubble reaches 2000 K or more. Such high temperatures can, according to [80], contribute to the initiation of almost all possible chemical reactions taking place in the cavitation volume. The products of gas reactions thermally specified in the cavitational pocket diffuse into the surrounding solution, where they interact with solutes to cause some chemical processes - secondary reactions. For example, to the secondary one in the paper [81] refers the formation of hydrogen peroxide, which occurs in the treated water only in the presence of oxygen:

$$H_2O + \frac{1}{2}O_2 \rightarrow H_2O_2$$

Moreover, this reaction takes place at a lower temperature than the next one:

$$2H_2O \rightarrow H_2O_2 + H_2 \; .$$

The products of the thermal decomposition of water molecules - free radicals OH^- cause intense oxidation processes in the working environment. At the same time, the yield of the reaction depends on the ratio of the heat capacities of the gases entering the cavitation pocket. For example, it has been shown in [82] that when carbon tetrachloride is sonicated in water, more chlorine is converted to the active form in a solution saturated with noble gases (γ=1.66) than in a solution containing oxygen and nitrogen (γ=1.4).

The chemical mechanisms of cavitation are not only due to the mechanical and thermal forces generated by the collapse of resonant bubbles. Chemical reactions can also occur as a result of electrochemical and photochemical processes caused by the occurrence of high electrical voltages in the cavitation pocket. According to Frenkel's theory, the electric field strength in a cavitational pocket can be determined by the following equation [76] (Formula 10):

$$E = \frac{4e}{r}\sqrt{N\alpha}\, , \tag{10}$$

where α – the distance between ruptured fluid layers, r – cavitation rupture radius, e – monovalent ion charge, and N – number of dissociated molecules per volume unit. Suppose, N equally $1\cdot10^{18}$, α and r equal $5\cdot10^{-8}$ cm и $1\cdot10^{-4}$ cm, accordingly, then E will be equal to 600 kV/cm, and there are conditions for the ionization of gas particles in the cavity. If there is an electrical breakdown between the walls of the cavity as a result of ionization, then a significant proportion of the radiation from the channel will be in the ultraviolet part of the spectrum. This will contribute to the photochemical nature of some of the chemical processes in the working medium.

A water molecule can split to form atomic hydrogen H and the radical OH^-, creating valence-unsaturated particles of high reactivity in the solution. Under the influence of the energy released during the high-voltage breakdown of the liquid, an electron is knocked out of the water molecule, leading to the formation of an ionized water particle ($H_2O - e \rightarrow H_2O^+$). This water particle in turn decomposes into the hydrogen ion H^+ and the free radical OH^-. An electron knocked out of a molecule travels a distance determined by the energy of the impact on the molecule and the properties of the medium. Along the way, it can attach itself to a water molecule or a hydrogen ion, resulting in the formation of atomic hydrogen. The formation of hydrogen atoms occurs at a considerable distance from free OH^- radicals, making their recombination difficult. There is a high probability of interaction between free radicals and individual atoms, resulting in the formation of other chemical compounds and free radicals. For example, the following reactions are possible:

$$OH\cdot + OH\cdot \rightarrow H_2O_2$$

$$H\cdot + H\cdot \rightarrow H_2$$

$$OH\cdot + OH\cdot \rightarrow H_2O + O^-$$

$$O\cdot + O\cdot \rightarrow O_2$$

$$H_2O_2 + OH\cdot \rightarrow H_2O + HO_2\cdot$$

$$HO_2\cdot + H\cdot \rightarrow H_2O_2$$

$$H_2O_2 + HO_2\cdot \rightarrow H_2O + O_2 + OH\cdot$$

In addition to the above-mentioned reactions leading to the formation of radicals and radical groups, the hypothesis of the formation of hydrogen superoxide H_2O_4 owing to the interaction of a hydrogen atom with molecular oxygen and the subsequent recombination of low-stable $HO_2\cdot$ radicals is considered [83]:

$$HO_2\cdot + HO_2\cdot \rightarrow H_2O_4 .$$

Thus, the decomposition of water molecules under the influence of factors characterizing cavitation consists of the occurrence of two parallel reactions leading to the formation of free radicals, hydrogen peroxide molecules, and atomic hydrogen. The ionization of water molecules takes place in the gas phase - in cavitation bubbles, when they collapse, chemically active objects enter the working medium. They cause oxidation processes (e.g. iron ions) even in the absence of oxygen molecules. In the presence of molecular oxygen, the process of oxidation of iron ions is enhanced by the formation of a hydroperoxide radical in the solution:

$$Fe^{2+} + HO_2 \rightarrow HO_2 \cdot + Fe^{3+}$$

$$H + HO_2 \cdot \rightarrow H_2O_2$$

Oxidation reactions of iron ions have not been detected in intentionally degassed aqueous solutions. This is evidence that the reactions are specified by the primary chemical reactions taking place in the cavitation pockets [84].

The analysis of the phenomena described has allowed us to assume that two stages in the chemical reactions initiated by cavitation exist. Each of these steps is associated with a specific stage in the development of the cavitation bubble.

Stage 1. Photochemical and electrochemical phenomena take place in the cavitation pocket when the pressure in the cavity is very low. At this stage, conditions are created in the cavitation region that are analogous to electrical discharges in a low-pressure vapor and gas medium. The gases in the cavity are ionized and activated. The process of activated and ionized particles forming is completed by an electronic breakdown of the cavity.

Stage 2. The further development of the cavitational pocket is accompanied by an increase in the pressure within it and then by its collapse. At the same time, the relatively long-lived active radicals and atoms formed are released into the medium. In addition, the collapse of the cavitational pocket is accompanied by the appearance of a local shock wave acting on the molecules of the substance, as shown above.

The chemical reactions initiated by cavitation can be therefore divided into the following groups:

- reactions in a gaseous medium (cavitational pocket);

- reactions at the interface between the cavitational pocket and the liquid as a result of the interaction of radicals and atoms in the cavity with molecules at the interface;

- reactions caused by active substances formed in the gas phase entering the surrounding liquid (water) as a result of the collapse of cavitational bubbles;

- reactions in a liquid medium under the influence of local shock waves caused by collapsing cavitational pockets.

The presence of a particular gas in an aqueous solution not only accelerates or slows chemical processes, but also determines the nature of the chemical reactions in the cavitation fields. For example, in the presence of hydrogen, the oxidation of iodine ions stops completely, but under the same conditions, iodine molecules dissociate into individual atoms and then reassemble as a result of interaction with hydrogen atoms. The process of iodine rebuilding appears to take place in the gas phase, i.e. in cavitation bubbles. During cavitation in an aqueous solution containing molecular iodine and molecular hydrogen, both water vapor and the above substances diffuse into the cavitation pockets. The energy of dissociation of iodine molecules into atoms is 1.53 eV. In the case of photodissociation (ultraviolet radiation from the plasma channel of the main discharge and discharges in cavitational bubbles), the iodine molecule is split into an iodine atom and an excited radical of this element:

$$I_2 + hv \rightarrow I \cdot + I \cdot .$$

The limiting quantum capable of triggering the photodissociation process must have an energy equal to or greater than the sum of the dissociation energy and the excitation energy of the radical or atom. For example, in the case above, this energy is 8.45 eV.

The hydrogen molecule can dissociate directly in the cavitation pocket:

$$H_2 \rightarrow H \cdot + H \cdot .$$

Hydrogen atoms, on the other hand, can be produced by the reaction of molecular hydrogen with $OH\cdot$ radicals:

$$H_2O \rightarrow H \cdot + OH \cdot , \; H_2 + OH\cdot \rightarrow H_2O + H \cdot .$$

This means that when a molecule of water interacts with a molecule of hydrogen, two hydrogen atoms are created, which can rebuild two atoms of dissolved iodine. The amount of atomic iodine formed depends on the concentration of molecular iodine in the reaction mixture. At low concentrations of molecular iodine, only a fraction of the hydrogen atoms formed will recombine to form molecular hydrogen. In the low concentration range, under the same physical conditions of cavitation, the amount of recombined iodine increases as the initial concentration of molecular hydrogen is increased. It is this phenomenon that we used in our experimental work to determine the intensity of cavitation [51]. If the iodine concentration is further increased, it may turn out that all the hydrogen atoms formed only bind part of the halogen present. In [82], assertory data were obtained by studying the effect of carbon tetrachloride on the kinetics of iodine ion oxidation in the cavitation field. The amount of iodine released in the presence of CCl_4 in an aqueous solution increases by a factor of 10 to 12. Starting from a given concentration of potassium iodide (0.5 N *KI*), the amount of iodine released remains constant both in the absence and in the presence of CCl_4. This means that, under the same physical conditions, the same number of active products capable of oxidizing the test substance is formed in a unit volume of aqueous solution. The amount of CCl_4 decomposition products that enhance oxidation processes also remains constant under the same conditions. The main decomposition product is atomic chlorine, which is released from carbon tetrachloride by cavitation. As a result of this reaction, hexachloroethane C_2Cl_6 can be obtained as a final product, which would indicate the appearance of the CCl_3 radical. Under the influence of cavitation, not only is the bond between the halogen and the carbon atom is broken, but the sulfur is also released from the carbon atom. For example, carbon disulfide (CS_2) in aqueous solution forms a very stable colloidal sol under the action of cavitation [85]. The issue of activation of molecules of various gases in the cavitational pocket also arises when analyzing the reactions of the formation of hydrogen peroxide in sonicated water. The formation of peroxide was predominantly observed when the water contained dissolved oxygen [86]. This is explained by the fact that in the absence of oxygen, most of the products of the ionized water particles decomposition recombine:

$$H^+ + OH^- \rightarrow H_2O .$$

In the presence of oxygen, the recombination of the free hydroxyl radical and atomic hydrogen slows down as a result of the reaction:

$$H \cdot + O_2 \rightarrow HO_2 \cdot .$$

The appearance of a radical $HO_2\cdot$ enhances oxidation processes, which are accompanied by the formation of H_2O_2:

$$HO_2 \cdot + HO_2 \cdot \rightarrow H_2O_2 + O_2 .$$

Hydrogen peroxide is also formed when a mixture of oxygen and hydrogen is forced into sonicated water. They interact with the products of the decomposition of the water molecules as follows:

$$H_2O \rightarrow H\cdot + OH\cdot,$$

$$H\cdot + O_2 \rightarrow HO_2\cdot,$$

$$OH\cdot + H_2 \rightarrow H_2O + H\cdot,$$

$$2HO_2\cdot \rightarrow H_2O_2 + O_2.$$

Under these conditions, for every molecule of water broken down, one molecule of hydrogen peroxide should be formed. However, the HO_2 radical interacts more readily with the hydroxyl radical than with the hydrogen molecules in the solution. Therefore, the process is shown as

$$OH\cdot + H_2 \rightarrow H_2O + H\cdot,$$

inhibited by a more easily occurring reaction:

$$OH\cdot + HO_2\cdot \rightarrow H_2O + O_2.$$

The greatest amount of hydrogen peroxide is produced when the ratio of dissolved hydrogen to oxygen in the sonicated medium is 1:4. Oxygen molecules decompose directly in the cavitation pocket and ozone is formed:

$$O_2 \rightarrow O\cdot + O\cdot,\ O\cdot + O_2 \rightarrow O_3.$$

In the cavitation region, nitrogen molecules from the air dissolved in water also dissociate. They interact with oxygen dissociation products to form nitric oxide - a chemically highly reactive free radical that can act as both an oxidant and a reductant. The primary elementary process that determines nitrogen oxidation reactions is mainly due to the ionization of the nitrogen molecules: $N_2 \rightarrow N_2^+ + e$. The resulting particle dissociates into atomic nitrogen and a cation: $N_2^+ \rightarrow N^+ + N$, then they interact with molecular oxygen:

$$N_2^+ + O_2 \rightarrow NO^+ + NO,$$

$$N_2^+ + O_2 \rightarrow NO_2 + N^+,$$

$$N + O_2 \rightarrow NO + O.$$

In this case, the rate of nitrogen oxidation is proportional to the efficiency of nitrogen ionization under the influence of secondary electrical discharge factors, particularly in cavitation bubbles.

Nucleic acids (including DNA and RNA) must be very sensitive to the effects of cavitation. A decrease in the relative viscosity of the DNA solution by ultrasonic cavitation is observed after only one minute of treatment; with increasing exposure, the relative viscosity of the DNA solution continues to decrease [87]. This decrease is permanent; the sonicated solution does not change its viscosity even after 24 ... 48 hours of sedimentation. Qualitative tests for the presence of free monosaccharides, phosphoric acid, purine, and pyrimidine bases in the treated DNA solutions did not give positive results, i.e. degradation of the DNA molecule is observed. However, the degradation of fragments formed in the field of ultrasonic waves does not occur if the sonication of DNA solutions takes place in the presence of gases that prevent the development of oxidative reactions. In the paper [88] it is assumed that the disintegration of a giant nucleic acid molecule into separate fragments is caused by destructive mechanical effects occurring in the cavitation region. We believe that such degradation does not occur only as a result of mechanical action, but mainly due to the formation of free hydroxyl radicals in solution under the influence of physical and chemical factors. For example, it is known [88] that in the presence of hydrogen peroxide and iron, the depolymerization of thymonucleic acid is rapid and their interaction is accompanied by the appearance of free hydroxyl radicals: $H_2O_2 + Fe^{2+} \rightarrow OH \cdot + Fe^{3+}(OH)^-$. As shown above, the active formation of such chemically active particles is a phenomenon accompanying cavitation in aqueous solutions. In sonicated protein solutions, protein peroxide radicals appear with a lifetime of 5...10 minutes; the main condition for their appearance is the saturation of the solutions with oxygen and not with hydrogen or an inert gas [89]. According to the authors, organic peroxides are formed by the direct interaction of an oxygen molecule with an excited molecule: $RH + O_2 \rightarrow ROOH$. According to their data, peroxide compounds are formed during the auto-oxidation of hydrocarbons under the influence of ionizing radiation. This is preceded by the formation of peroxyl radicals which react with hydrocarbon radicals. According to [83], complex molecules in a metastable state are highly reactive and are biradicals. The lifespan of biradicals is a hundredth of a second, whereas electronically excited molecules lose their energy within $1 \cdot 10^{-8}$ ... $1 \cdot 10^{-9}$ s. When biradicals interact with molecular oxygen, they are likely to form biradicals with a lifetime of several minutes. The long lifetime of the peroxide radical and its high reactivity contribute significantly to the conversion of the excitation energy into a chemical form.

CONCLUSION

A synergistic effect has been observed when contaminated water is treated with both a chlorine agent and electric discharge simultaneously. Leveraging this effect enables the reduction of bactericidal chlorine doses to 0.4–0.5 mg/L, which is ten times lower than current standards. The energy consumption for electric discharge treatment is approximately 25 kJ/dm³, six times less than when oxidizers are not used. This method also significantly reduces the disinfection process time while maintaining a prolonged bactericidal effect.

Experimental studies have confirmed that volumetric cavitation plays a critical role in the disinfection process when using electric discharge. The powerful volumetric cavitation generated by electrodischarge in a specific mode serves as a key driver for significantly reducing the amount of disinfectants required, lowering temperatures, and shortening treatment times for water disinfection. The primary mechanism behind electrical discharge cavitation is the production of a large number of chemically active particles from the treated water, which enhances oxidation processes.

It has been experimentally demonstrated that the intensity of the high-frequency range of the acoustic radiation spectrum produced by an electric discharge in water can be controlled by adjusting the length of the non-insulated end of the anode electrode protruding into the discharge gap and modifying the discharge circuit's inductance.

Previously unidentified frequencies in the range of 70–120 kHz have been discovered in the acoustic radiation spectrum of an underwater electric discharge operating in cavitation mode, alongside the previously confirmed frequencies of 15–65 kHz. This indicates that an electric discharge in cavitation mode generates acoustic radiation frequencies that align with the resonance conditions of all bubbles initially present in the working medium. Acoustic waves across this broad frequency range induce resonant vibrations of the bubbles, leading to intense cavitation in the treated water. The phenomena associated with this cavitation process effectively contribute to the inactivation of microbiological contaminants in the purified water.

In the cavitation mode of electrical discharge, factors such as local shock waves, acoustic flows and turbulence, flotation effects, and rectified diffusion play a secondary role. While these elements contribute to the overall process, the primary mechanism driving the disinfection and purification efficiency remains the generation of chemically active particles and the resonant cavitation effects induced by the electric discharge. These secondary factors, though less dominant, still support the process by enhancing mixing, particle aggregation, and the overall dynamics of the treatment.

Experimental studies have demonstrated the similarity between the effects of ultrasound and electric discharge in cavitation mode on water systems. Underwater electric discharge as a cavitation source overcomes certain limitations inherent to ultrasonic methods, such as the erosion resistance of ultrasonic emitters, cavitation does not directly affect the plasma channel of the electric discharge in the liquid. Furthermore, the intensity and total power of cavitation processes induced by underwater electrical discharges consistently exceed those of ultrasonic treatment, owing to the broader range of acoustic frequencies generated. As a result, the potential for industrial applications of water disinfection using electric discharge in cavitation mode is significantly greater than with ultrasonic methods. This makes underwater electrical discharges a highly promising technology not only for accelerating oxidation processes but also for enhancing other chemical engineering processes in practical settings.

At this stage, the electric discharge method's ability to disinfect water efficiently with reduced chemical doses, lower energy consumption, and shorter treatment times makes it particularly advantageous for remote or decentralized locations where conventional water treatment systems are impractical or unavailable. This approach could provide a reliable and sustainable solution for ensuring safe water in such settings.

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GREEN SYNTHESIS OF PLASMONIC NANOPARTICLES

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ABSTRACT

This study is dedicated to the review of the recent achievements in the fields of the green synthesis of metallic nanoparticles. The main focus is made on the plasmonic nanoparticles with a response in the infrared region as nanomaterials with a perspective of use in nanomedicine as photothermal agents. Theoretical calculations, based on the Mio theory, and results of the characterization of nanoparticles using UV-Vis-NIR spectroscopy and transmission electron spectroscopy were involved. The available data allowed stating that gold nanoparticles remain the most prospective material for the production of biocompatible nanoparticles with controlled optical properties. However, more attention needs to be paid to the development of green approaches in the synthesis of irregularly shaped (nanorods, nanotriangles, nanoshells, etc.) nanoparticles.

Keywords: phytosynthesis, plant extract, surface plasmon resonance, nanomaterials

INTRODUCTION

Nowadays, the nanomaterials have become a new and fast-developing trend in modern science due to their extraordinary properties, which differ from their bulk material counterparts. The advancements in nanotechnology and analytical techniques allowed scientists to explore and manipulate materials at the nanoscale, where unique behaviors emerge. Their exceptional optical, electrical, magnetic, and catalytic properties opened new possibilities for new applications in medicine, electronics, energy storage, and environmental sustainability.

The biocompatibility and unique optical characteristics, such as surface plasmon resonance (SPR), of noble metal nanoparticles have paved the way for their use in the rapidly evolving field of nanomedicine [1]. Noble metal nanoparticles, particularly those composed of gold, found prospective for use as a target drug delivery followed by controlled drug release systems [2] and photothermal therapy agents [3]. The optical properties of metal nanoparticles are highly dependent on the environment, their composition, size, and shape.

Gold nanoparticles are highly suitable for biomedical applications due to their remarkable chemical stability and biocompatibility. However, smaller Au NPs, with sizes less than 60 nm, typically exhibit surface plasmon resonance (SPR) within the range of 510-560 nm, which lies outside the biological transparency (therapeutic) window of 650-1350 nm [4]. This spectral range is essential for deeper light penetration in biological tissues and is divided into two near-infrared regions of 650-850 and 950-1350 nm. From the point of view of the application, the second near-infrared range is the most interesting due to the deeper tissue penetration by long-wave radiation. Consequently, researchers have focused significant efforts on synthesizing gold nanoparticles with diverse shapes such as spheres [5, 6], nanostars [7], nanorods [8], nanoshells [9], nanoprisms [10], nanotriangles [11], and nanohexagons [12; 13].

Over recent decades, numerous methods for the preparation of metal nanoparticles have been developed, including hydrothermal synthesis, co-precipitation, microemulsion, inert gas condensation, ion sputtering scattering, microwave techniques, pulse laser ablation, sol-gel processes, sonochemical methods, and biological synthesis [14; 15]. Physical approaches often necessitate costly equipment and fail to provide precise control over the morphology (like monodispersity, size, and shape) of the nanoparticles. Traditional wet chemistry methods are more favorable in this regard, but the most effective protocols necessary involve the toxic reducing and capping agents (for example, cetrimonium bromide), which persist in the resulting nanocolloid solutions. Consequently, obtained nanoparticles can exhibit high cytotoxicity toward living organisms, rendering them unsuitable for biomedical applications.

Biological synthesis methods—utilizing whole or parts of plants, fungi, and bacteria—present a promising, cost- and energy-effective, time-efficient, and eco-friendly alternative [16]. Phytosynthesis, involving plant extracts and natural surfactants, offers a particularly green approach to creating biocompatible non-spherical gold nanoparticles [17]. However, widespread application of such methods remains limited due to the complexity of plant extracts, the variability of extract chemical composition from different factors (place and time of growing, climate of locality, technique of the extract preparation), and the incomplete understanding of the mechanisms involved in forming nanoparticles and their effect on the morphology [18; 19].

Another metals, which have the similar to gold chemical and physical properties, are platinum and palladium. Platinum-based chemotherapeutic drugs, including carboplatin and oxaliplatin, are widely used in cancer treatment. However, their clinical applications are significantly hindered by limited selectivity and systemic toxicity. Recent advancements in nanotechnology and chemical synthesis have enabled substantial progress in the development of platinum-based anti-cancer drugs. Additionally, platinum-based nanodrugs, such as platinum nanoclusters, introduce innovative anti-cancer mechanisms and hold considerable promise for tumor-targeted therapy, demonstrating encouraging outcomes in clinical applications [20]. The interest to preparation of platinum and palladium nanoparticles is stimulated by other applications. For example, catalysis, where platinum- and palladium-based catalysts have attracted significant attention due to their exceptional activity, stability, and selectivity in various reactions pivotal to green energy and sustainable technologies. These applications span industrial petrochemical processes, fine chemical synthesis, environmental protection, renewable energy conversion, and microbial activities. However, the development of cost-effective electrodes and catalysts with high performance and stable electrochemical properties is essential for achieving long-term progress in these fields [21].

The aim of this study is the analysis of recent reports about the synthesis of metal nanoparticles with a response in the near infrared range as prospective materials for use in nanomedicine.

METHODS AND EXPERIMENTAL PROCEDURES

The typical plant extract-mediated synthesis of metal nanoparticles consists of the direct interaction of plant extract with diluted (>1 mM) aqueous solutions of metal salts at room temperature. In some cases, the solutions were heated to 80 or 100 ^{o}C. For example, gold nanoparticles were prepared utilizing the aqueous extracts of elderberry fruits (*Sambucus nigra*) [5] and juniper (*Juniperus communis* L.) [11] and leaves of Canadian goldenrod (*Solidago canadensis* L.) [12] and peppermint (*Mentha piperita*) [13] and at an ambient laboratory temperature (23 °C) by the direct interaction of the plant extracts with a concentration of dry matter of 0.5-2.0 mg/mL and 1 mM of $HAuCl_4$ aqueous solution under continuous stirring.

UV-Vis spectroscopy measurements have been performed using standard spectrophotometers, for example, Shimadzu UV-1800, in 1-cm quartz cuvettes in the range of 180-1100 nm. In a typical study, transmission electron microscopy (TEM) images are collected employing a transmission electron microscope, for example, the JEOL JEM-2100F [13].

THE RESEARCH RESULTS AND DISCUSSIONS

Theoretical study

Reducing the particle size of metals or other electrically conductive materials to tens and hundreds of nanometers dramatically changes their optical properties. Bulk silver is known as a shiny white metal, but nanocolloidal solutions of silver nanoparticles (AgNPs) have a brown to yellow color, depending on size and concentration. Nanocolloidal solutions of gold nanoparticles have a pink to purple color, depending on size and shape. The cause of such changes is the emergence of the physical phenomenon known as surface plasmon resonance. It arises from the absorption of electromagnetic radiation, which causes oscillation of electrons moving on the surface of the NPs. The frequency of the SPR absorption maximum of the electrons depends on the material (gold, silver, etc.), the environment (air, solvent, chemicals on the surface), and the size and shape of the NPs.

In the case of particles of the mentioned metals with sizes of tens to hundreds of nanometers, the surface plasmon resonance frequency is located in the visible range, which causes significant absorption at 390-430 nm for silver nanoparticles and 530-560 nm gold nanoparticles. For example, Fig. 1 presents simulated UV-Vis spectra of nanoparticles for different metals with the same size, which are calculated based on the Mie theory [22]. This is the reason for the unusual coloration of nanocolloidal solutions of nanoparticles, which is visible even to the naked eye. For some metals, such as copper or aluminum, the surface plasmon resonance peak is expected to occur outside the visible region of electromagnetic radiation (Vis), and special instruments, spectrometers, are required for their observation.

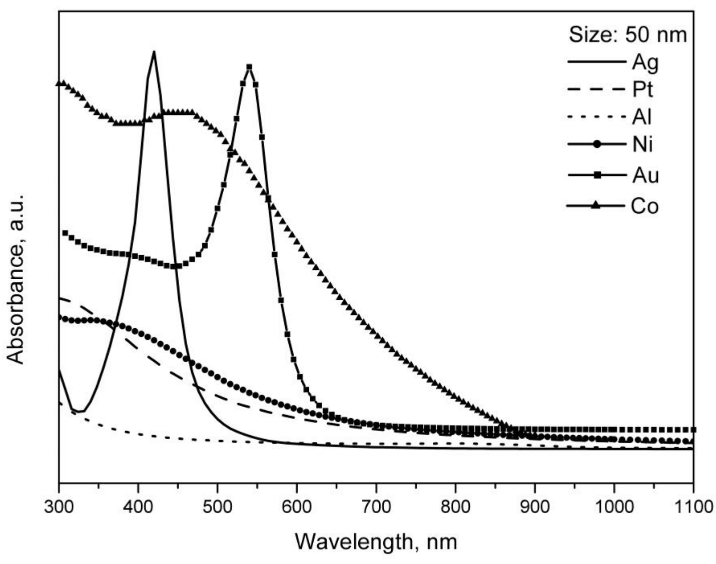

Fig. 1. Simulated UV-Vis spectra for 50-nm sized NPs of different metals in aqueous solution [22].

This phenomenon has opened the possibility of using gold nanoparticles in medicine, in phototherapy, because they can be heated in a controlled manner using electromagnetic radiation. The advantage of noble metals, such as silver, gold, platinum, etc., is their high chemical stability together with the ability to form strong chemical bonds with organic substances, so there is a possibility of chemical modification of the nanoparticles surface. However, for effective use as a photothermal agent, it is necessary that nanoparticles absorb electromagnetic radiation at least in the near-infrared band (NIR, >700 nm), where organic matter absorbs it weakly [4]. From the mentioned nanoparticles, the gold nanoparticles display the surface plasmon resonance maximum near the NIR range.

Another way to manage the optical properties of metal nanoparticles is the size. However, despite the fact that the position of the surface plasmon resonance maximum can be changed by changing the size of the nanoparticles, even a multiple increase in the size of gold nanoparticles will lead to only a minor shift (Fig. 2).

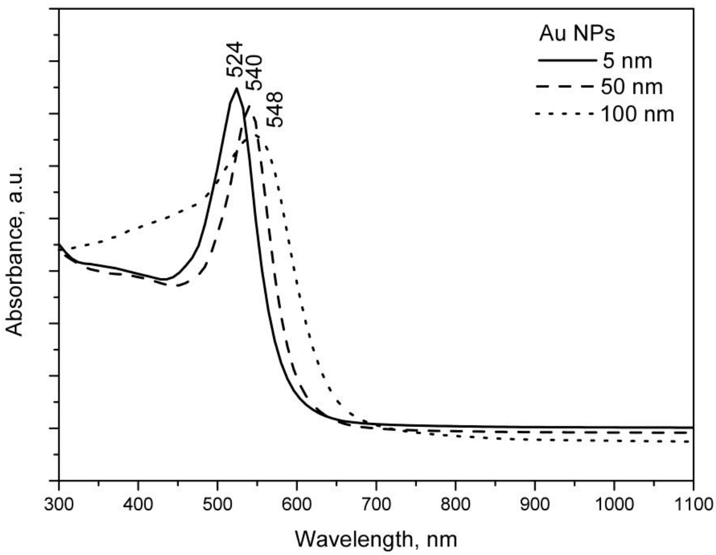

Fig. 2. Simulated UV-Vis spectra for Au NPs of different sizes in aqueous solution [22].

Other possibilities are provided by changing the shape of the nanoparticles. It is known that any deviation from the spherical shape of nanoparticles significantly affects the position of the surface plasmon resonance maximum [23]. For example, in Fig. 17, simulated spectra of NPs shaped like nanostars are presented. We can see how a larger deviation from the spherical shape leads to a more significant shift of the SPR peak to the infrared band. In the last decades, protocols have been proposed for the synthesis of NPs of various shapes, such as nanotriangles, nanohexagonals, nanotetrahedrons, nanorods, nanostars, etc.

Experimental study

Various plant extracts deliver different chemical systems that are involved in the reduction of initial metal cations and their further stabilization. Phytochemicals, depending on their nature, differently influence the formation of nanoparticles. For example, the leaf extracts of Canadian goldenrod (*Solidago canadensis* L.) [12] and peppermint (*Mentha piperita*) [13], as well as fruits of juniper (*Juniperus communis* L.) [11], support the formation of non-spherical gold nanoparticles (Fig. 3a). In contrast, extracts from elderberry fruits (*Sambucus nigra*) [5] and clove [6] support the formation of regularly shaped spherical gold nanoparticles (Fig. 3b).

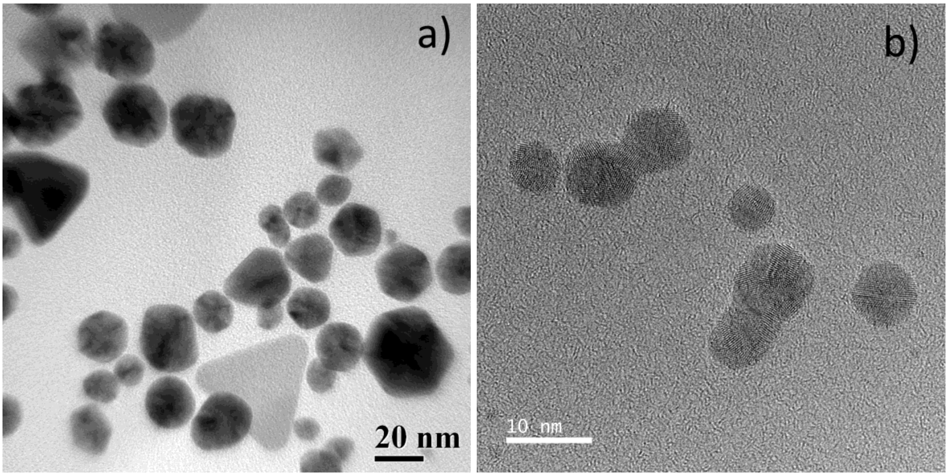

Fig. 3. Transmission electron microscopy images obtained using a) leaf extract of *Mentha piperita* and b) fruits of *Sambucus nigra* L.

The shape of gold nanoparticles influences the absorption of UV-Vis-NIR radiation (Fig. 4). For example, uniform spherical nanoparticles, as expected, absorb the radiation in the visible range. For example, the single and clear surface plasmon resonance maximum was observed at 528 nm. However, gold nanocolloid solutions that consist of a mixture of nanospheres, nanotriangles, and nanohexagons look different. One can see two clear maxima at 530 and 1050 nm that represent regularly and irregularly shaped nanoparticles.

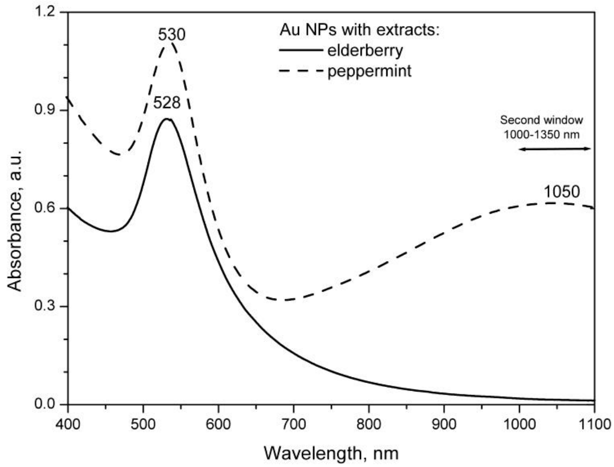

Fig. 4. UV-Vis spectra of nanocolloid solutions prepared using extracts of fruits of *Sambucus nigra* L. and leaves of *Mentha piperita*.

These achievements show the possibility of the preparation of gold nanoparticles with a response in the near-infrared range through the green approach, i.e., synthesis using plant extracts.

Challenges and limitations of the green synthesis of nanoparticles

Green synthesis of metal nanoparticles is recognized as a prospective route considering the advantages, like being environmentally friendly, fast, and cost- and energy-effective. However, certain challenges may impact the application of the green approach on a large-scale production.

The morphology of nanoparticles (size and shape) synthesized by different extracts is highly variable, and the properties determined are insufficient. For example, the particle size of gold nanoparticles prepared from *Moringa oleifera* leaves varied from 10 to 30 nm [24], while the size of nanoparticles synthesized by *Dendropanax morbifera* leaves ranged between 100 and 150 nm [25]. Similarly, the shape of nanoparticles synthesized from elderberry fruit had near-spherical-like shape [5], while nanoparticles synthesized from peppermint were triangular and hexagonal [13]. This difference in size and shape makes green technology not suitable for large-scale production and is one of the major challenges.

The scale-up for industrial and other applications is also problematic due to factors like equipment limitations, low raw material abundance, difficulty in controlling molecular composition, and plant extract heterogeneity. These challenges can be addressed by standardizing phytochemicals extraction.

Maintaining consistent results in the green synthesis of metal nanoparticles using plants is a challenging endeavor. Over the course of the year, plants face numerous environmental factors, such as water stress, imbalances in nutrient levels, shifts in soil pH, attacks from herbivores and parasites, interspecies competition, and variations in light intensity—whether excessive or insufficient. These factors lead to fluctuations in plant metabolites throughout the year. Variations in the concentration and composition of phytochemicals (metabolites) in a plant extract will result in the formation of unpredictable profiles of nanoparticles during synthesis.

Stability is another limitation for the large-scale utilization of green synthesis. Natural capping agents, such as proteins, polyphenols, or polysaccharides, have limited stability (light, oxygen of the air, etc.).

However, the main challenge in the green synthesis of nanoparticles is limited knowledge of the mechanisms that arise from the biological and chemical complexities. Unlike wet chemistry methods, which provide more precise control, green synthesis depends on biological agents like microorganisms and plant extracts, whose components and compositions may vary in concentration and reactivity. This can impact the reproducibility of nanoparticle properties [26].

And last, but not least, the regulatory challenges in regard to the unique properties of nanoscale materials.

CONCLUSION

Drawing from our study results, we analyzed the optical characteristics within the surface plasmon resonance region alongside the morphological traits of metal nanoparticles, including spherical and distinct irregularly shaped ones, synthesized through green protocols. It was observed that some plant extracts, such as those from elderberry fruits, facilitate the formation of nearly perfect spherical gold nanoparticles. Gold nanoparticles with response in the near-infrared range using other plants, for example, peppermint or goldenrod.

Despite the fact, that synthesis using plant extracts offer numerous advantages, the implementation of of green approach in the large-scale production is limited. The main challenges are: control over morphology, stability of phytochemicals, reproducibility, limited knowledges of mechanisms of the nanoparticle’s formation and regulatory challenges.

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ASSESSING CLIMATE CHANGE THROUGH ATMOSPHERIC TEMPERATURE DYNAMICS

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ABSTRACT

Throughout the 20th century and the first quarter of the 21st century, significant changes in the temperature regime have been observed. Atmospheric air temperature has been chosen as an integrated climate indicator, as it depends on geographical latitude, which determines the level of solar radiation, the characteristics of the underlying surface, and the specifics of atmospheric circulation. The latter is largely influenced by the proximity of the Black Sea. The temperature regime of the air is also affected by climate change, i.e., long-term trends in temperature variations caused by both natural and anthropogenic factors, including urbanization, industrial emissions, and land use changes.

The aim of this study is to analyze the dynamics of atmospheric air temperature as one of the key indicators of climate change and to identify the main factors influencing the state of water resources, using the example of Mykolaiv city and Mykolaiv region. The research object is Mykolaiv city and Mykolaiv region. The study employs methods such as observation, comparison and analogy, analysis, synthesis, and generalization. Additionally, Microsoft Excel and mathematical modeling, including regression analysis, have been used.

Between 1991 and 2024, the average annual temperature in the Mykolaiv region increased by 1.2°C, which is three times higher than the global warming rate. The highest recorded temperature was in 1998 (+40.1°C), while the lowest was in 2006 (−25.9°C). Recent years (2023–2024) have been the warmest in the entire observation period. The data indicate a consistent rise in the number of days with temperatures exceeding +25°C over the analyzed period, which may be a consequence of global warming and climate change. However, in certain years, the number of hot days may deviate from the trend due to natural climate variability and the influence of other climatic factors. Overall, the graph demonstrates a clear upward trend in the number of hot days, which serves as an important indicator of climate change in the region.

Keywords: climate change; atmospheric air temperature; environmental change; sustainable development.

INTRODUCTION

Throughout the twentieth century and into the first quarter of the twenty-first century, significant shifts in temperature patterns have been observed. According to the Intergovernmental Panel on Climate Change (Climate Change, 2013), abnormally high temperatures have been recorded across many regions of the planet. It has been established that the first two decades of the twenty-first century were 0.99°C warmer than the pre-industrial average (1850–1900), and during 2011–2024, this increase reached 1.09°C. Climate change presents substantial challenges to achieving the Sustainable Development Goals (SDGs), directly affecting global ecosystems, economies, and societies. Addressing these challenges is crucial to ensuring sustainable development and safeguarding the planet for future generations [9], [10], [11], [14], [18].

Examining the influence of environmental parameters on aquatic ecosystems provides valuable insights into preserving biodiversity and maintaining ecosystem resilience. This study serves as a foundation for developing sustainable water resource management strategies in response to global environmental changes [2], [3], [4], [12], [13], [15], [16].

Anomalies in global average temperatures between 2013 and 2024 were detected, with an increase of 1.14°C (ranging from 1.02°C to 1.27°C), indicating a continued warming trend (WMO, 2024). Similar abnormally high temperatures were last observed 125,000 years ago, during the Eemian Interglacial Period, when global temperatures were 0.5–1.5°C higher than pre-industrial levels. This period was marked by rising sea levels and widespread warming. Modern climate change, largely driven by anthropogenic factors, exhibits comparable trends in temperature rise. Since 1970, global temperatures have been the highest in the past 2,000 years, and the past decade has been the warmest in the last 6,500 years. This underscores the urgency of addressing climate change, reducing greenhouse gas emissions, and mitigating global warming [5], [7]. A change in air temperature indicates a significant change in the temperature regime of the entire climate system of the planet. According to scientists, the effects of climate change are predominantly negative and are projected to intensify in the future.

Meteorological observations have been carried out in Ukraine since 1881. Over the past decades, significant changes in the climate system have also been identified in Ukraine, the indicator of which is the temperature regime of atmospheric air [21].

The study [20] provides an analysis of changes in annual temperature in Ukraine since 1901. The thesis that the stability of the modern low-water phase of the Southern Bug River is caused by a steady increase in the annual temperature in Ukraine, which has been observed since 2000 to the present, is substantiated.

We consider it necessary to focus on the fact that during 1991-2024, the highest rates of change in the average annual atmospheric air temperature were observed compared to 1961. They were almost three times higher than the rate of change in the average annual global temperature (0.21°C/10 years) during this period. As a result, according to the UN, Ukraine fell into the regions of our planet, except of polar latitudes, where the temperature increase occurred at the highest rate [23].

According to the Copernicus Climate Change Service analysis, the global average surface air temperature of April 2024 was higher than any previous April in the reanalysis dataset since 1940 [1], [6]. According to the Ukrainian Hydrometeorological Center, over the past 30 years, the average temperature in our country has increased by 1.2°C. The rate of increase in air temperature in some regions of Ukraine has reached 0.82°C over the past 10 years, while in neighboring countries – 0.47−0.59°C/10 years, and in the northern hemisphere and Europe – 0.34 and 0.47°C/10 years, respectively. These data indicate that the rate of increase in air temperature in Ukraine is significantly higher than global and European rates [25].

April 2024 is the eleventh consecutive month, which is the warmest of the corresponding month of the year. April and July 2024 were 1.58°C warmer than the average for the pre-industrial baseline period (1850−1900). For example, the global surface air temperature in April 2024 was 15.03°C, 0.67°C higher than the average for April 1991-2023. and 0.14°C above the previous high set in April 2016. This is the month in which temperature records are set for the corresponding period. Overall, globally, the 12 months (May 2023 to April 2024) were warmer than any previous 12-month period, 0.73°C above the 1991-2023 average. and 1.61°C above the pre-industrial average [1].

Thus, open data from monitoring observations of the Copernicus Climate Change Service show that global temperature records are observed during the last months of 2023 and 2024 in various regions of the World Ocean. July 21, 2024 is the hottest day on record. The average temperature on the planet on this day was 17.09 ° C. This is the highest temperature recorded since 1940. The previous record was set in 2023 at 17.08°C [22], [24].

The main characteristics of atmospheric air temperature are average monthly and seasonal indicators that reflect the temperature distribution throughout the year. Average monthly temperature is an indicator of the average temperature for a given month, which allows you to understand temperature trends during each month of the year. Seasonal average temperature is a measure of the average temperature for a given season (winter, spring, summer, autumn), reflecting longer trends in temperature changes throughout the year. These metrics are essential for climate change analysis, weather forecasting, agriculture, and many other industries. They help to understand the distribution of temperature throughout the year and identify long-term trends in climate change.

Temperate climates are characterized by the following features:

- there is a pronounced seasonality due to the allocation of four seasons – winter, spring, summer and autumn, each of which has its own characteristic temperature and weather conditions.

- moderate temperatures that do not reach extremes. Winters can be cold but not too harsh, and summers can be warm but not too hot.

- the variety of rainfall can vary depending on the geographical location, but in general, temperate climates are characterized by having sufficient rainfall that is distributed throughout the year. Precipitation can be in the form of rain, snow, fog, etc.

- mild transitional seasons because spring and autumn in temperate climates are usually characterized by mild temperatures and a gradual transition from cold winters to warm summers and vice versa.

- changes in day length. There are significant changes in the length of the day throughout the year. In summer, the days are long and the nights are short, while in winter it is the opposite.

- the diversity of landscapes can include different landscapes, such as forests, steppes, mountains, and coasts, which creates diverse ecosystems.

The main feature of the temperate climate is the presence of four seasons: two main ones, winter and summer, and two intermediate ones – spring and autumn. This peculiarity of the climate is also characteristic of Mykolaiv, Ukraine.

Weather and climate observations in the city are carried out by a meteorological station located in Mykolaiv. Mykolaiv is located in the steppe agro-climatic zone of Ukraine, in the basin of the lower reaches of the Southern Buh and Inhul rivers. Thus, according to long-term data from meteorological observations, it was determined that during 1991−2024. The climate of the city was temperate continental, arid. Thus, in Mykolaiv, about 60−67 days with a negative average air temperature per day, which is a characteristic feature of the winter period, and about 32 days with a negative maximum air temperature per day, are recorded. The duration of the period with a negative minimum air temperature can be three times longer – an average of 93 days per year: 64 in winter, 16 in spring and 14 in autumn.

The purpose of the research is to study the dynamics of atmospheric air temperature as one of integrated indicator of climate change and the main factors influencing the state of water resources on the example of the territory of Mykolaiv city and the Mykolaiv region. These territories geographically belong to the Northern Black Sea region.

The object of research is the city of Mykolaiv and Mykolaiv region. Mykolaiv region is located in the south of Ukraine, within the Black Sea lowland. The region occupies the territory in the basin of the lower reaches of the Southern Buh River and is washed by the waters of the Black Sea. Its geographical position is characterized by a temperate continental climate with warm summers and mild winters. The Mykolaiv is a regional center and is located at the mouth of the Inhul River, where it flows into the Southern Buh. The geographical coordinates of the city are 46°58′, and 31°48 approximately. The Mykolaiv region has a variety of landscapes: from steppes to forest-steppes, as well as significant water resources.

MATERIALS AND METHODS

The study employed various methods, including observation, comparison and analogy, analysis, synthesis, and generalization. Additionally, Microsoft Excel and mathematical modeling, specifically regression analysis, were utilized for data processing.

The research was based on results obtained from the study, along with data from the regional hydrometeorological service. To assess environmental parameters in Mykolaiv and the Mykolaiv region, databases of strategic and program documents were consulted [17]. Furthermore, data from the Ventusky resource were used as a tool to provide precise meteorological indicators and track weather changes over time, both globally and at specific locations [22].

RESULTS AND DISCUSSION

Temperate climates are characterized by the following features:

• there is a pronounced seasonality due to the allocation of four seasons – winter, spring, summer and autumn, each of which has its own characteristic temperature and weather conditions.

• moderate temperatures that do not reach extremes. Winters can be cold but not too harsh, and summers can be warm but not too hot.

• the variety of rainfall can vary depending on the geographical location, but in general, temperate climates are characterized by having sufficient rainfall that is distributed throughout the year. Precipitation can be in the form of rain, snow, fog, etc.

• mild transitional seasons because spring and autumn in temperate climates are usually characterized by mild temperatures and a gradual transition from cold winters to warm summers and vice versa.

• changes in day length. There are significant changes in the length of the day throughout the year. In summer, the days are long and the nights are short, while in winter it is the opposite.

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The temperature regime begins to change for the study area from February. Thus, there is an increase in the influx of solar radiation, which leads to an intensive increase in air temperature, so March is warmer than February by almost 5.1°C, and April in March by 7.0°C. The warm period in the Mykolaiv region lasts about 300 days. May is dominated by summer temperatures, with an average monthly temperature of around 17.01°C and an average maximum of 23.6°C. Thus, in the Mykolaiv region, spring is quite warm, as evidenced by the average air temperature for the season of 10.3°C (Table 1), which, in general, is higher than the temperature of the growing season. So, in the spring of 2024, the flowering of many plants in the Mykolaiv region began three weeks earlier than the average period. Then, it is believed that the average start of active vegetation in the Mykolaiv region is mid-April, and the end of the growing season is October 15. The active growing season lasts about 187 days.

Table 1 − Values of temperature characteristics for the year and season in Mykolaiv and Mykolaiv region during 1991−2024.

Indicator	Season	Mykolaiv	Mykolaiv region
Average temperature, °C	Winter	-0.9	-1.1
	Spring	10.4	10.3
	Summer	22.7	22.3
	Autumn	10.9	10.6
	Year	10.1	10.5
Maximum average temperature, °C	Winter	2.2	2.0
	Spring	15.7	15.9
	Summer	29.0	28.6
	Autumn	15.0	15.5
	Year	15.7	15.4
Minimum average temperature, °C	Winter	-3.7	-3.9
	Spring	5.6	5.3
	Summer	16.9	16.3
	Autumn	6.8	6.4
	Year	6.4	6.0

The average summer temperature is +22.3°C. September in the Mykolaiv region covers an average of 20 days. The highest temperature is observed mainly (58%) in August, the average temperature of which is +24.3°C, the average maximum is +29.6°C, and the average minimum is +17.2°C. Much less often (43%) the highest temperature occurs in July. The analysis of winter temperatures showed that the average winter temperature is about -1.01°C, and has a range of fluctuations from -0.27°C to -1.71°C. It was determined that in the south of the Mykolaiv region, the average temperature below 0°C is observed only in January and February. The coldest month in the Mykolaiv region is January. The average temperature regime in January is -2.02°C, but the average minimum is -4.75°C, and the average maximum is +0.91°C. In a large area of the Mykolaiv region, autumn is warmer than spring, as evidenced by the data in Table. 1. Thus, the average air temperature for the season is 10.6°C, the average maximum is 15.4°C, and the average minimum is 6.4°C. In the Northern Black Sea region, the maximum and minimum temperatures in autumn are higher than in spring [13].

A graphical analysis of the dynamics of changes in average annual temperatures in Mykolaiv in the period from 1980 to 2024 is shown in Fig. 1. The graph in Fig. 1 indicates the presence of a stable linear trend in the direction of a gradual increase in average annual temperatures. The warmest years for this period of observations are 2023 and 2024, the coldest are 1985 and 1987. It is important to note that the growth of the average temperature is 0.61° C for every ten years. Separately analyzing trends in changes in maximum annual temperatures, shown in Fig. 1, it is also possible to note a gradual stable dependence on the increase in maximum annual temperatures. The trend line relative to minimum temperatures highlights constancy. By determining the correlation coefficient, which is 0.7 and is positive, it indicates that when one variable increases, the other also tends to increase. A correlation coefficient 0.7 indicates a strong relationship between variables, but not absolute. This means variables tend to change together, but with some variation. We are talking about the correlation between the year and the average temperature.

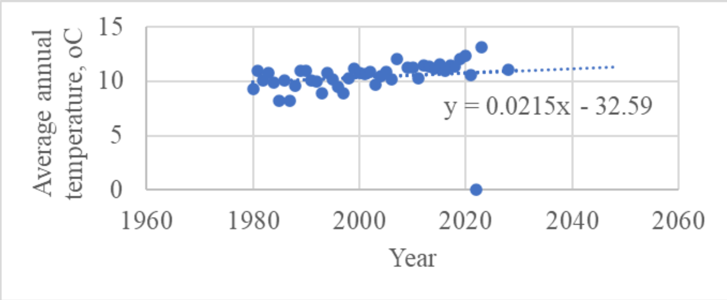

Fig. 1. Dynamics of changes in the average annual temperature.

However, the defined correlation does not mean causation, i.e. a correlation of 0.7 indicates a linear relationship, but does not take into account nonlinear relationships. The temperature maximum in the city during 1980 – 2024 was recorded in 1998 (+40.1°C); temperature minimum − in 2006 (−25.9°C). The trend equation y=0.0215x−32.59 means that the average annual temperature increases by about 0.021 °C each year. From Fig. 2.1. it can be seen that there are some temperature fluctuations around the trend line, which is common for climate data. If this trend continues, it can be predicted that the average annual temperature will continue to rise. Based on the trend equation, 2050 the average annual temperature may be approximately: 0.0215×2050−32.59=10.7175−32.59=11.4°C. Therefore, the graph in Fig. 1 shows a long-term increase in the average annual temperature, which may be a sign of global warming or other climate changes. This is an important indicator for environmental research and planning of climate change adaptation measures.

At the same time, it was determined that in the region during the period from 1991 to 2024, February was colder than January in 37.0% of years. During the winter period in the Mykolaiv region, up to 10 days are observed with a minimum air temperature below −10.0°C, of which, up to 3 days with severe frosts, when the air temperature was observed below −20.0°C. 2. Orange dots indicate the maximum temperatures, and blue dots indicate the minimum. Trend lines show trends of change for both temperature series. According to trend lines, maximum temperatures are increasing at a rate of 0.0884°C per year; minimum temperatures are decreasing at a rate of 0.0136°C per year. Both trends indicate a change in temperature extremes over time, which may be related to global climate change. Also, it was determined that in the Mykolaiv region during 1991−2024, not a single case was recorded when the highest temperature in June was noted.

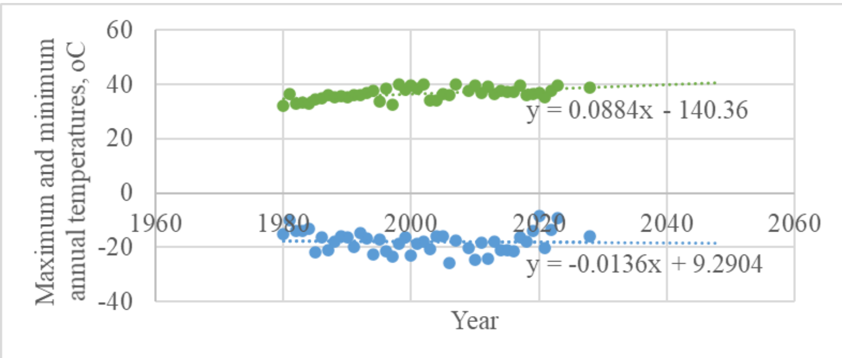

Fig. 2. Dynamics of changes in maximum and minimum annual temperatures.

An increase in maximum temperatures may indicate a general warming of the climate. A decrease in minimum temperatures indicates that colder winters or nights are possible. An increase in maximum temperatures can lead to an increase in the frequency of heat waves, which can affect human health, agriculture, and energy needs.

Using the obtained trend line equations, it is possible to make a forecast for future maximum and minimum temperatures. For example, for 2030: Maximum temperature: y=0,0884×2030−140,36 =+39,09. Minimum temperature: y=−0,0136×2030+9,2904 =−18,32. During the study period, about 98 days of hot weather were observed in the region, when the maximum air temperature exceeded 25.0°C. Temperature conditions under which the minimum air temperature exceeds 20.0°C are typical for tropical latitudes ("tropical nights"), typical for the Mykolaiv region. On average, there are about 20 tropical nights per year. Such extreme temperature conditions are most frequent during July – August, which causes heat stress and heat load on living organisms. In addition, an increase in this load is facilitated by an increase in relative humidity, a decrease in wind speed, as well as an increase in the influx of solar radiation. It is known that at the same temperatures, air humidity and wind speed, the heat load on the human body will be greater in cloudless weather, compared to the same meteorological conditions in cloudy weather. The largest number of days accompanied by heat stress (up to 90%) is observed in July - August. An important characteristic of the temperature regime is the deviation of the daily values of the minimum and maximum temperature from their average long-term values. Such jumps in temperature conditions determine the intensity and duration of periods of warming and cold snaps, which create certain environmental risks for water resources. The values of the 5th percentile of the minimum air temperature characterize very severe cold snaps. In summer, with a very strong cold snap in the Mykolaiv region, the same air temperatures can be observed as in winter, with extreme warming. It is determined that the season will last up to 5 days with such extreme temperatures. Extreme warming is when the maximum daily air temperature is more than 95 percentiles of its long-term average values for that day, and cold snaps, in which the minimum air temperature per day is below the 5th percentile for this day. Such heat waves are observed in summer, average 35.6°C per season and characterize very intense heat in the region.

At the same time, during the winter period, there are from 3 days with very high air temperature, when its maximum values exceed 95%, and the average maximum excess is 2.6°C. Strong warming in spring is observed more often than in autumn (4.08 and 3.06, respectively). On average, in the Mykolaiv region, about 15 days with a very high maximum air temperature for this season is observed≥. 2024 is shown in Fig. 3, from which a steady gradual increase in the number of hot days each year can be traced. The slope ratio of 1.9353 shows that, on average, the number of hot days increases by 1.9353 days each year. The intercept of 226.18 indicates the initial value of hot days in a year, when x=0. The highest number of hot days is observed closer to 2024, confirming the trend towards rising temperatures.

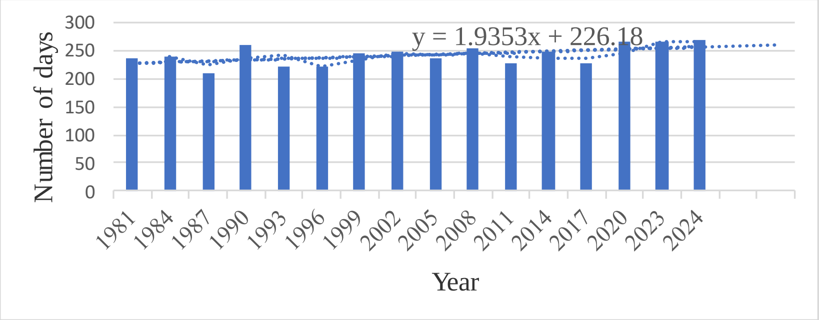

Fig. 3. Dynamics of changes in the number of hot days (Tmax≥25°C).

For about 30 years there have been anomalies in the latitude and longitude of Mykolaiv and the region. In general, if earlier intra-latitudinal circulation prevailed 3/4 days a year, then in recent decades the interlatitudinal direction of movement of air masses has significantly increased, as evidenced by numerical maps of the movement of air masses of hydrometeorological centers (Copernicus Interactive Climate Atlas, 2024). According to research by the Copernicus Climate Change Service global monitoring system, it was determined that a high-pressure ridge has been established between two areas of high pressure - over tropical North Africa and the Arctic. This leads to the formation of stable and dry conditions characteristic of anticyclones. For summer in the northern hemisphere, this is the norm. However, earlier such a ridge passed much further west, namely such countries as Italy, Spain, France. In 2024, this crest moved to the countries of Eastern Europe, in particular to Ukraine. A high-pressure crest is usually accompanied by stable weather conditions, clear skies, and low humidity.

The question is: are 2023 and 2024 isolated cases in terms of installing a high-pressure crest? Will this nature of circulation become a pattern?

So far, it is impossible to unequivocally answer this question, since abnormal heat waves were observed in the summers of 1998, 2000, 2002, 2010, 2017. From later periods, these were 1934, 1946, 1975, and in the summer of 1934, the drought in Mykolaiv lasted 137 days. Nevertheless, changes in terms of a gradual increase in temperature have taken place recently.

The question of whether 2023 and 2024 are isolated cases of high-pressure crest installation, or whether this nature of circulation will become a pattern, is complex and requires the analysis of various factors, including climate change and long-term trends in atmospheric circulation.

To answer this question, let's outline the factors affecting the installation of a high-pressure crest:

Changes in global climate can lead to changes in atmospheric circulation behavior, including the frequency and duration of high-pressure ridges.

An increase in global average temperature can affect pressure distribution and the formation of high-pressure ridges.

Greenhouse gas emissions, land-use changes, military actions and other anthropogenic actions can alter regional climatic conditions and affect atmospheric circulation.

Natural climatic phenomena, such as El Niño and La Niña, can affect pressure distribution and the formation of high-pressure ridges.

In addition, the answer to the question posed requires the analysis of historical data and modeling. Analysis of climate data from recent decades can help determine whether recent years are isolated occurrences or part of a longer trend. The study already shows that the frequency and duration of high-pressure ridges are increasing due to global warming, leading to more frequent extreme weather events such as heat waves and droughts. Forecast calculations indicate a significant probability of an increase in the frequency and intensity of such phenomena in the future if global warming continues. However, in order to give an accurate answer to the question of whether such phenomena will become a pattern, further research and analysis are needed. At the moment, there is a tendency to increase the frequency and duration of high-pressure ridges due to climate change, but long-term observations and improvements in climate models are needed to determine the exact pattern.

CONCLUSIONS AND PROSPECTS

Between 1991 and 2024, the average annual temperature in the Mykolaiv region rose by 1.2°C, with some areas experiencing an increase of up to 0.82°C per decade—significantly exceeding the global rate of 0.34°C per decade. The highest rise in average annual temperatures was observed in 2023 and 2024, whereas the coldest years were 1985 and 1987. The overall rate of temperature increase stands at 0.61°C per decade.

Extreme temperatures are most pronounced during the summer months, with the average maximum temperature in August reaching +29.6°C. Additionally, July experiences up to 20 tropical nights, where minimum temperatures remain above 20°C. Over the past 30 years, the region has seen an annual increase of 1.94 hot days, with 2024 significantly surpassing the average values of previous decades. Globally, April 2024 recorded a temperature of +15.03°C, exceeding the 1991–2023 average by 0.67°C and setting a new record. However, the highest temperature in Mykolaiv was recorded in 1998 (+40.1°C), while the lowest was in 2006 (−25.9°C).

Climate change has led to an extension of the warm period to approximately 300 days per year. The active growing season now lasts around 187 days, shifting the flowering period three weeks earlier than the historical average.

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EFFECTIVE SOLUTIONS FOR MANAGING WASTE FROM DESTRUCTION TO RESTORE THE POST-WAR ECONOMY

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ABSTRACT

The article explores effective solutions for managing waste from destruction to support the post-war economic recovery in Ukraine. It analyzes methodologies for assessing demolition waste, quantifying its volume, and determining its economic potential. A case study of several territorial communities in the Mykolaiv region is presented, highlighting waste composition, storage locations, and processing costs. The study proposes strategies to enhance the financial sustainability of waste management operations, including cost reduction, revenue growth, and state support. The findings emphasize the role of recycling in minimizing environmental impact and advancing a circular economy in post-war reconstruction efforts.

Key words: demolition waste; waste management; construction materials; economic assessment.

INTRODUCTION

In Ukraine, by order of the Ministry of Economy of Ukraine and the State Property Fund of Ukraine dated October 18, 2022 No. 3904/1223, the Methodology for determining the damage and extent of losses caused to enterprises, institutions and organizations of all forms of ownership as a result of the destruction and damage to their property in connection with the armed aggression of the Russian Federation, as well as lost profits from the impossibility or obstacles to conducting economic activities, was approved [9].

The assessment (determination of the amount) of real losses, lost profits and assessment of restoration needs, given in this Methodology, was developed on the basis of national and international assessment standards, as well as the World Bank guidelines on damage assessment and other materials developed by organizations recognized in the international community.

It has been determined that this methodology is mandatory for use when assessing the damage caused to victims as a result of armed aggression, conducting a forensic examination (expert study) related to the assessment of damage caused to victims as a result of armed aggression, and its provisions prevail over other provisions of regulatory legal acts, methods, recommendations, etc., which regulate the issue of determining the amount of damage caused to enterprises, institutions, organizations, and other business entities of all forms of ownership [1]; [4].

The calculation of the residual replacement (reproduction) value of real estate before the damage is carried out using the following formula 1:

$$V_O^{DRC} = V_L \times (1 + i) + V_C \times (1 + i)^{0.5} \times (1 - d), \quad (1)$$

V_O^{DRC} – the residual replacement (reproduction) value of real estate before the damage;

V_L – the market value of the land plot;

V_C – the replacement (reproduction) value of each building (structure) located on the land plot, associated equipment, or other type of improvement

i –the compounding rate, the value of which is determined by the duration of the real estate development period and corresponds to the interest of the investor i_F and the interest of the develop i_D;

d – the degree of depreciation of the building (structure) or other improvement.

The generation rate calculation (GRC) method is a methodology for estimating the amount of construction and demolition waste. It can be implemented for construction, renovation and demolition at both regional and project level. The principle of this methodology is to obtain the waste generation rate for a given unit of activity (e.g., kg/m^2 and m^3/m^2). This principle has introduced several methods using alternative parameters in previous studies, such as the per capita multiplier, the extrapolation of financial value and the area-based calculation [12]; [13].

The amount of waste generated is calculated using a waste generation index, such as the waste generation rate, obtained through a statistical analysis based on the gross floor area (GFA).

Researchers have attempted to improve existing tools for quantifying construction and demolition waste in the construction of new residential buildings in Spain.

A general formula is proposed (2) to estimate the approximate generation of construction and demolition waste:

$$V_{CDW} = i_x \cdot S_B, \quad (2)$$

V_{CDW} – expected volume of construction and demolition waste generation;

i_x – indicator value (m^3 waste m^2);

S_B – total built-up area (m^2).

Object of research: the amount of waste generated on the territory of territorial communities of Mykolaiv region.

Subject of research: accounting and processing of waste from demolitions in territorial communities of Mykolaiv region.

The purpose of the study is to assess the feasibility of accounting for and processing demolition waste in territorial communities of the Mykolaiv region.

METHODS AND EXPERIMENTAL PROCEDURES

Methodological recommendations for determining the volume of waste generated due to damage (destruction) of buildings and structures as a result of hostilities, terrorist acts, and sabotage were developed and presented by the NGO "RESINK", which operates within the framework of the Ukraine Support Team (UST) coalition, during the implementation of the project "ReThink: Recommendations for the Management of Destruction Waste in Frontline Territories" with the support of the United States Agency for International Development (USAID). It was decided to use the presented methodology as a basis for assessing waste from the destruction of the Mykolaiv region [7].

To perform calculations and construct graphical characteristics and diagrams, Microsoft Excel software and Mathcad mathematical processor were used. Cartographic images of waste generation sites were taken using Google Maps.

THE RESEARCH RESULTS AND DISCUSSIONS

The assessment of the generation of demolition waste was carried out on the relevant territory of the following territorial communities (TC):

- Bashtanska urban TC (southwest of the city along the N-11 highway) – 9.0 hectare.
- Novobuhska urban TC, temporary storage site for demolition waste (coordinates: 47.652305, 32.448731) – 5.0 hectare.
- Mykolaiv urban TC: temporary storage site for demolition waste - Mykolaiv city landfill – 1.0 hectare.
- Pervomaiska settlement TC, at the site of waste generation.
- Shyrokivska village TC, landfill outside the village of Shyroke – 10.0 hectare.
- Pryvilnenska village TC: at the site of waste generation – 2.0 hectare.
- Snihurivska urban TC: temporary storage site for demolition waste under cadastral number 4825710100:28:000:0001 – 1.0 hectare.
- Snihurivska urban TC, at the place of waste generation.
- Shevchenkivska rural TC, place of temporary storage of waste from destruction at coordinates 46.821604, 32.201390 (fig. 1) – 5.0 hectare.

a

b

Fig. 1. Location of temporary waste storage of Novobuhska TC (a) and Shevchenkivska TC (b) on the map.

To assess the resource potential of waste, minimum tariffs for the cost of waste components as secondary raw materials were determined. Calculations of the total cost of waste components were made for the relevant communities (tabl.1–5):

Table 1− Bashtanska TC.

№	Name of the components of demolition waste	Volume, t	Total cost of waste component, UAH
1	Concrete (concrete, reinforced concrete structures and products, their fragments, mineral (cement-sand, gypsum, lime, etc.), polymer-cement masonry and finishing (plastering, finishing) mortars)	280.20	40862.5
2	Brick (brickwork)	0.0	0.0

3	Wood	0.0	0.0
4	Glass (glasswork)	2.0	3000.0
5	Plastics (parts (fragments) of plastic pipes for water supply, drainage, electrical wiring, polymer moldings, glass units, polymer sealants, etc.)	0.0	0.0
6	Facing tiles, roof tiles and ceramics (including ceramic tiles, stones, sanitary ceramics)	26.0	5460.0
7	Mixtures or separate fractions of concrete, bricks, facing tiles and other ceramics	91.0	15166.7
8	Bituminous mixtures	0.0	0.0
9	Metals (including their alloys), cast iron and steel	0.0	0.0
10	Mixed metals	0.0	0.0
11	Soil and stones	0.0	0.0
12	Insulating materials and asbestos-containing building materials	0.0	0.0
13	Building materials containing asbestos	0.0	0.0
14	Other mixed components of demolition waste	0.0	0.0
TOTAL			64489.2

Table 2 − Mykolaiv TC.

№	Name of the components of demolition waste	Volume, t	Total cost of waste component, UAH
1	Concrete (concrete, reinforced concrete structures and products, their fragments, mineral (cement-sand, gypsum, lime, etc.), polymer-cement masonry and finishing (plastering, finishing) mortars)	2890.57	421541.5
2	Brick (brickwork)	1376.67	206500.5
3	Wood	10.3	735.7
4	Glass (glasswork)	246.28	369412.5
5	Plastics (parts (fragments) of plastic pipes for water supply, drainage, electrical wiring, polymer moldings, glass units, polymer sealants, etc.)	93.0	186000.0
6	Facing tiles, roof tiles and ceramics (including ceramic tiles, stones, sanitary ceramics)	2.7	567.0
7	Mixtures or separate fractions of concrete, bricks, facing tiles and other ceramics	0.0	0.0
8	Bituminous mixtures	11.37	29551.6
9	Metals (including their alloys), cast iron and steel	1.02	5085.0
10	Mixed metals	0.0	0.0
11	Soil and stones	55.0	52250.0
12	Insulating materials and asbestos-containing building	1.73	12110.0

	materials		
13	Building materials containing asbestos	0.0	0.0
14	Other mixed components of demolition waste	0.0	0.0
TOTAL			1283753.8

Table 3 − Pervomaiska TC

№	Name of the components of demolition waste	Volume, t	Total cost of waste component, UAH
1	Concrete (concrete, reinforced concrete structures and products, their fragments, mineral (cement-sand, gypsum, lime, etc.), polymer-cement masonry and finishing (plastering, finishing) mortars)	30.0	4375.0
2	Brick (brickwork)	50.0	7500.0
3	Wood	0.0	0.0
4	Glass (glasswork)	13.0	19500.0
5	Plastics (parts (fragments) of plastic pipes for water supply, drainage, electrical wiring, polymer moldings, glass units, polymer sealants, etc.)	17.0	34000.0
6	Facing tiles, roof tiles and ceramics (including ceramic tiles, stones, sanitary ceramics)	0.0	0.0
7	Mixtures or separate fractions of concrete, bricks, facing tiles and other ceramics	0.0	0.0
8	Bituminous mixtures	0.0	0.0
9	Metals (including their alloys), cast iron and steel	0.0	0.0
10	Mixed metals	0.0	0.0
11	Soil and stones	0.0	0.0
12	Insulating materials and asbestos-containing building materials	0.0	0,0
13	Building materials containing asbestos	0.0	0.0
14	Other mixed components of demolition waste	0.0	0.0
TOTAL			65375.0

Table 4 − Shyrokivska TC.

№	Name of the components of demolition waste	Volume, t	Total cost of waste component, UAH
1	Concrete (concrete, reinforced concrete structures and products, their fragments, mineral (cement-sand, gypsum, lime, etc.), polymer-cement masonry and finishing (plastering, finishing) mortars)	68.0	9916.7
2	Brick (brickwork)	39.0	5850.0

3	Wood	5.0	357.1
4	Glass (glasswork)	5.0	7500.0
5	Plastics (parts (fragments) of plastic pipes for water supply, drainage, electrical wiring, polymer moldings, glass units, polymer sealants, etc.)	4.0	8000.0
6	Facing tiles, roof tiles and ceramics (including ceramic tiles, stones, sanitary ceramics)	15.0	3150.0
7	Mixtures or separate fractions of concrete, bricks, facing tiles and other ceramics	0.0	0.0
8	Bituminous mixtures	0.0	0.0
9	Metals (including their alloys), cast iron and steel	5.0	25000.0
10	Mixed metals	6.0	72000.0
11	Soil and stones	0.0	0.0
12	Insulating materials and asbestos-containing building materials	0,0	0.0
13	Building materials containing asbestos	12,0	1260.0
14	Other mixed components of demolition waste	0,0	0,0
TOTAL			133033.8

Table 5 − Pryvilnenska TC.

№	Name of the components of demolition waste	Volume, t	Total cost of waste component, UAH
1	Concrete (concrete, reinforced concrete structures and products, their fragments, mineral (cement-sand, gypsum, lime, etc.), polymer-cement masonry and finishing (plastering, finishing) mortars)	66.0	9625.0
2	Brick (brickwork)	40.0	6000.0
3	Wood	20.0	1428.6
4	Glass (glasswork)	5.0	7500.0
5	Plastics (parts (fragments) of plastic pipes for water supply, drainage, electrical wiring, polymer moldings, glass units, polymer sealants, etc.)	4.0	8000.0
6	Facing tiles, roof tiles and ceramics (including ceramic tiles, stones, sanitary ceramics)	30.0	6300.0
7	Mixtures or separate fractions of concrete, bricks, facing tiles and other ceramics	0.0	0.0
8	Bituminous mixtures	0.0	0.0
9	Metals (including their alloys), cast iron and steel	0.0	0.0
10	Mixed metals	0.0	0.0
11	Soil and stones	0.0	0.0

12	Insulating materials and asbestos-containing building materials	0.0	0.0
13	Building materials containing asbestos	0.0	0.0
14	Other mixed components of demolition waste	0.0	0.0
TOTAL			38853.6

Table 6 − Snihurivska TC.

№	Name of the components of demolition waste	Volume, t	Total cost of waste component, UAH
1	Concrete (concrete, reinforced concrete structures and products, their fragments, mineral (cement-sand, gypsum, lime, etc.), polymer-cement masonry and finishing (plastering, finishing) mortars)	36883.87	5378775.3
2	Brick (brickwork)	30947.91	4642186.5
3	Wood	6116.67	436730.0
4	Glass (glasswork)	0.0	0.0
5	Plastics (parts (fragments) of plastic pipes for water supply, drainage, electrical wiring, polymer moldings, glass units, polymer sealants, etc.)	139.69	279380.0
6	Facing tiles, roof tiles and ceramics (including ceramic tiles, stones, sanitary ceramics)	0.0	0.0
7	Mixtures or separate fractions of concrete, bricks, facing tiles and other ceramics	0.0	0.0
8	Bituminous mixtures	0.0	0.0
9	Metals (including their alloys), cast iron and steel	0.0	0.0
10	Mixed metals	1007.63	12091560.0
11	Soil and stones	0.0	0.0
12	Insulating materials and asbestos-containing building materials	0.0	0.0
13	Building materials containing asbestos	701.82	73691.1
14	Other mixed components of demolition waste	1410.92	183419.6
TOTAL			23085742.5

Table 7−Shevchenkivska TC.

№	Name of the components of demolition waste	Volume, t	Total cost of waste component, UAH
1	Concrete (concrete, reinforced concrete structures and products, their fragments, mineral (cement-sand, gypsum, lime, etc.), polymer-cement masonry and finishing (plastering, finishing) mortars)	20.0	2916.7
2	Brick (brickwork)	10.0	1500.0

3	Wood	2.0	142.9
4	Glass (glasswork)	0.0	0.0
5	Plastics (parts (fragments) of plastic pipes for water supply, drainage, electrical wiring, polymer moldings, glass units, polymer sealants, etc.)	0.0	0.0
6	Facing tiles, roof tiles and ceramics (including ceramic tiles, stones, sanitary ceramics)	0.0	0.0
7	Mixtures or separate fractions of concrete, bricks, facing tiles and other ceramics	0.0	0.0
8	Bituminous mixtures	0.0	0.0
9	Metals (including their alloys), cast iron and steel	0.0	0.0
10	Mixed metals	0.0	0.0
11	Soil and stones	0.0	0.0
12	Insulating materials and asbestos-containing building materials	0.0	0.0
13	Building materials containing asbestos	0.0	0.0
14	Other mixed components of demolition waste	0.0	0.0
TOTAL			4559.6

The total cost of waste is more 24 billion UAH. For clarity, a diagram of the total cost of each waste component in the presented communities is presented (fig. 3).

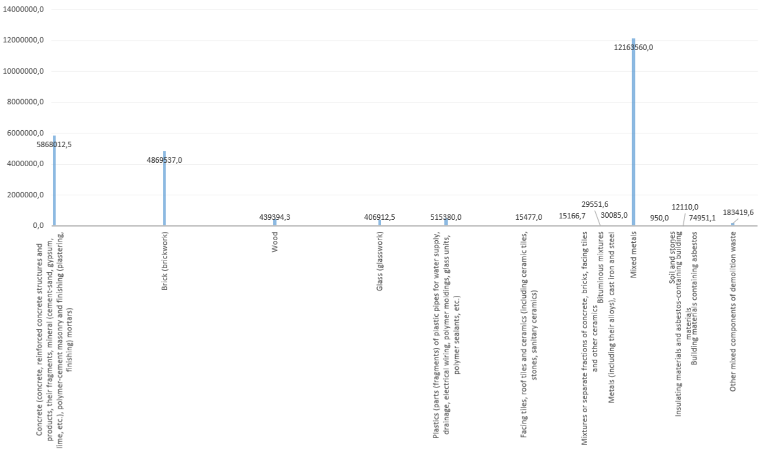

Fig. 3. Waste components in UAH.

Given the obtained indicators of income from the processing of construction waste from demolitions, in all six communities the business is operating at a loss, only the Snihurivska rural TC has the potential for self-sustaining production.

In order to gradually increase the profitability of the business, which will make it possible to achieve self-sufficiency and profit, we offer the following action plan:

Reducing operating costs. Optimizing the payroll, considering the possibility of partial automation. Reviewing electricity and fuel costs (possible use of alternative energy sources). Renting or purchasing more economical equipment for work.

Increasing income. Expanding processing volumes by attracting new customers and partners. Increasing the cost of services, if the market allows. Introducing additional services, for example, receiving and selling secondary raw materials. Participation in state tenders for waste disposal.

Attracting state funds. Applying for state and regional grants for environmental projects. Preparing documents for obtaining preferential loans from environmental funds. Cooperation with state programs for waste sorting and recycling. Interaction with international environmental organizations to obtain additional funding [5]; [6].

Recycling construction materials reduces the amount of waste going to landfills and reduces the environmental impact. Minimizing pollution – improper handling of construction waste can lead to soil, air and water pollution with toxic substances (asbestos, paints, heavy metals). Reducing CO_2 emissions, namely recycling materials such as concrete and metal, reduces the need for mining and producing new resources, which significantly reduces greenhouse gas emissions. Wood, metal, glass and plastic can be selected and sent for recycling, which reduces the volume of mixed waste [3]; [8]; [10].

Crushed concrete and bricks can be used as a base for road surfaces, in foundations and as an aggregate for new concrete mixtures. Recycled wood is used to make chipboard, pellets or construction elements. Metal structures are melted down and used to create new building materials [11].

The use of recycled materials reduces the need to extract natural stone, sand, clay and other resources. This reduces the destruction of landscapes and the negative impact on natural ecosystems. The construction industry can move to a closed-loop model, where most materials are not thrown away, but reused. This contributes not only to sustainable development, but also to economic benefits for construction companies, who can reduce the cost of purchasing new materials [1]; [2].

CONCLUSION

Seven territorial communities were surveyed for construction waste from demolition. The total area of the studied territories was 33 hectares.

The main components of demolition waste were identified (in tons): concrete – 40237.8, brick – 32463.58, wood – 6151.52, glass – 271.28, plastics – 257.69, facing tiles – 73.7, mixtures or separate fractions of concrete, brick, etc. – 91.0, bituminous mixtures – 11.37, metals – 6.02, mixed metals – 1013.63, soil and stones – 55, insulating materials and asbestos-containing materials – 1.73, building materials containing asbestos – 713.82, other mixed components – 1410.92. The total volume of waste in communities was 82.759.05 tons.

Implementing the proposed measures will help achieve financial stability, expand operations, and contribute to environmental conservation. It is necessary to focus on reducing costs, attracting investment, and active marketing promotion to ensure the successful implementation of the business plan.

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EDUCATIONAL COURSE «EUROPEAN GREEN DIMENSIONS» IN PREPARATION OF ECOLOGISTS

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ABSTRACT

One of the key challenges in modern education is shaping its content. Defining the theoretical foundations of an integrated approach holds scientific significance (by specifying its distinct features), social significance (by modernizing specialist training), and applied significance (by ensuring continuity between educational objectives and students' field of study). This research proposes the use of an integrated approach in the student training process. The study aims to develop an effective didactic system for interdisciplinary knowledge in natural science courses within environmental education, with a particular focus on professional orientation.

Object is the educational content of the student training process, specifically the preparation of students specializing in environmental sciences. Subject is the integrated approach to structuring educational content in the student training process.

Methodology. The study employed methods of analysis, synthesis of knowledge, educational experiments, and mathematical statistics to achieve its objectives.

Results. An educational experiment implementing the integrated approach demonstrated its effectiveness in enhancing students' knowledge quality. The research involved university students specializing in environmental sciences. A functional didactic system for interdisciplinary knowledge in natural science courses was developed. The study identified the levels, objectives, and key aspects of the integrated approach in environmental education. As a result, a concept of the integrated approach to environmental education was formulated, the specifics of its implementation were defined, and the methodological system for training environmental specialists was introduced and experimentally validated. The integrated approach to education serves as a unique framework for designing educational content, revealing interdisciplinary connections while coordinating, unifying, and systematizing knowledge about fundamental natural science theories, key categories, and principles of the modern scientific worldview. The study confirmed the didactic effectiveness of the integrated approach in shaping the content of natural science courses. Future research should focus on refining the theory and practice of integrated natural science education based on the developed conceptual framework, as well as enhancing methodologies for assessing students' knowledge quality in integrated courses.

Keywords: natural education; education content; an integrated approach; European green dimensions.

INTRODUCTION

Among the list of foreign policy guidelines of Ukraine, the intention to integrate into the European Union (EU) is declared, which sets the task of gradually harmonizing the national strategy of action with the European standards. Ukraine has to adopt more than 30 EU Directives and Regulations on environmental protection. Among the priorities of the movement of Ukraine to the EU there are directives and regulations concerning sustainable development goals, namely the issue of green dimension especially in the context of climate change. To date, Environmental security is one of the priorities of countries' development towards achieving the goals of sustainable development (SDGs). The latter is the goal of the roadmap for the implementation of environmental policy both in the EU and in Ukraine, as a country that has set a course for European integration in terms of implementing programs aimed at national security and sustainable development of society. Green initiatives; green roadmap; adaptation to the effects of climate change in the framework of the European green dimension; green economy; energy efficiency, renewable energy; water resources management: water quality, wastewater treatment; protection of atmospheric air; environmental control and monitoring systems; industrial and household waste management, eco-friendly technologies, and others remain important and extremely relevant issues of directing the national strategy to the European green policy [1], [2], [3], [4].

The European Union considers environmental safety as an important component of European stability. Green policy is defined as a priority area of cooperation between Ukraine and the European Union. Integration of Ukraine into the EU in the field of environmental protection, adapting to climate changes, rational management of natural resources, and ensuring of environmental security should be achieved through the creation of a harmonized legal, regulatory, methodological, and organizational base that should meet the requirements of national and European environmental security. Environmental security in the context of climate change is one of the priorities of national and European policies to ensure the goals of sustainable development. It is important to note that Ukraine has a number of topical environmental issues of climate change and, at the same time, has an important role in ensuring environmental sustainability in Europe. Actual new challenges are in preparing environmentalists and students others educational programmes in the higher education system. Therefore, it is extremely important to improve the content of the training of environmentalists and students others educational programmes and to ensure specialists' knowledge [5], [6].

Enhancing the content of education has been recognized as a strategic priority and a fundamental direction in higher education reform. This commitment was emphasized in key international declarations, including the 2015 Yerevan Communiqué, the 2018 Paris Communiqué—where ensuring and improving the quality and relevance of learning and teaching was identified as a core mission of the Bologna Process—and reaffirmed in the 2020 Rome Communiqué. The latter reinforced these goals through the adoption of the Recommendations to National Authorities for the Enhancement of Higher Education Learning and Teaching in the EHEA.

In line with the priorities of the Rome Communiqué and the recommendations for national and governmental actions, Ukrainian higher education institutions must strengthen teaching and learning by adopting student-centered and competence-based approaches. These efforts should integrate innovation, structured dialogue with stakeholders, and empirical research findings.

Developing educational content remains a complex challenge. It encompasses a system of scientific knowledge, practical skills, and ideological, moral, and aesthetic values that students must acquire throughout the learning process.

Several objective factors shape the content of education, including:

- Advancements in science and technology, leading to new theoretical concepts and technological innovations. For example, the evolution of molecular biology, genetic engineering, and green chemistry has necessitated updates in the content of natural science education.
- The demands of modern society, which define the qualities and competencies required for the younger generation.
- State policy directions, which influence educational priorities and reforms.

The historical development of differentiation and integration in science has demonstrated that overcoming the limitations of a purely disciplinary approach is essential. The integrated or interdisciplinary approach serves as an alternative, facilitating the synthesis of knowledge across fields. Integration in science takes various forms, from applying concepts and methods of one discipline to another to the emergence of systemic methodologies in the 21th century. Today, systems thinking is particularly crucial, as it allows for a comprehensive understanding of objects and phenomena in their interconnectedness.

A key trend in contemporary scientific development is integration, which manifests through:

- Research conducted at the intersection of related disciplines.
- Development of universal scientific methods applicable across fields.
- Formulation of overarching theories, such as the Grand Unified Theory in physics or global evolutionary synthesis in biology and chemistry.
- Creation of methodologies like general systems theory, cybernetics, and synergetics, which serve multiple disciplines.
- Addressing complex challenges, such as climate change and environmental sustainability, that require interdisciplinary collaboration.

Ukraine's integration into the European Higher Education Area (EHEA) and its commitment to the Bologna Process necessitate the modernization of higher education content and a shift in educational philosophy. The culture of the 21st century is increasingly characterized by integration rather than specialization, requiring professionals who are innovation-driven and socially responsible. The philosophy of modern education emphasizes systemic pluralism, the dialogue of diverse perspectives, and the enrichment of knowledge through interdisciplinarity.

Higher education institutions must train a new generation of professionals who align with contemporary global challenges. Natural science education plays a crucial role in fostering sustainability and environmental awareness. Consequently, curricula should be restructured to incorporate interdisciplinary approaches, integrating sustainability issues within educational frameworks. Our research underscores the necessity of curriculum reorientation to reflect integrated knowledge structures. As a practical application, we have developed an interdisciplinary training course that demonstrates how natural science education, through an integrated didactic system, enhances understanding of sustainable development.

The purpose of research is the creation of an effective didactic system through the integrated approach of a natural education for example of «EUROPEAN GREEN DIMENSIONS» course with a special emphasis on professional orientation [12].

The object is the natural education content of the students' preparation process, namely, students' training of the environmental specialty.

The subject of the research is the content of the interdisciplinary course on «EUROPEAN GREEN DIMENSIONS» for students of environmental specialties of universities.

METHODS AND MATERIALS

Using partial scientific methods (component analysis of ecological knowledge, postoperative analysis of subject skills, etc.), general scientific methods (educational experiment, etc.), organizational, empirical, and methods of mathematical statistics determined the principles of selection of educational material, created the content of integrated training course, staging an educational experiment, summarized its results and analyzed the data [13].

To evaluate the completeness of students' knowledge and skills were defined by the ratio of the notions number of applied by students to the number of definitions that can be used. The tasks consisted of their reproductive level of educational material. The quantitative characteristic of the completeness of the knowledge factor was the acquisition coefficient of knowledge by students. The formula 1 used for this:

$$\overline{K} = \frac{\sum N_i}{n\sum N} \times 100\% \qquad (1)$$

where

n – the total number of students who performed work;

$\sum N$ – the number of correct answers in the test;

$\sum N_i$ – the number of correct answers of students.

RESULTS AND DISCUSSIONS

The course «European Green Dimensions» deepens teaching in European Union studies embodied in an official curriculum of a higher education institution and provides in-depth teaching on European Union environmental security matters for future professionals-ecologists in the green field which is in increasing demand on the labour market. The Jean Monnet Chair has a multidisciplinary character. The one includes knowledge of green initiatives; green roadmap; adaptation to the effects of climate change in the framework of the European green dimension; green economy; biodiversity conservation; energy efficiency, renewable energy; water resources management: water quality and wastewater treatment; protection of atmospheric air; environmental land management; environmental control and monitoring systems; industrial and household waste management and others.

The activities equip a wide spectrum of the stakeholders with European experience of this knowledge. Thus, it be introducing the introduction of the European Union practices into environmental policy and practices in the field of environmental security in Ukraine. The course promotes European research and study experience with regard to environmental management, instruments, eco-innovations, implementation of environmentally friendly technologies in the EU. The attractive and close collaboration with European colleagues through mutual participation in research and teaching activities will promote the transfer of first-hand experience and practical knowledge, and prepare local academics and young researchers for the independent management of future European studies. The course has a strong impact on students (bachelors, masters, Ph.D) in Ecology and Environmental Management at the Petro Mohyla Black Sea National University as one of the target groups through getting knowledge about actual green policy in the field of environmental security and best environmental protraction practices. The students and young researchers have a valuable learning experience to compare and evaluate national environmental practices with the EU experience and impacts of individual member states. The realization of the course in the practice of students study will promote future young professionals' understanding of the EU green principles and experience of environmental security and foster transforming the economy of Ukraine into EU and also provides teaching/lectures to students from other departments (e.g. economics, medicine, etc.) to better prepare them for their future professional life, conducts, monitors, and supervises research on EU subjects, also for other educational levels such as bachelors training; activities targeting policymakers at the local, regional and national level as well as civil society.

There are main target groups in the project: 1) Master's, Ph.D students and young researchers in environmental science, and other natural education programmes; 2) Bachelor's students in environmental science, and other natural education programmes; 3) teachers and researchers; 4) policy-makers, industry experts, representatives of NGOs; 5) pupils. Thus academic and non-academic learners are involved in the project.

This study is implemented by Programme EU Erasmus+ Jean Monnet Activities as part of the interdisciplinary European studies in Petro Mohyla Black Sea National University. The effective didactic system of interdisciplinary knowledge of natural-science courses was created.

Principles, meaningful lines of the integrated approach to students-environmentalists teaching are defined. The principles of selection and structuring of educational material for the preparation of students-environmentalists are defined and substantiated.

These are the principles: systematic (systemic factors are the goal of natural education in the context of the integrated approach, leading laws and theories, basic categorical concepts, principles of natural science, objects of study); interdisciplinary connections; fundamentalization; professional orientation of the education content; orientation of the content of training to the disclosure of environmental problems, such as climate change, sustainable development etc.

The integrated approach to education is a special type of designing its content that opens the system of interdisciplinary communications, and it also coordinates, unites and systematizes knowledge about the main natural-science theories, basic categories, and principles of the modern natural-science picture of the world.

Levels of the integrated approach implementation are internal disciplinary and interdisciplinary of knowledge and the highest level – methodological synthesis. Internal and interdisciplinary integration is being implemented through selection into the content of education the facts, concepts, laws, methods, theories according to specialization and humanization. Dialectic categories are set off at the level of methodological synthesis, for example, unit, system, structure, element, cause, consequence, content, form, causality, randomness, pattern, etc.

The course constructs on the interdisciplinary basis and covers key elements of the strategy for sustainable development and European experience in the field of the European green policy, environmental security, including the world's and EU's practices for sustainable development and the processes of environmental policy integration. The Chair will cover topical issues that contribute to a better understanding of the environmental, economic, social, technological, and institutional influencers of current and future global environmental security to achieve the goals of sustainable development. In addition, it is planned to develop and study questions about climate change, environmental pollution monitoring, the treatment technology, environmental quality, the limits of sustainability of the planet, zero carbon emission target, the integration of green politics into regional practices. Also, Chair will include issues in order to better understanding the European green deal the potential for social and economic instruments to drive conservation efforts (Table 1).

Learning outcomes:

- understand the difference between policies and tools of EU and Ukraine for environmental monitoring and management;

- explain goals and system of environmental management at national, regional/EU and global levels;

- understand and articulate key ecological challenges;

- articulate and understanding of the evolution of systems thinking, ecosystems thinking, the ecosystem approach and ecosystem services, and the implication of this for the continued evolution of integrated water and environmental management contexts;

- knowledge and understanding of EU green policy and its role in a globalized society;

- understand and use topical and correct terminology related to the environmental management in Ukrainian and English;

- ability to conduct analysis, synthesis, creative reflection, evaluation and systematization of various information sources in conducting research European green policy;

• make use of information sources pertaining to global instruments and multilateral environmental agreements (MEAs) as well as EU environmental policy;

• knowledge of the basic principles, types, methods and means of environmental monitoring and their ability to assess and predict the state of the objects of the environment;

• understand of the environmental management system and procedures for activities of enterprises in order to environmental security, its functions, tasks at the global and national levels;

• knowledge of the latest advanced green technologies and innovations;

• discuss the evolving green policy and tools, principally addressing EU and Ukraine practices of adapting to climate change, natural resources, biodiversity.

Table 1 - The main content of the course.

№	Topic	Main issues of the topic
1.	The green initiatives and green roadmap.	The green initiatives and green roadmap. The role of the EU in international environmental motions (e.g. Kyoto Protocol, UNESCO Roadmap for Implementing the Global Education for Sustainable Development, Sustainable Development Strategies, European Green Deal) [11], [15], [16].
2.	The strategies of EU environmental policy.	General characteristics of EU environmental policy; the United Nations Environment Programme; UN climate conferences and the EU position; United Nations Environment Programme (UNEP), UN Climate Change Conferences: Bali, Poznan, Copenhagen, Cancún Transatlantic relations and climate change / EU & US relations on environmental issues [13].
3.	Green circular economy	Basic principles of circular green economy. The history of the issue of resource efficiency of the economy. Decoupling as a condition for the transition to a circular economy. Circular economy action plan. Business models of the circular economy. Development of low-carbon economy [14].
4.	Natural resources, environmental quality and climate change.	A scientific view of our planet and its natural resources. Systems that determine the stability of Earth. The water cycle as a factor in the stability of the biosphere. Circulation of nutrients as a condition for the existence of the biosphere. Anthropogenic pollutants. Ozone layer. The limits of the stability of the planet. Tasks regarding zero carbon emissions.
5.	Atmospheric air protection.	Environmental problems of atmospheric air. Directive 2008/50/EC of the European Parliament and of the Council. European air quality index. Copernicus atmospheric monitoring service.

6.	Integrated water management: challenges for the 21st century.	Integrated water management: challenges for the 21st century. Water and development in Europe: environmental sustainability as precondition of European environmental policy and its best practices in water monitoring [17].
7.	Sustainable and environmental land management.	Land as a constituent element of a single productive force of nature. Scientific aspects of the land resources use. Paradigm of land use balanced development. State policy on the land use balanced development. Doctrine of balanced development "Ukraine-2030". Innovative forms of land management. Land use risk management. Land market [5].
8.	Biodiversity conservation.	Biodiversity as the main factor in the planet stability. Main Directives in the "Nature Protection" sector: Poultry and Housing. Network of protected areas NATURA 2000. Emerald Network. EU Biodiversity Strategy until 2030. European experience in the development of nature conservation areas. Nature Reserve Fund of Ukraine. The impact of war on the natural environment.
9.	Energy efficiency, renewable energy.	Energy efficiency and energy saving in the European Union. Directive 2009/28EC. Energy situation in Ukraine. Target energy efficiency programme for 2022−2026. National action plan on energy efficiency for the period until 2030. Concepts of "green" energy transition of Ukraine until 2050. Renewable energy sources.
10.	Industrial and household waste management.	National policy and strategic planning in the field waste management. Structure of waste generation and main problems in the field of waste management. Requirements for handling hazardous waste. Control system in the field of waste management. Law of Ukraine "On Improvement of Settlements". Status of waste storage facilities.
11.	The best latest advanced green, eco-friendly technologies.	The best latest advanced green, eco-friendly technologies and innovations for sustainable development. Green nanotechnology and green chemistry.
12.	Zero pollution for the purity of the environment.	Zero pollution for the purity of the environment. Concerted efforts towards achieving Zero pollution levels by minimizing, recycling/reusing of liquid effluents, gaseous emissions and hazardous solid wastes.
13.	Energy and resource efficient construction. Policy options to promote green buildings.	Evolution of approaches to nature management. Energy efficiency of construction objects. Environmental characteristics of building materials and products. Product life cycle. Building ecology. Objectives of green construction. Features of the development of construction services in the EU. Green bond market in the world.

14.	European best environmental practices: air, water, soil, waste management.	The main environmental problems of atmospheric air. "Greenhouse effect" of the atmosphere − the cause of climate change and methods of fixing greenhouse gases. Agriculture and methods of reducing greenhouse gas emissions. The main environmental problems of water resources. Sources of pollution of the World Ocean and inland waters. Wastewater treatment methods. World innovative practices of water preparation and rational use of water resources. Soil resources of the Earth and the main ecological problems of soils. Promising practices of soil protection. Current practices of processing and disposal of waste.
15.	Challenges for Ukraine in green policy, and practice due to association with the EU.	The path to climate neutrality of Ukraine: challenges for Ukraine. "Growth points" of Ukraine in the EEC. Basic principles for reliable and successful "green" reconstruction. Sectoral challenges and opportunities.

As far as the project impacts bachelor, master, and Ph.D students, young researchers, and teachers from PMBSNU, who automatically come into contact with European studies, as well as manager professionals and industry experts from all over Ukraine, and also pupils it is expected to have strong feedback from all participants/learners of the project during and after the teaching period. At the end of every teaching course, the final test has been. The final test has 40 questions, which mathematically accurately determine the coefficient of completeness of the student's knowledge, as the ratio of the number of correct answers to the total number of questions. The results of success will be considered satisfactory if the coefficient of completeness of knowledge is more than 60 percent. The results were quantitatively processed annually over a three-year experiment, and the average values were derived. The findings demonstrate that the chosen educational material was effectively mastered by the students, as indicated by an average knowledge completion coefficient of 0.87.

After the course, its participants were offered an anonymous questionnaire, which asked questions about the quality of the presentation (indicators, that will be used: relevance of the topic, completeness of the material, methods, and forms of presentation of educational/scientific information on a scale of 2 (unsatisfactory), 3 (satisfactory), 4 good), 5 (excellent), and there were open-ended questions about further recommendations and suggestions for improving the course.

The survey results show a high level of satisfaction among participants regarding various aspects of the course. The dominant purple bars indicate that most respondents rated the course with the highest score (5). Key aspects such as well-structured materials, clarity of explanations, relevance of information, engaging activities, and practical assignments received overwhelmingly positive feedback. The majority of learners found the course informative, well-organized, and beneficial for their knowledge and skills development. A small portion of respondents rated certain aspects with a score of 3 or 4, suggesting minor areas for improvement. These could relate to personal preferences, expectations, or individual learning styles. However, negative feedback (scores of 1 or 2) is nearly absent, showing that dissatisfaction was minimal. Notably, the aspects related to practical applications, real-world relevance, and accessibility of course materials were rated highly, reinforcing the course's effectiveness. This suggests that participants not only enjoyed the theoretical content but also found the practical components valuable. Overall, the survey reflects a successful learning experience, with the vast majority of participants feeling that the course met or exceeded their expectations. Minor refinements could enhance engagement further, but the general perception is highly positive (Fig. 1). The survey results show that the most influential factor in choosing this course was trust in the project team (70.5%). The uniqueness of the course topic was the second most important factor, influencing 62.3% of respondents. Recommendations from other participants played a role for 27.9% of respondents, while the lecturer's personality influenced 14.8%. Other factors, such as interest in the topic, its relevance, and the availability of certification, were chosen by only 1.6% of respondents each. This suggests that credibility and content originality were key motivators for enrollment.

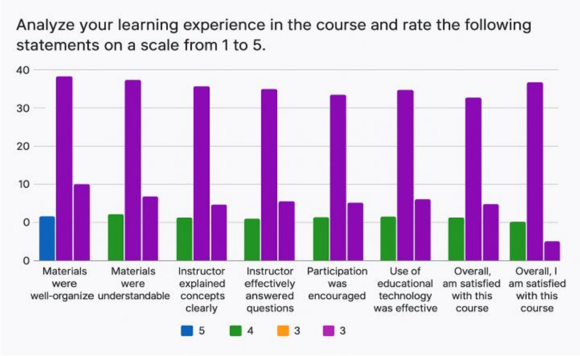

Fig. 1. Educational course «European green dimensions» evaluation.

The survey results indicate high satisfaction with various course elements. The majority of respondents rated all aspects with a 5, as represented by the dominant purple bars. The registration page, video lectures, visual design, email notifications, and chat participation all received overwhelmingly positive feedback, suggesting that these features met or exceeded expectations. A small percentage of participants gave ratings of 3 or 4, indicating that while the course elements were generally well-received, some minor improvements could be made. Ratings of 1 and 2 were minimal, showing that dissatisfaction was rare. The video lectures and chat participation were among the most highly rated aspects, highlighting their importance in the learning experience. Visual design and email notifications were also well-received, suggesting an effective and user-friendly course structure. Overall, the results reflect a well-organized and engaging course, with only slight room for refinement in specific areas based on individual preferences (Fig. 2).

In summary, the overwhelming majority of participants were satisfied with the course, with a small percentage expressing partial satisfaction. This suggests that the course was generally successful in meeting the expectations of those who took it. The most significant portion, 91.8%, indicates that the course "Fully met expectations," suggesting a high level of satisfaction among the respondents. A smaller fraction, 8.2%, reported that the course "Partially met expectations." Notably, no respondents indicated that the course "Did not meet expectations" at all.

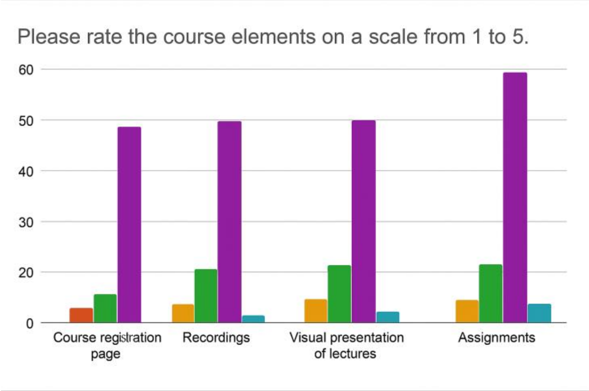

Fig. 2. Evaluation of the elements of the educational course «European green dimensions».

The responses to the question "What did you like most about the course?" highlight several key aspects that participants found valuable. The most prominent theme is the relevance and depth of the course content. Many respondents praised the topicality of the subjects covered and the thoroughness of their presentation. This suggests that the course effectively addressed current issues and provided comprehensive insights. Another significant point of appreciation was the accessibility and convenience of the learning materials. Participants favored the video lectures and well-structured course materials, which facilitated understanding and knowledge acquisition. The availability of recorded sessions on Facebook was also highly valued, allowing for flexible learning. Furthermore, the practical application of the course content was noted, with one participant mentioning its direct relevance to their teaching disciplines. The modern and up-to-date information provided on contemporary ecological problems was also a highlight, indicating that the course kept pace with current developments.

So, the course was well-received for its relevant and in-depth content, accessible materials, and practical applicability, catering to the diverse needs and interests of its participants.

CONCLUSIONS

The course is on the interdisciplinary base and cover key elements of strategy for sustainable development and European experience in the field of the green policy. The course includes such issues: green initiatives; green roadmap; adaptation to the effects of climate change in the framework of the European green dimension; green economy; biodiversity conservation; energy efficiency, renewable energy; water resources management: water quality, wastewater treatment; protection of atmospheric air; environmental control and monitoring systems; industrial and household waste management, green, eco-friendly technologies, etc.

The integrated approach itself extrapolates all modern processes of the development of scientific knowledge and is relevant in the formation of the content of natural education in solving issues of students' understanding of sustainable development. The prospect of further research activities is to improve the theory and practice of the integrated study of natural courses based on the developed conceptual provisions of the education content integration, and also to improve the methodology of assessing the quality of students' knowledge during the study of integrated courses.

As the interdisciplinary course focuses on integration of environmental policy requirements into other policy areas. Also, the course comprises the international dimension, with the role of the EU in international environmental motions (e.g. Kyoto Protocol, UNESCO Roadmap for Implementing the Global Action Programme on Education for Sustainable Development, Sustainable Development Strategies, European Green Deal) and so on and the impact of European policy on other regions of the world. The course is interdisciplinary and connects the policy and tools of environmental management, principally addressing EU and Ukraine practices of environmental quality, natural resources, biodiversity and their progressive integration. A didactic system of an integrated approach has been created, which has shown fairly high efficiency. This system covers the principles of selection of educational content, levels of implementation of the integrated approach. The course is interdisciplinary and connects the greening policy and tools, principally addressing EU and Ukraine practices.

The coefficient of completeness of knowledge was determined. It is proved that the selected educational material is quite fully assimilated by students, as evidenced by the average coefficient of 0.87. The course was well-received for its relevant and in-depth content, accessible materials, and practical applicability, catering to the diverse needs and interests of its participants.

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THE PROBLEM OF PRESERVING BIOTIC AND LANDSCAPE DIVERSITY IN UKRAINE DURING THE WAR

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ABSTRACT

The article examines the issue of preserving of conservation of biotic and landscape diversity in Ukraine in the context of war. The author analyzes the impact of military operations on protected areas, the eco-network and Emerald Network sites for each administrative region where military operations have taken place or are ongoing. Particular attention is paid to the condition of wetlands, which play a key role in maintaining the ecological balance. The threats caused by the destruction of natural ecosystems, environmental pollution and changes in landscape structure are highlighted. The consequences of military actions in natural areas are outlined. Measures to minimize the negative impact of war on natural complexes are discussed. Prospects for ecosystem restoration after the end of hostilities are outlined.

Keywords: protected areas, eco-network, emerald network, wetlands, biotic and landscape diversity.

INTRODUCTION

Biodiversity conservation is a key condition for the sustainability of the natural environment, as it ensures its ability to regenerate and adapt to environmental changes. The ongoing military operations in Ukraine for more than 11 years have resulted in significant environmental losses, including degradation of natural landscapes, destruction of habitats and a decrease in the number of species. The destruction of biotic and landscape diversity has cascading effects that threaten not only local ecosystems but also regional environmental security.

Russian's aggression is causing large-scale destruction of Ukraine's protected areas, which is a manifestation of ecocide. The occupiers are deliberately destroying forests and wetlands, as well as changing the hydrological regime of rivers, which can have irreversible consequences for biodiversity. These actions not only violate international environmental agreements, but also those responsible for environmental damage to justice necessitate holding.

The loss of natural areas makes it more difficult to maintain ecological balance and reduces nature's ability to self-regulate. In these circumstances, strategies for preserving the natural environment, rehabilitating the affected areas, and building a network of environmental protection facilities are of particular relevance. A comprehensive approach to solving this problem is necessary to ensure the country's environmental stability during the war and post-war periods.

The purpose of the study is to analyze the nature of the impact of military operations on different categories of protected areas in Ukraine and to identify key threats to them.

To achieve this goal, the following objectives were formulated:

– to analyze the results of research conducted in Ukraine on the impact of military operations on protected areas;

– to evaluate the extent and nature of the impact of military operations on the biotic and landscape diversity of protected areas;

– to identify the main risks and long-term consequences of degradation of natural areas as a result of military operations.

War is a challenge not only for people but also for the environment. The war imposed by Russia in Ukraine is destroying the objects of the National Nature Reserve Fund (NRF) and protected areas of international status of all types – elements of the Emerald Network, wetlands of international importance, IBA areas, UNESCO sites.

Recent scientific publications studies on the war's impact on Ukraine's protected areas highlight the significant environmental losses and challenges caused by the hostilities.

The consequences of the impact of active hostilities on the territories and objects of NRF in Ukraine have become relevant for scientists, public figures, journalists and representatives of the public administration system since 2014, from the beginning of the occupation of Donetsk and Luhansk regions and the Autonomous Republic of Crimea. Roman L.Y. [20], Shcherbatiuk T., Syvak R. [21], Kravchenko O., Vasyliuk O., Voitsikhovska A., Norenko K. were actively engaged in researching the state of especially valuable natural areas that were in the occupation zone or on the front line [2, 7]. Their joint work "Study of the Impact of Military Operations on the Environment in Eastern Ukraine" reveals all aspects of the war's impact on various components of the environment: soil, forests, and air. Special attention is paid to the protected areas of the region. The authors provide a detailed classification of mechanical damage caused by various types of weapons.

The members of the International Charitable Organization "Environment-Law-Human" pay a lot of attention to the study of the impact of hostilities on the environment in eastern Ukraine at the beginning of the Russian-Ukrainian war [11, 14]. They provide the main characteristics of the environment in Donetsk and Luhansk oblasts before the conflict and assess the damage caused to the environment during active hostilities. They investigated the factors of pollution and destruction of natural objects, in addition to analyzing international studies of environmental damage caused by military conflicts conducted by international organizations in post-conflict countries, and provide the main aspects of national and international legislation on environmental protection during the war [11]. This charitable organization also presented the results of research using Earth remote sensing (ERS) on the territory of the "Biloberezhzhia of Sviatoslav" National Natural Park (NNP), most of which has been under occupation since March 2022 [11].

The Ukrainian Helsinki Human Rights Union also presents a detailed analysis of various types of military impact on natural areas [12].

Udovenko I., Mamchur V., and Serzhantova Y. study the impact of military aggression on the nature reserves of Ukraine. They focus on the destruction of forests, pollution of water bodies and changes in animal migration routes, which leads to the loss of biodiversity and destruction of ecosystems [25].

Tsaryk L. P., Kuzyk I. R. conducted a detailed analysis of the protected areas affected by the war from 2014 to 2023 in the context of administrative regions. They presented calculations for the areas of the territories occupied by the enemy [24]. The impact of the current phase of the full-scale war on the protected areas of different regions of Ukraine is analyzed in the work of Parkhomenko V.V. and Vasyliuk O.V. [7]. They describe the state of the objects at the beginning of the Russian invasion.

The works devoted to the situation in certain administrative regions are of considerable interest. The research by Zalyubovska O., Zalyubovskyi M. and Sinna O. concerns the state of protected areas in the Kharkiv region during active hostilities. The authors found that a significant part of the protected areas was destroyed by shelling, fires and mining, which negatively affected the biological and landscape diversity of the region [28]. The situation regarding the state of the

NRF of Mykolaiv region is presented in the results of the research of Vasyluk O., Romanenko M., Skorobohatov V. [22], Patrusheva L. [18, 19]. Information about the Crimean NRF was provided to Radio Liberty by Veselova V. and Kravchenko H. [7]. They state the loss of 17 thousand hectares of the nature reserve fund, which are now being used for construction or military activities. The Russian military is using all possible resources, including Crimean nature reserves, to fight against Ukraine. Moisienko I., Khodosovtsev O. conducted a study of the consequences of the Kakhovka dam explosion on protected areas [12].

In the article "Protected Areas and War: Two Years of Humanitarian Aid" O. Vasyliuk examines the impact of war on protected areas and the role of volunteer support in preserving nature reserves and emphasizes the importance of humanitarian aid in ensuring the functioning of nature reserves in war. The researcher also notes that the large-scale invasion also affected protected areas in regions remote from the war zone, which became centers for humanitarian aid and places to receive displaced persons [27].

It will be possible to understand the scale of the environmental catastrophe that has engulfed the NRF of Ukraine only if a full comprehensive monitoring of the state of protected areas is carried out. Proposals and first results of such research are presented in the work of Spryahailo O., Bezsmertna O., Havryliuk M., Iliukha O., Osypenko V., Shevchyk V. [23]. The researchers proposed a mechanism for assessing the impact of hostilities on the state of nature reserves and their biodiversity. A comprehensive analysis of the consequences of the Ukrainian-Russian war on the state and functioning of the NRF of Ukraine, the identification of the main risk zones and the developed recommendations for restoration and ensuring their long-term stability can be found in the work of Udovenko I., Mamchur V., Serzhantova Y. [25].

Using ERS and GIS methods, recommendations for safe monitoring of the NRF state during the war and in the post-war period are proposed by Bondar O.I., Finina G.S., Shevchenko R.Y. [3, 29]; Zatserkovnyi V., Savkov P., Pampukha I., Vasetska K. developed a methodology for analyzing forest fires using remote methods [29]. The results of the analysis of Sentinel-2 satellite imagery on the territory of the "Biloberezhzhia of Sviatoslav" NNP (Fig. 1), most of which has been under occupation since March 2022, are presented in the work of the "Ecology-Law-Human" public organization. The methods developed by Kozlova A., Pestova I., Patrusheva L., Shvedeniuk M. will allow studying the state of biodiversity remotely [5, 6].

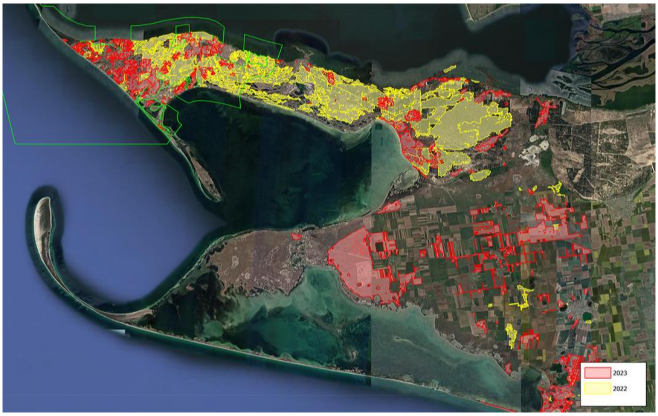

Fig. 1. Kinburn Spit of the burned forest in 2022 and 2023 [1].

METHODS AND EXPERIMENTAL PROCEDURES

We studied the spatial and temporal characteristics of the state of the NRF areas, the Emerald Network, Ramsar wetlands, IBA areas, and elements of the ecological network of Ukraine using the cartographic method. To analyze the situation with the location of the front line, its temporal dynamics, and the occupied and liberated territories, we chose maps from the Deep State Map

[4] resource, which provide informative, reliable, and objective representations of current situation with regard to active hostilities. Information on individual hits in areas remote from the frontline was obtained from maps and descriptions of the Liveuamap website. They allow us to assess the location of protected areas in the context of military impact and provide initial estimates of potential losses of ecosystem diversity. In addition, the spatial information is supplemented with detailed events coming in real time.

Additionally, the administrative-region-based map of Ukraine's NRF from the "Nature of Ukraine" portal was used to analyze the state of protected areas [16]. This map contains up-to-date spatial, quantitative, and descriptive information on the NRF areas of all categories. Its level of accuracy is sufficient to conduct a comprehensive assessment of the level of conservation of protected areas and their possible losses as a result of hostilities. To familiarize ourselves with the situation with the Emerald Network and Ramsar sites, we used the relevant thematic maps [10, 26].

Methodologically, the comparison of the maps of hostilities, NRF and the Emerald Network is correct, as they are based on the same mapping base – Open Street Map. This ensures the unity of scale, coordinate reference and geospatial accuracy, which allows for a correct analysis of the overlap of hostilities with protected areas. This approach helps to identify the regions that have experienced the greatest anthropogenic pressure as a result of military operations, as well as to predict potential risks to protected areas.

In addition to cartographic analysis, Sentinel-2 and Landsat satellite images were used for a comprehensive assessment of the state of natural areas, which allows us to determine the extent of changes in vegetation cover, hydrological regime, and the overall state of landscapes. This type of monitoring provides additional data on the impact of hostilities on ecosystems and allows us to assess potential recovery scenarios after the end of active hostilities.

Thus, the analysis of the spatial and temporal characteristics of the state of Ukraine's protected areas in the context of the war shows the need to constantly update mapping information, develop remote monitoring methods, and create a unified information platform for assessing damage and developing strategies for restoring the country's natural ecosystems.

THE RESEARCH RESULTS AND DISCUSSIONS

As of March 2025, as a result of the military actions of the Russian Federation against Ukraine, the environmental safety has been disrupted in about a third of the total area of all protected territories,, including: about 900 protected areas, which is more than 900 thousand hectares, or 21.9% of the total area of protected areas of Ukraine (of which 514–800 thousand hectares are occupied); almost 200 sites of the Emerald Network with an area of 2900 thousand hectares; 17 Ramsar wetlands covering approximately 500 thousand hectares, 2 biosphere reserves belonging to the UNESCO World Natural Heritage remain occupied [8, 13]. The war has directly affected the Autonomous Republic of Crimea, Donetsk, Luhansk, Kherson, Mykolaiv, Zaporizhzhia, Kharkiv, Sumy, Chernihiv, Kyiv and Odesa regions [17].

Depending on the nature of the hostilities and the speed of the occupation of the territory, the situation with regard to the state of protected areas varies greatly.

All protected areas of Crimea have been affected by the most prolonged impact. Since the annexation in February 2014, the peninsula has been actively used as a militarized zone for the deployment of further military operations, which has led to extreme anthropogenic pressure on natural areas (the Tavrida highway, the Crimean Bridge, etc.). The new government did not consider the issue of nature protection, conservation of landscape and biotic diversity. The region's ecosystems are gradually degrading under the influence of military infrastructure and exercises. The use of unique territories for military purposes indicates a disregard for environmental standards and may have long-term consequences for the peninsula's natural environment.

The current situation in the NRF on the territory of the temporarily occupied Crimean peninsula remains uncertain. The occupation has lasted for more than eleven years, and it is likely that ecosystems have undergone significant transformations during its stay in Russian realities. According to limited, remote monitoring studies based on information from specialists who remained in the occupation and the authors' retrospective knowledge of the issue, the area of forests in Crimea decreased by more than 10% between 2014 and 2021 alone, due to both illegal construction and tree felling.

In addition, a number of unique protected areas have been negatively impacted by uncontrolled exploitation. For example, the territory of the Opuk and Kazantip nature reserves is increasingly being used for military exercises, which causes destruction of steppe ecosystems and threatens populations of rare bird and animal species. On the territory of the Opuk Nature Reserve, which is home to dozens of species listed in the Red Book of Ukraine and international protection lists, cases of soil destruction and changes in landscape complexes due to the active movement of military equipment have been recorded.

On the territory of the Crimean Nature Reserve, huge areas, including the protected zone, on the southern coast of Crimea were withdrawn from state and municipal ownership for construction, 89.5 hectares of the protected area were excluded from the reserve. And on the basis of the Crimean Nature Reserve, the Crimean National Park was created, i.e., its status was downgraded. According to the project of functional zoning of the park's territory, it was planned to use approximately 40% of the national park's territory for economic and recreational activities, which actually meant the destruction of most of the protected area. The area of the national park's protected area will continue to be less than 50%. The situation is further aggravated by the fact that the protected area will exist as separate islands next to the economic and recreational zones [15].

The Cape Martian Nature Reserve was transformed into a nature park of regional significance. The downgrading of the reserve's status and the elimination of the protection zone around it, already in the first years of the occupation, allowed us to consider the possibility of implementing large-scale infrastructure projects around it [15].

The environmental situation is also deteriorating due to the use of coastal waters, particularly in the area of the Karadazh Nature Reserve and Cape Martyan, for naval maneuvers. This affects marine ecosystems and poses a threat to dolphin populations, which are increasingly dying in the Black Sea due to acoustic impact and pollution. If such processes continue, it could lead to the irreversible loss of the region's unique natural complexes [15].

In Luhansk and Donetsk regions, the war also began in March 2014. However, unlike in Crimea, where there were no military operations at the time, the protected areas began to feel the impact of the war from the very beginning.

During the period 2014-2022, 4 southern districts of Luhansk region (26.71% of the region's territory) were occupied; as of the beginning of 2025, the enemy occupied more than 95% of the region's territory. Accordingly, almost all protected areas are under occupation, and their condition may differ only in the duration and intensity of hostilities. One branch of the Luhansk Nature Reserve with an area of 587.5 hectares was occupied in 2014, and three others with a total area of 4815.5 hectares in 2022, and since that year the only national nature park in the region and the only regional landscape park with an area of 7269 and 14011 hectares, respectively, have been occupied. As of the beginning of 2025, the only botanical natural monument of local importance (118.56 hectares) remains outside the occupation, but in the area of active hostilities.

In 2014, 32% of Donetsk region was occupied, and today the territory occupied by the enemy has doubled and amounts to about 65%. At the beginning of 2014, there were 117 protected areas in the region (about 92 thousand hectares). Of these, 40 sites (23 thousand hectares) were in the occupied territory, some of which were damaged by hostilities. In particular, the Donetsk Ridge Regional Landscape Park was almost completely burnt down. The fighting took place on the territories of the Ukrainian steppe nature reserve branches "Kreidova Flora" and "Kalmiuske", as well as in the national parks "Sviati Hory" and "Meotida".

The situation worsened with the start of the full-scale invasion in 2022. As of October 2024, the following areas were reportedly damaged: the Chalk Flora branch of the Ukrainian Steppe Nature Reserve (16.0 hectares), the Holy Mountains National Nature Park (314.003 hectares), the Kramatorsk Regional Landscape Park (9.5 hectares), and the Slavic Resort Regional Landscape Park (0.034 hectares).

In general, during the period of Russian aggression, the nature reserve fund of Donetsk region suffered significant losses, but efforts to restore and expand it continue.

Since February 24, 2022, Kyiv, Sumy, Chernihiv, Kharkiv, Zaporizhzhia, Kherson, and Mykolaiv regions have experienced Russian occupation and active military operations on their territory. The worst situation is in the regions, some of which remain under occupation for more than 3 years.

Among these regions, Zaporizhzhia has been most affected by the war. About 72% of its territory has been occupied since the first days of Russia's full-scale aggression. Small areas north of the front line have been liberated, but active hostilities continue there. The situation with the most significant NRF sites of the region is presented in Table 1.

Table 1 − Current situation in the NRF of Zaporizhzhia region

Object category	The situation at the beginning of 2025					
	occupied		dismissed		affected	
	amount	area, ha	amount	area, ha	amount	area, ha
NNP	2	94882.9	–	–	–	–
Regional Landscape Park (RLP)	1	1025	–	–	–	–
Customers of national importance	11	31330	–	–	2	1783
Natural attractions of national importance	3	310	–	–	4	102

Two NNP and the only one RLP in the region remain on the lands occupied by the enemy.

As of March 2025, Russian troops control approximately 75% of the territory of the Kherson region. The Armed Forces of Ukraine liberated the right-bank part of the region, which is about 6,000 square kilometers. The nature reserve fund of the Kherson region has suffered significant losses. Out of 84 protected areas in the region, only 29 have been de-occupied, while 55 remain under temporary occupation and hostilities, covering about 354,180.6 hectares, which is 95% of the total protected area (Table 2). Among the largest and most famous occupied protected areas in Ukraine are UNESCO sites: Biosphere Reserves (BR) "Askania-Nova" and "Chornomorskyi".

Table 2 − Current situation in the NRF of Kherson region.

Object category	The situation at the beginning of 2025					
	occupied		dismissed		affected	
	amount	area, ha	amount	area, ha	amount	area, ha
BR	2	142562.4	–	–	–	–
NNP	4	154431.6	1	12261.1	–	–
Customers of national importance	5	32532	3	2075	–	–

A large number of protected areas in the Kherson region were affected by the explosion of the Kakhovka dam (Fig. 2). The sites located below the dam were washed away by the wave from the Kakhovka Reservoir. The sites located above the dam are gradually being transformed due to the falling in groundwater level.

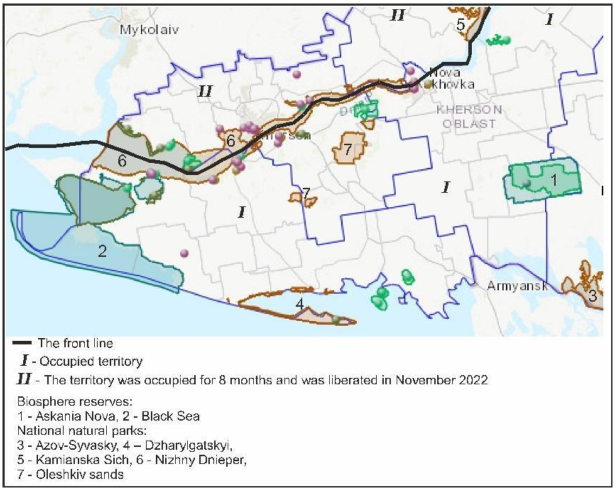

Fig. 2. Kherson region: NRF sites in the zone of impact of the Kakhovka dam explosion [9].

As a result of the enemy's full-scale offensive, 10% of the territory of Mykolaiv region was in the zone of active hostilities, and 3% remain under temporary occupation (Table 3). The Kinburn Peninsula, where the "Biloberezhzhia of Sviatoslav" National Natural Park and the Kinburn Spit are located, suffered the most. The shelling and fires destroyed large areas of natural ecosystems, resulting in the loss of unique biotic and landscape diversity. In particular, the habitats of 161 species of animals listed in the Red Data Book of Ukraine, which is more than 70% of all protected species in the region, are under threat.

Table 3 − Current situation in the NRF of Mykolaiv region

Object category	The situation at the beginning of 2025					
	occupied		dismissed		affected	
	amount	area, ha	amount	area, ha	amount	area, ha
BR	1	681	–	–	–	–
Nature Reserve (NR)	–	–	–	–	1	3010.7
NNP	1	35221.1	–	–	–	–
RLP	1	17890.2	–	–	1	2712.6
Customers of national importance	–	–	–	–	1	1782
Natural attractions of national importance	–	–	–	–	1	11
Zoo	–	–	–	–	1	18.5

The impact of the hostilities on nature conservation sites in Kyiv, Sumy, Kharkiv, Chernihiv, and Zhytomyr regions is less long-lasting but also very important.

Mostly, they were occupied for a short period of time, from several days to 1–2 months, but their location near the border with the aggressor may be the reason for frequent shelling

(Table 4). The exception is Dvorichanskyi NNP (3131.2 hectares), which still remains partially under occupation, and the rest of its territory is directly on the front line.

Table 4 − NRF sites that are not under occupation but have been affected by military operations.

Region	NR		NNP		RLP		Reserves		Natural attractions	
	amount	area, ha	amount	area, ha	amount	area, ha	amount	area, ha	amount	area, ha
Sumy	1	882	2	39575	–	–	10	17780	3	62.1
Kharkiv	–	–	2	19558	5	20756	2	853	–	–
Chernihiv	–	–	2	40701	3	85045	12	10421	7	297
Kyiv	–	–	2	21850	1	467	17	63276	2	92

In Odesa region, despite its remoteness from the hostilities, rockets or drones hit the territories of NRF sites. Explosions were observed on the territory of the Tuzly Estuaries NNP and the Dunaysky Nature Reserve.

The situation in the Black and Azov Seas is also extremely complicated. The Russian military has occupied a part of it and is causing significant damage by launching missiles and maneuvering warships from there. In addition, the enemy is mining the territory. Since sea mines can be pulled off the anchor and floating mines do not always self-destruct, they gradually move throughout the water area when they get into the sea currents. It is also worth noting the possibility of shipwrecks resulting in the release of oil products, fuels and lubricants, and various toxins into the water environment, which, accordingly, pose a potential danger to marine biodiversity not only in Ukraine but also along the entire Azov-Black Sea coast.

The researchers also recorded important changes in the marine ecosystem after the Russian occupation authorities built a bridge across the Kerch Strait despite the protests of Ukraine and the international community.

In total, 17 Ramsar sites with a total area of 474,089 hectares out of 50 located in Ukraine are occupied or on the front line (Table 5). This is 49.8% of the total area of such lands in the country. By administrative affiliation, they include all the Ramsar sites of the Autonomous Republic of Crimea, as well as Donetsk, Luhansk, Kherson and Zaporizhzhia regions. Due to military operations, these areas are experiencing significant environmental changes, which can lead to the degradation of unique wetland ecosystems.

Possible negative impacts on all of these coastal and marine wetlands include mining of the coastal zone, possible landmines from the sea, construction of fortifications, fires, and artillery strikes. In addition, the wetlands along the Dnipro River were catastrophically affected after the Kakhovka Dam was blown up, resulting in a dramatic change in the hydrological regime of the area.

Table 5 − List of occupied wetlands of Ukraine protected by the Ramsar Convention.

Ramsar site	**Area, ha**	**Administrative region**
Kryva Bay and Kryva Spit	1400	Donetsk region
Bilosarayska Bay and Bilosarayska Spit	2000	Donetsk region
Berdy River estuary area, Berdiansk Spit and Berdiansk Bay	1800	Zaporizhzhia region
Obytichna Spit and Obytichna Bay	2000	Zaporizhzhia region
Molochnyi Estuary	22400	Zaporizhzhia region

Eastern Syvash	165000	AR of Crimea, Kherson region
Aquatic and Rock Complex of Cape Kazantip	251	AR of Crimea
Aquatic and Coastal Complex of Cape Opuk	775	AR of Crimea
Aquatic and Rock Complex of Karadag	224	AR of Crimea
Karkinit and Dzharylgach Bays	87000	AR of Crimea, Kherson region
Central Syvash	80000	AR of Crimea, Kherson region
Tendrivska Bay	38000	Kherson region
Yahorlytska Bay	34000	Kherson and Mykolaiv regions
Dnipro Delta	27000	Kherson region
Seven Lighthouses Floodplain	2140	Zaporizhzhia region
Big and Small Kuchugury Archipelago	7740	Zaporizhzhia region
Velykyi Chapelskyi Sub	2359	Kherson region
Total	474089	

CONCLUSIONS

Clearly, any military action has a negative impact on biotic and landscape diversity. The nature of the impact may vary:

1. Direct physical destruction or damage as a result of a shell, missile, aircraft, or fire. As a result of the passage of heavy military equipment also. Such impacts can affect both individual organisms and their groups and landscape complexes as a whole.

2. Damage and disturbance by blast waves, which may result in full or partial damage to vegetation, destruction of bird nests, etc.

3. Contamination of the territory and water areas with the remains of destroyed military equipment, fuel and lubricants, air pollution due to fires at infrastructure facilities and in natural ecosystems, explosions of ammunition, mineral fertilizer warehouses, and accumulation of building destruction products.

4. Forced migration and death of animals due to noise impact, which is extremely dangerous for animals, especially in the spring and summer, during breeding; that is, there are sensitive species that stop nesting and their place is taken by alien species that are typical of disturbed ecosystems (for example, storks). Among mammals, the jackal is becoming more widespread, especially since there are many favorable conditions for it (overgrowth of former pastures and meadows, frequent deaths of wild animals and people). Animals can also change their traditional habitats as a result of the destruction of their food supply.

5. Changes in microrelief by fortifications and the passage of heavy machinery. These actions can accelerate the process of water erosion or deflation.

6. Possible changes in micro and meso climate as a result of the draining of the Kakhovka reservoir and the construction of the Kerch bridge.

7. Disruption of the hydrological regime due to the destruction of dams, dikes, and reservoirs. Changes in the depth of groundwater and underground water, as well as water levels in rivers and lakes. Pollution of water resources due to the ingress of oil products and heavy metals.

8. Mined areas and their long-term danger. The presence of explosive devices in forests, fields, and water bodies. Inability to restore landscape complexes due to the risk of mining.

9. Increased poaching and illegal use of resources. Loss of control over territories contributes to illegal deforestation. Increased hunting of rare animal species due to reduced control.

10. Destruction of the infrastructure of protected areas. Destruction of administrative buildings of nature reserves and national parks. Loss of material and technical base for scientific research and protection of NRF.

11. Disruption of scientific research and monitoring. Loss of data due to the destruction of scientific centers. Inability to conduct long-term observations of the state of biotic and landscape diversity.

12. Psychological and socio-economic impact due to the loss of jobs in the field of environmental protection. Reduction of tourism, which affects the funding of nature reserves.

The longer the war lasts, the more damage it will cause to the environment, and the more consequences we will have in the future.

The consequences of the hostilities are comprehensive and unpredictable. We will be able to assess the extent of the damage only after the front line is pulled back and active hostilities on the territory of Ukraine end. Primary research can be carried out using remote methods of aerial photography and satellite imagery. Direct field surveys can only take place after the territories are demined. A full understanding of losses among the animal population will come in a few years as a result of systematic monitoring observations.

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AN EFFECTIVE MODEL OF MUNICIPAL SOLID WASTE MANAGEMENT AS A PART OF UKRAINE’S NATIONAL CLIMATE POLICY

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ABSTRACT

The article considers the approach to the development of an effective system of solid waste management in the regions of Ukraine. To achieve the objectives of the National Strategy and the transition to a new model of municipal solid waste management, the author's Concept for the management of municipal solid waste suggested the feature of the separation of easily decomposing organic waste at the beginning of the MSW life cycle. This stream will reach the complex recovery, combining two successive stages – anaerobic digestion and aerobic composting. The National multicomponent model, mass balances are used methods of research. The paper presents an assessment of the resource potential of the solid waste stream, subject to the introduction of the Concept in the conditions of Odessa and Vinnitsa regions of Ukraine. The estimated income obtained from the sale of energy derived from biogas at the green tariff, as well as from the sale of the main types of secondary raw materials, is calculated. As an environmental result, a decrease in greenhouse gas emissions from landfills and solid waste landfills in Odessa and Vinnitsa regions is presented.

Keywords: municipal solid waste, recovery, concept, greenhouse gases, landfill and dumps, easily-decomposed organic waste.

INTRODUCTION

Today, climate change is one of the world's major environmental challenges, prompting the global and European community to develop measures to solve it. Today, the European climate goal is achieving carbon neutrality by 2050, should fundamentally change EU policy, economy, international relations and lives of Europeans. The European Green Deal (2019) is a response to these challenges.

One of the components of a comprehensive approach to limiting climate impacts is to solve the problem of municipal solid waste (MSW). The amount of waste generation is growing every year, due to population growing and social-economic development. But the main approach to settling the MSW problem is disposing on landfills and dumps. As of 2020, 68% of the world's waste was disposed, 38% of which was uncontrolled dumping [1]. In some EU countries more than 60% of MSW is still disposed. As of 2023, 89.65% of municipal waste was disposed in Ukraine [2]. All this exacerbates the problem of climate change due to greenhouse gases (GHG) emissions from the Waste sector. It is known that anaerobic fermentation of biodegradable waste at waste disposal sites leads to the production of landfill gas as a mix of the main GHG – methane and carbon dioxide. According to the latest data, the Waste sector emits up to 3.3% of GHG and 20% of methane by the world. According to the National Inventory Report [3], the Waste sector in Ukraine accounted for 6% of total GHG emissions in 2022. All this makes it relevant to develop effective models of MSW management. On the one hand, it contributes to solving the problem of waste and related environmental effects. On the other hand, it reduces the emission of GHG and the impact on the climate system.

According to the data of The Ministry for Communities, Territories and Infrastructure Development of Ukraine (Ministry of Infrastructure), over 44 million m^3 of MSW, or more than 9 million tones, was generated in Ukrainian settlements in 2023, 89.5% of which is landfilled in 6107 dumps and landfills with a total area of more than 9172 hectares. Today, the total mass of disposed MSW exceeds 235 million tones. In addition, 26610 illegal dumps with a total area of 746.9 hectares were detected during 2023 [2].

Solid waste disposal accounts for 61% of total GHG emissions in the Waste sector in Ukraine. Despite the general downward trend in GHG emissions from the Waste sector during 1990-2022, GHG emissions from waste disposal increased by 16.5%. This and much more facts make it important to develop effective models of MSW management. The objective of this study is to present an optimal approach to solving the MSW problem, in particular, its main waste stream – biodegradable waste. Today it is the main part of the total MSW mass in Ukraine. In spite of the available resource potential, these wastes are practically not used today, but disposed into landfills and dumps, causing secondary effects in the environment.

The crisis situation in the MSW management in Ukraine can be characterized as follows [4, 5]:

- although a separate collection was implemented in 1440 localities of Ukraine in 2022, 8.24% of municipal waste was sent to collection points for recyclable materials and waste processing lines;
- prevails the MSW collection without separation into components, and collection of recyclable materials is carried out through reception facilities, which is often not connected with the general system of MSW management, if it exists;
- there has also been a gradual increase of MSW rates of formation influenced by socio-economic development and consumption changes (during 1920-2017 MSW formation indexes had increased up 4 times by volume and 1.6 times by mass as for example);
- there is a lack of information on the quantitative and qualitative characteristics of the MSW stream; information on the impact of waste disposal places on the environment;
- the main factor in choosing the MSW disposal methodology is the value: the cheapest way is disposal into dumps, especially illegal;
- the existing MSW landfills came to life from the 80s-90s of the 20th century and were designed for 15-20 years of operation. This means that such landfills should be closed and rehabilitated now; however, they continue to work in conditions of strong leverage of capacity (overload) and due to the lack of alternative disposal sites and MSW disposal methodology;
- the growing contradictions in the "environment-waste" system and the crisis in solving the waste problem are particularly characteristic of urban agglomerations, but they should be the first to switch to an alternative model of the MSW management system.

Currently, the effective management of MSW is hampered by the lack of legal and regulatory framework, infrastructure and financial assistance and war conditions. However, Ukraine is currently facing challenges in the field of waste management, and the need to switch to a new management model is constantly growing.

METHODS AND EXPERIMENTAL PROCEDURES

The National multicomponent model, based on the first order decay method of third detalization level (the National Model) [3] were used by us to estimate GHG emission from waste disposal sites (WDS). Some parameters of National Model has been determinated for the Odessa and Vinnitsa regional conditions in our earlier researchers (for example, [7]).

We performed some calculations using the example of Odessa and Vinnitsa regions.

One of the largest regions of Ukraine is Odessa region. About 3.4 million m^3 of MSW is generated in the Odessa region per year; it is 8% from the total volume of MSW in Ukraine.

Almost all MSW mass is disposed into landfills and dumps. In 2023 the total amount of them comprises 628 and the total area – 1,040.32 hectares [2]. “Dalnitskyi Carrier” – is the largest landfill in the Odessa region, the total area of which comprises 96 hectares. It has been accepting waste from the Odessa metropolitan area since 1968 and is in the “top seven” hazardous landfills of Ukraine. In 2021, a landfill gas collection and recovery system began operating in “Dalnitskyi Carrier”.

According to official data, there was no MSW separate collection in Odessa region [2], but in fact there are some MSW separate collection private initiatives in Odessa – “Vtorma”, “Misto maibutniogo”. We don’t have data on the volumes of recyclables selected, but we assume that it is insignificant at the city level and especially at the region level. In parallel of the initiatives for the MSW separate collection there is a system of recycling points in the region. But there is no data concerning the volumes of accepted recyclables types, and it is typical situation for all regions of Ukraine.

As for Vinnitsa region, in 2021 1.6 million m^3 of MSW was generated (or 3.8% from the total MSW volume in Ukraine). 11,740 tones of MSW passed through secondary raw materials collection centers, 94% of them are separated as secondary raw materials. The rest part of MSW was disposed into 741 landfills and dumps, the total area of which comprises 731.9 hectares [2]. “Stadnitskyi” landfill has been functioning since 1984, where about 600 thousand m^3 of MSW are exported from Vinnitsa per year.

THE RESEARCH RESULTS AND DISCUSSIONS

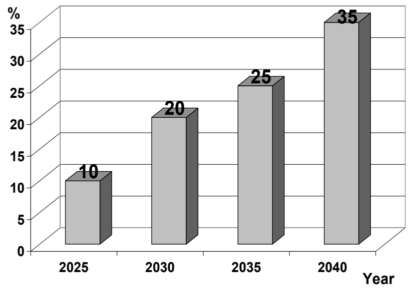
Analyzing changes in the regulatory and legal framework in the waste sector. Ukraine is on the way to significant changes in waste legislation and MSW management in particular. The first was an amendment to The Law of Ukraine on Waste according to which disposal of untreated MSW was forbidden from 1 January, 2018, which complies with the requirements of Directives 1999/31/EU and 2008/98/EU. But in the absence of a mechanism for practical implementation, this requirement of the Law is not brought into effect in real life.

As it was noted earlier, Ukraine has started a new way in MSW management since 2017 when the National Strategy of Waste Management in Ukraine by 2030 was adopted [8]. This document is based on the Waste Hierarchy, transition to a circular economy, risk management, extended manufacturer responsibility, and the implementation of the "polluter pays" principle. So, the National Strategy (2017) was developed in accordance with Directive 2008/98/EC. All of them formed a fundamentally new base for MSW management at regional level. The next step was the development of the framework law "On Waste Management", which underwent public discussion at the end of 2018 and was adopted by the Verkhovna Rada of Ukraine on June 20, 2022 [9]. Table 1 shows some differences between “previous” and “new” approach to MSW management system development at regional level.

Table 1 − Some principles of MSW management strategy at regional level (composed by the authors on the basis of Regional MSW management Programs by 2017, The Regional waste management Plan in Odessa region; The National Strategy, 2017 etc.).

Previous (by 2017)	New (since 2017)
number of landfill and dumps increasing environmental control straightening; technical re-equipment of garbage trucks; increasing the coverage of waste collection and transportation services; separate collection; liquidation of wild dumpsites; waste disposal sites accounting and certification	based on The Waste Hierarchy realization of polluter pays principle and extended producer responsibility existing landfills and dumps closure and organization of modern highly-equipped regional landfills based on intermunicipal cooperation specialized municipal waste collection points organization for collection hazardous, biodegradable, WEEE, packaging waste etc.

This Law "On Waste Management" sets target indicators for the reuse and recycling of municipal solid waste (Figure 1, a). The target indicators of the National Strategy (2017) are presented in Figure 1, b [6]. . The successful implementation of MSW management goals can lead to significant achievements in the realm of sustainable development, particularly in the Sustainable Development Goals (SDGs) 11 - "Sustainable Cities and Communities," 12 - "Responsible Consumption and Production," and 13 - "Climate Action."



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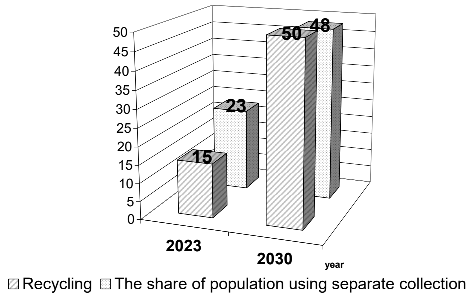

b

Fig. 1. The goals of MSW recycling by Waste Management Law (2022) (a) and indicators of recycling by National Strategy (2017) (b).

In 2021, Ukraine adopted the Law "On Restricting the Circulation of Plastic Bags on the Territory of Ukraine" aiming to prevent environmental pollution caused by plastic bags. With some exceptions, the use of ultra-lightweight, lightweight, and oxo-degradable plastic bags is prohibited in the retail sector. Also, in 2023, a draft law "On Packaging and Packaging Waste" was developed, which establishes the principle of Extended Producer Responsibility (EPR), aimed at solving the problem of packaging waste. There are drafted projects of law "On Batteries, Cells, and Accumulators" and "On Electronic and Electrical Waste" in the queue.

It is also been noted, that new legislative initiatives and projects are put forward for public discussion, and also undergo the procedure of strategic environmental assessment (Law of Ukraine "On Strategic Environmental Assessment").

In 2020, Ukraine supported the European Green Deal, which aims to achieve climate neutrality by 2050, and set a national goal of climate neutrality by 2060. The Strategy for Environmental Security and Adaptation to Climate Change until 2030 (2021) and the Law of Ukraine 'On the Basic Principles of State Climate Policy' (2024) contain tasks for efficient waste management to reduce the impact on the climate system. These and other regulatory documents state that the main way to achieve climate goals in the context of MSW is to reduce its volume and implement a circular economy.

As we can see, there is a new point of view on MSW problem solution. The new model of MSW management in Ukraine is based on modern European principles and experience. And, of course, it requires new approaches for this new model implementation.

The European experience concerning the 'waste problem' solution exhibit abundant examples of organization for municipal waste collection with the purpose of further recycling. Yet there persist some obstacles for implementation of the European waste management system and, especially, organization of MSW collection in Ukraine among which the following should particularly be mentioned: 1) waste disposal costs less than organization of waste collection (the average tariff for MSW treatment in Ukraine is 4.24€ per m^3, including 1.31 € per m^3 for the disposal [2]; 2) lack of a clear legislative framework for effective MSW management; 3) low financing of MSW management, even if the principle of full cost recovery is implemented; 4) public opinion due to lack of educational work and distrust to the waste collection organizations. Many people do not want to participate in the separate waste collection, especially if there are a lot of containers for individual components of waste.

The concept of creating an effective MSW management system. As an alternative to the existing models of waste management at the regional and local level, we propose an approach to the development of a waste management system based on The Municipal Solid Waste Treatment Concept (the Concept) which has been developed at Odessa State Environmental University [10, 11].

In accordance with the MSW Concept the overall stream of MSW in a place where they are generated is separated into the following streams:

1) easily-decomposed organic material ("wet steam");

2) potentially recyclable material resources + inert mineral bulk waste;

3) hazardous waste.

The essential condition of the Concept realization is MSW stream differentiation at the beginning of its "life cycle".

Separation of MSW into streams is implemented in the following way. People separate the easily-decomposed organic wastes at the moment of generation making use of specially designed storage containers, and the rest of MSW components is collected into separate container (or different containers) and sent then to a waste sorting plant for sorting and further recycling and recovery. So, at the beginning of an MSW 'life cycle' easily-decomposed organic material is to be separated. This stream consists of food and park & garden waste (green waste). Minimization of this stream generation is achievable by means of household grinders which could be installed in homes, small hotels, restaurants etc. at the owners' discretion and be made binding in the case of large hotels, elite houses etc. Another way to separate and collect easily-decomposed organic material is through provision of special containers for its collection. For private households' recovery of this type of waste may take place in the same territory through aerobic composting or vermicomposting. Incidentally, it actually takes place in some small private households in the rural areas.

It is also necessary to organize collection and transportation of another type of easily-decomposed waste which is leaf litter. This should be responsibility of a special municipal economy department. And if it is difficult to separate them from the rest of the waste generated in the residential sector in the case of food waste, park and garden waste is already separated from the total mass of MSW at the time of its formation. But according to the current treatment practice, they are involved in the overall stream of MSW, which then goes to disposal sites. According to experts' opinion, the best way to manage green waste is to compost it.

The separation of easily-decomposed waste components at the stage of generation makes it possible to obtain "pure" resource for compost production. Moreover, elimination of this stream at the first set-out provides obtaining of other components in an uncontaminated form. It is very important because the recovery technologies for some kinds of waste (e.g. waste paper) yield appreciable results only in case of use of pure materials.

The stream of inert mineral bulk waste, having been created during construction and repair works, is separated at the beginning of MSW "life cycle". This type of waste may be used in road building and repair and, as an inert layer, in landfills. The management principle for this stream is financial incentive for the entities generating this type of waste and waste collectors.

The stream of potentially recyclable material resources is distributed by components, and is then sent to special organizations for recycling and recovery. For example, old furniture and household appliances are taken apart with the subsequent recovery of some components; such waste components as package, waste paper, metals, glass, rags etc. can be collected into specially designed containers with due account of recoverability of the components, which may vary depending on a place. Or it may be one container for mixed "dry" waste that is further sent for waste sorting [10-12].

In fact, among the wide diversity of waste components that can be considered as potentially recyclable material recourses, only paper and cardboard, plastic bottles, metals, tyres and glass bottles is recycled and recovered in Ukraine. The stream of hazardous waste shall be separated through organization of targeted collection of different waste types. Old batteries shall be returned to a service station, cells – to special collector departments in supermarkets, expired medicine – to pharmacies and so on.

Dissemination of information on various types of hazardous waste is very important. People must prevent the uncontrolled hazardous waste emission into the environment and its mixing up with other MSW components. However, at the first stage of the Concept implementation the hazardous waste may be extracted from the stream of potentially recyclable material resources at a waste sorting station. In this case they cannot contaminate easily-decomposed organic waste as a material for compost production.

The separation of waste stream according to the MSW Concept may be implemented in public offices and at enterprises with the use of facilities to control sorting processes. For example, grain and wood wastes may be co-recycled with easily-decomposed organic material of MSW. The same way is applicable in case of food industry waste, as well as for packaging and administrative wastes. Nowadays, private initiatives for separate collection of waste in offices are being developed in Ukraine. In 2018 the project "Compolla" began: 200 Ukrainian schools received composters for food waste recovery. During the year of the project, more than 52 tons of food waste was composted and about 26 tons of compost was received.

The city of Lviv became the first Ukrainian city, where in 2020 the first system of centralized collection and recovery of organic waste was started. It includes an organic waste collection system from the population and individual enterprises and further processing it into compost at the city's composting station. For example, in April 2022, the station received 462.7 tons of organic waste, 2/3 of which was park and park waste [12]. Today, it is the only city with food waste separate collection.

Some communities in Ukraine also have initiatives for public composting, sites for shredding branches, but systemic solutions are still lacking. There is some experience of composting in small communities with the development of a roadmap for the implementation of a bio-waste management system [13].

Easily-decomposed organic waste recovery. For the stream of easily-decomposed organic waste, the technique of organic waste complex recovery was developed by Safranov and others in Odessa state environmental university [14]. Industrial easily-decomposed organic waste, agricultural waste and sludge generated in aerobic treatment of wastewater at treatment plants (but only in the condition of its environmental safety) may be considered as an additional source of organic waste.

The technique scheme of organic waste complex recovery is presented at fig. 2. Easily-decomposed organic waste is exposed to the downstream bioconversion: anaerobic digestion with getting of biogas and digestate, which may be exposed to aerobic composting.

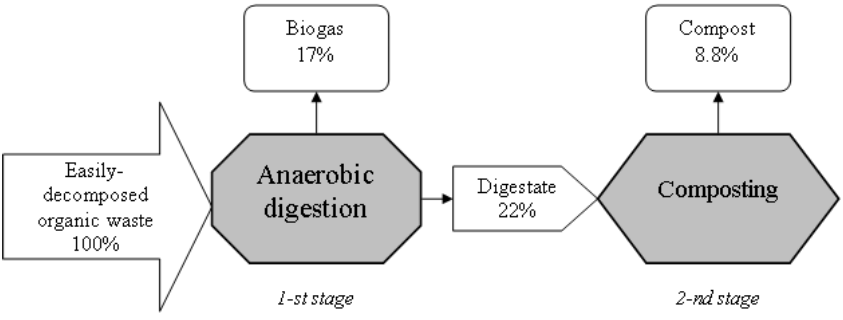

Fig. 2. The organic waste complex recovery scheme.

At the first stage we receive two useful products: digestate (organomineral fertilizer) and biogas. Under condition of lacking demand for digestate, it is exposed to the second stage of complex recovery – aerobic composting. As a result of this process the mass of digestate has been reduced. We can receive a one useful product – compost realizing the 2nd stage.

Easily-decomosed organic waste is the main part of MSW (above 45-50%) [12]. Approach to separation of easily-decomposed organic waste at the beginning of the "life cycle" and their further recovery, will allow to develop an effective MSW management system and decrease the environmental pollution from WDS.

As it was shown in our earlier research, the complex recovery, unlike waste disposal, significantly reduces the time of organic waste decomposition and allows us to receive useful products: biogas, to which 35% of carbon passes, and digestate (fertilizer), 65% of carbon is concentrated in. Using of these products will allow returning carbon from the waste to the environment and including it in the natural cycle [16]. During the realization of the 2nd stage of the complex recovery, 65% of carbon transfers from digestate to compost, and 35% goes to the atmosphere with CO_2. Realization the 1st stage only allows us to obtain GHG "zero emission".

MSW resource value estimation. Some components of MSW are considered as resource-valuable depending on the treatment capabilities. By the traditional approach, paper and cardboard, glass, metal, polymers and textiles are considered as resource-valuable components. Extraction of these separate collected fractions is possible in the existing separate collection system and subsequent treatment of recycled materials. However, even the most successful projects can collect only about 20% of packaging waste or about 4% of MSW. Therefore, ukrainian recycling plants have a significant shortage and are forced to import recyclables. As an example, the production capacity of our glass factories can process 800,000 tons, but 350,000 tons are used in fact, 20,000 tons of which are imported. Ukraine imports about 340,000 tons of paper waste per year, while its own is sent to landfills and dumps [17]. We have identified the main groups of waste materials - packaging waste, food and garden waste, recyclable materials with the existing supply chain "source of formation - processing production" (Table 2).

Table 2 − Potentially recyclable material resources and recycling opportunities in Ukraine [6].

Food waste	Paper and cardboard	Polymers (plastics)	Glass	Garden waste	Textile	Metal	Total
Average content in total MSW mass, %							
36,1	14.3	5.8	6.2	9.8	3.4	2.3	77.9
Separation option from general MSW flow							
TC WMA	RC TC CP	RC TC P&R CP	RC TC P&R CP	TC WMA	TC	RC TC CP	

Note: RC - retail chains; TC - targeted collection; P&R - procurers and recyclers; CP - Collection points for recyclable materials ("grey" sector); WMA (collection and disposal) - administrator of waste management service.

An alternative approach based on the Concept implementation allows using easily-decomposed waste – the largest part of MSW that accounts more than 45% of the MSW mass. The efficiency of recyclable material separation from the total "dry" stream is also increased – up to 80%. Therefore, we have developed the Concept based on "zero waste" principle. Only in case of total MSW stream separation at the beginning of the waste "life cycle" it is possible to use resource potential of MSW components in full. But due to the lack of waste recycling and recovery facilities we couldn't involve to 3R some MSW components at the beginning stage of the Concept implementation.

We can estimate MSW resource value potential based on waste composition and existing waste facilities for Odessa and Vinnitsa regions in 2021 (table 3). Table 4 shows some information about expected extraction rates and prices for recyclables.

Table 3 − Resource value of MSW (in case of the Concept implementation).

MSW stream	MSW component	Odessa region		Vinnitsa region	
		%	tones	%	tones
easily-decomposed organic waste	food waste	35	322700	42.4	200234.4
	park and garden waste	10	92200	6.6	31168.6
potentially recyclable material resources	paper and cardboard	15	138300	6.3	29751.8
	plastic (PET)	3	27660	3	14167.5
	glass	6	55320	5	23612.6
	metal	2	18440	3	14167.5

To assess the benefits of the Concept implementation, we have made an approximate calculation of the income from sale of the electricity produced from biogas obtained by anaerobic disgestion (see fig. 2), as well as the income from sale of fertilizers and some types of recyclables demanded in Ukraine. The Concept implementation will help to reduce the MSW impact on an environment, by reducing GHG emissions from WDS in particular.

Input conditions of calculation:

1) acceptance of 100% separation of food and garden waste at the time of waste generation, which will allow us to obtain rather high extraction rates for the main types of recyclables on waste sorting lines (Table 4);

2) technological loss of biogas about 5% was taken into account;

3) income from the sale of recyclables was calculated using minimum prices;

4) the baseline scenario for GHG emissions estimating is the existing situation when the all MSW mass is disposed into landfills and dumps, and the alternative scenario is the disposal of non-utilizable part (at the first stage of the Concept implementation) of the biodegradable waste in landfills and dumps.

5) we have calculated GHG emission from WDS for MSW mass generated per year and for the first year after disposal;

6) we take into account the condition of biogas collection existing at the Stadnitskyi landfill. We assume that the collection system covers 80% of the landfill area and the efficiency of biogas collection by a separate well is 75%. Thus, the biogas collection system at the Stadnitskyi landfill makes it possible to isolate 60% of the generated methane.

Table 4 - Information about extraction rate, treatment and prices of products).

MSW stream	MSW component	Extraction rate, %	Treatment options	Price*, €	
Easily-decomposed organic waste	food waste	100	the complex recovery (see fig. 1)	biogas energy** 0.05 €/kWh	organomineral fertilizer 18.85 €/ton
	park and garden waste	100			
Potentially recyclable material resources	paper and cardboard	15			
		85	recycling	113 €/ton	
	plastic (PET only)	80		120-171 €/ton	
	glass	80		17 €/ton for mix	34 €/ton for sorted by colors
	metal	100		154 €/ton for black metals	925 €/ton for aluminum cans

* Actual prices for recyclables (http://recyclers.com.ua/ua/pricing)

** Landfill gas in Ukraine (https://ubr.ua/market/industrial/bogaz-v-ukran-rozrahovumo-zelenii-tarif-dlia-energ-z-bogazu-174468)

Fig. 3, 4 shows some benefits from the Concept implementation at regional level.

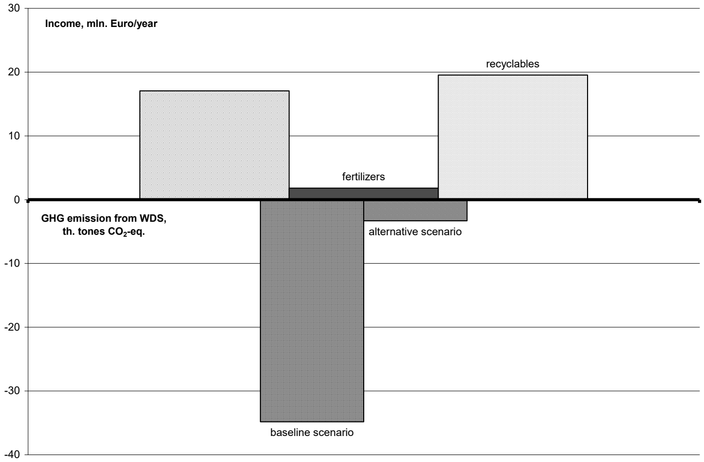

Fig. 3. Economic and environmental results of the Concept implementation in Odessa region.

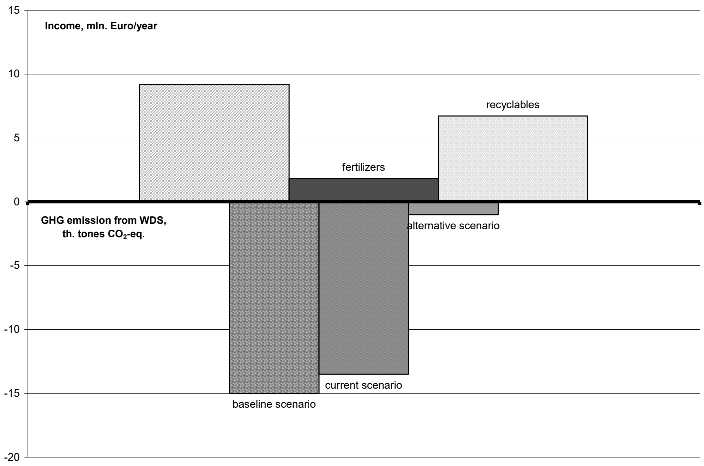

Fig. 4. Economic and environmental results of the Concept implementation in Vinnitsa region.

As we can see from fig. 3, realization of the Concept at Odessa regional level allows to receive the income in 38 million of euro. In additional, we have GHG emission reducing at the rate of 31.51 thousand tones CO_2-eq. due to involve biodegradable waste in the complex recovery by scheme (see fig. 2). Realization of the Concept at Vinnitsa regional level allows to receive the income in 16 million of euro (fig. 4). In additional, we have GHG emission reducing at the rate of 12.48 thousand tones CO_2-eq. due to involve biodegradable waste in the complex recovery. It is shown that even the presence of a biogas collection system at the Stadnitskyi landfill does not significantly reduce GHG emissions. Although the obtained estimates are rather conditional due to the assumed high levels of waste separate collection and further recycling and recovery, nevertheless, there is a definite economic effect. It is also necessary for the achievement of the objectives of the National Strategy (2017) and the Waste Management Law (2022) (fig.1).

CONCLUSION

As we noted, significant reforms are ongoing in the regulatory and legislative field of municipal solid waste management in Ukraine. This lays the foundation for the implementation an effective model of MSW management, based on the involvement of biodegradable waste in the system of its recovery. The application of the Concept at the regional level will produce raw materials for mechanical-biological treatment and potentially recyclable material resources unpolluted by easily-decomposed waste stream for recycling on waste sorting lines. Thus, this approach is consistent with the developed regional programs and will provide raw materials for regional complexes for the MSW recycling and recovery. Furthermore, there is also a positive environmental effect – reducing the amount of waste for disposal at WDS, primarily of easily-decomposed organic waste, which comprises about 50% of the MSW mass. This means reducing the impact of MSW on the environment: reducing of GHG emission, filtrate quantity, land integration and etc.

The implementation of the Concept at the regional level will increase waste extraction and recycling rates in the long term. If at the first stage of the MSW Concept implementation we define and recycle traditional types of recyclable materials – waste paper, glass, metal and some types of plastic, then this list could be extended in the future.

Under the MSW Concept the hazardous wastes do not reach the stream of easily-decomposed waste, which means that we have high-quality raw materials for compost production. The use of such compost will overcome the lack of organic matter in the soil.

By implementing an effective MSW management model based on the Concept, we are also reducing GHG emissions from the Waste sector accounted for 6% of total GHG emissions in 2022.

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ASSESSMENT OF THE STATE OF ENVIRONMENTAL SAFETY IN THE SPHERE OF WASTE MANAGEMENT IN THE LVIV REGION

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ABSTRACT

Every year, the problem of handling municipal solid waste, hazardous waste, bulky waste, medical waste, organic waste, and liquid waste is escalating in Ukraine. The total volume of waste in all landfills, including industrial waste, exceeds 450 million tons per year, many of which are hazardous. Research on prevailing trends in waste management, along with an assessment of waste generation dynamics, will help address the issue of waste management effectively. Therefore, evaluating the state of environmental safety in the field of waste management in cities and regions, particularly in the Lviv region, is currently a highly relevant task. EU member states have legitimate reasons to demand that Ukraine take control of its waste situation, as tons of garbage lying in the open across hundreds of square kilometers undergo decomposition, chemical reactions, and other interactions that lead to a range of negative consequences. The research methodology involves processing, analyzing, and summarizing data, as well as synthesizing and interpreting the obtained information regarding the volumes of municipal solid waste generation and management in the Lviv region in 2018–2022. The lowest volumes of imported waste were observed in 2020 and 2021, while the highest volume was recorded in 2022. In 2019, waste imports decreased fourfold compared to 2018. Subsequently, in 2020, waste imports dropped eightfold compared to 2019. However, in 2022, the volume of imported waste was 42 times higher than in 2020. This trend is likely related to quarantine restrictions due to the spread of COVID-19. Regarding the volumes of exported waste, no significant fluctuations were observed compared to waste imports. The highest export volumes were recorded in 2021, while the lowest were in 2018. The highest total waste generation and highest values of waste generation per square kilometer and per capita in Lviv Region occurred in 2020, were also observed in 2020. The highest amount of waste was incinerated in Lviv Region in 2020, reaching 116.6 thousand tons. In 2021, the volume of incinerated waste was approximately half of that. The solution to the issue of safe handling of solid household waste in the Lviv region can be achieved through: the creation of modern waste sorting lines, landfills, and specialized enterprises for waste collection; preventing waste generation; preparing waste for reuse (sorted waste should be used as secondary raw materials); waste processing (which can be done in various ways, the most modern and widely used of which is mechanical-biological treatment).

Keywords: municipal solid waste, waste management, landfills, environmental safety, waste generation.

INTRODUCTION

The issue of municipal solid waste (MSW) disposal in Ukraine has taken on a global scale. While the rest of the world is combating waste by converting it into useful components to support the well-being of their citizens [1-5], Ukraine has yet to overcome the first barrier to a clean environment.

Every year, the problem of handling municipal solid waste, hazardous waste, bulky waste, medical waste, organic waste, and liquid waste is escalating in Ukraine [6-10]. However, the most common type of waste encountered by every resident is the municipal solid waste they generate themselves.

The footprint of municipal solid waste landfills covers over 1,000 hectares in some regions of Ukraine (Fig. 1). While there are nearly 6,000 official (regulated) landfills in the country, the number of illegal (unregulated) dumpsites is estimated to be up to 30,000—approximately 7% of Ukraine's total land area. The total volume of waste in all landfills, including industrial waste, exceeds 450 million tons per year, many of which are hazardous. Currently, 99% of Ukraine's landfills do not meet environmental standards, with about 25% of them being overfilled.

Such landfills can no longer function properly, as they pose the following dangers: the spread of infectious diseases, contamination of groundwater, formation of landfill gas, and self-ignition [11-16].

Illegal dumpsites may contain highly hazardous waste and are often located without consideration of sanitary regulations. These sites are typically found near residential areas, in forest strips, ravines along highways, riverbanks, and steppe zones, where large areas are contaminated with toxic substances. This leads to the destruction of rare plant and animal species, while local populations suffer from polluted water and the acrid stench of toxic emissions into the air.

Fig. 1. The footprint of municipal solid waste landfills in Ukraine.

Waste management in Ukraine is carried out in accordance with state norms and standards. These regulations are established in the laws of Ukraine, including the "Law on Housing and Communal Services," the "Law on Waste," and the "Law on Local Self-Government in Ukraine" [22-27]. According to the "Law on Waste," waste management encompasses not only landfill disposal but also actions aimed at preventing waste generation, as well as waste collection, transportation, sorting, storage, processing, recycling, utilization, disposal, neutralization, and burial.

Research on prevailing trends in waste management, along with an assessment of waste generation dynamics, will help address the issue of waste management effectively.

Therefore, evaluating the state of environmental safety in the field of waste management in cities and regions, particularly in the Lviv region, is currently a highly relevant task.

METHODS AND EXPERIMENTAL PROCEDURES

The input data for the study consists of information on the volumes of municipal solid waste generation and management in the Lviv region, based on reports on the results of environmental monitoring of Lviv Region for the years 2018–2022, developed by the Lviv Regional State Administration's Department of Ecology and Natural Resources.

The research methodology involves processing, analyzing, and summarizing data, as well as synthesizing and interpreting the obtained information regarding the volumes of MSW generation and management in the Lviv region in 2018–2022.

THE RESEARCH RESULTS AND DISCUSSIONS

EU member states have legitimate reasons to demand that Ukraine take control of its waste situation, as tons of garbage lying in the open across hundreds of square kilometers undergo decomposition, chemical reactions, and other interactions that lead to a range of negative consequences [28−31].

In Sweden, more than 99% of garbage is recycled annually, in Germany – more than 60%, in Poland – 43%. There are practically no modern waste processing plants in Ukraine, which make it possible to generate secondary raw materials and reduce the volume of waste disposal. For example, in Germany there are more than 400 waste processing enterprises, the industry has an annual turnover of more than 200 billion euros. It grows every year by an average of 14% and provides work for 250,000 people.

According to the Waste Management Association, 94% of household waste in Ukraine ends up in landfills, less than 5% is recycled, and only 1% is incinerated.

At the same time, according to the Association, local secondary raw material processing enterprises in Ukraine (such as cardboard and paper mills, glass factories, and companies that process polymers and plastics) operate at only 70% capacity.

To maintain even this level of operation, businesses are forced to purchase raw materials from abroad. For example, in 2020, Ukraine imported $50 million worth of waste paper, $12 million worth of polymer materials, and $1.5 million worth of cullet (waste glass).

In 2021, Ukraine imported secondary raw materials worth $70 million, including waste paper, polymer materials, and cullet.

The main reason for the underutilization of recycling facilities is poor sorting quality: every third batch of local secondary raw materials is of inadequate quality and unsuitable for processing.

Fig. 2 illustrates the volumes of waste imports and exports in Ukraine from 2018 to 2022. The lowest volumes of imported waste were observed in 2020 and 2021, while the highest volume was recorded in 2022. In 2019, waste imports decreased fourfold compared to 2018. Subsequently, in 2020, waste imports dropped eightfold compared to 2019. However, in 2022, the volume of imported waste was 42 times higher than in 2020. This trend is likely related to quarantine restrictions due to the spread of COVID-19.

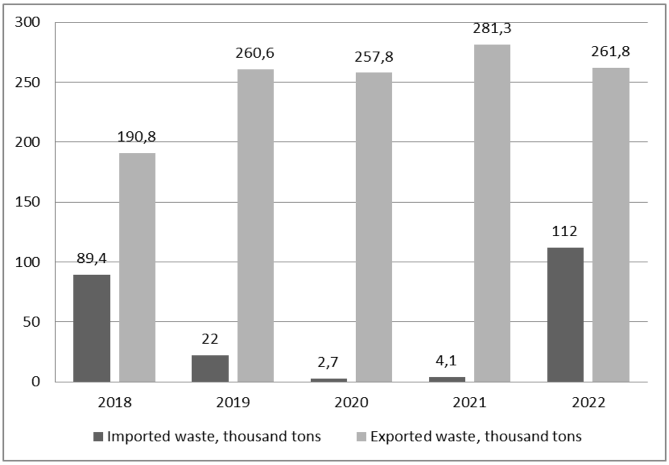

Fig. 2. Import and export of waste in 2018–2022.

Regarding the volumes of exported waste, no significant fluctuations were observed compared to waste imports. The highest export volumes were recorded in 2021, while the lowest were in 2018.

General Dynamics of Waste Generation in Lviv Region and Trends in Waste Management

The primary generators of household waste from the population are the city of Lviv and large industrial cities in the region (Drohobych, Chervonohrad). The amount of waste generated in these settlements significantly exceeds the amount of waste produced in individual districts.

According to this indicator, the territory of the Lviv region exhibits clear zoning. The amount of waste generated by rural residents is higher in the southwestern districts (Sambir, Drohobych, Stryi districts). In the northern regions of the oblast, the rate of waste generation between rural and urban populations is either balanced or shows a predominance of waste from urban residents.

The issue of environmentally safe collection and disposal of solid household waste (SHW) remains critical. Annually, more than 2 million tons of Class 4 hazardous waste are generated in Lviv Region, the vast majority of which is SHW. Following the closure of the largest landfill in Lviv Region, located in the village of Velyki Hrybovychi within the Lviv Municipal Territorial Community of Lviv District, the problem of SHW management has become particularly urgent.

A key component of SHW management is sorting waste into separate fractions and reducing the organic fraction in SHW. Through processing, organic fertilizer—compost—is produced, which can be used for urban landscaping or agriculture. The composting station is located at 13 Plastova Street, Lviv.

Figure 3 demonstrates that the highest total waste generation in Lviv Region occurred in 2020, reaching 3,121.1 thousand tons. Additionally, the highest values of waste generation per square kilometer and per capita were also observed in 2020.

In Lviv Region, separate waste collection is partially implemented through the installation of containers in settlements for collecting recyclable fractions (plastic, glass, paper) at waste collection sites.

The region is also working on the rehabilitation of existing landfills through reclamation and restoration, specifically in the cities of Sambir, Stryi, Zolochiv, and Novoyavorivsk. All projects have received positive environmental impact assessments from Ukraine's Ministry of Environmental Protection and Natural Resources.

One of the hazardous waste categories includes used energy sources such as batteries and accumulators from phones and other electronic devices.

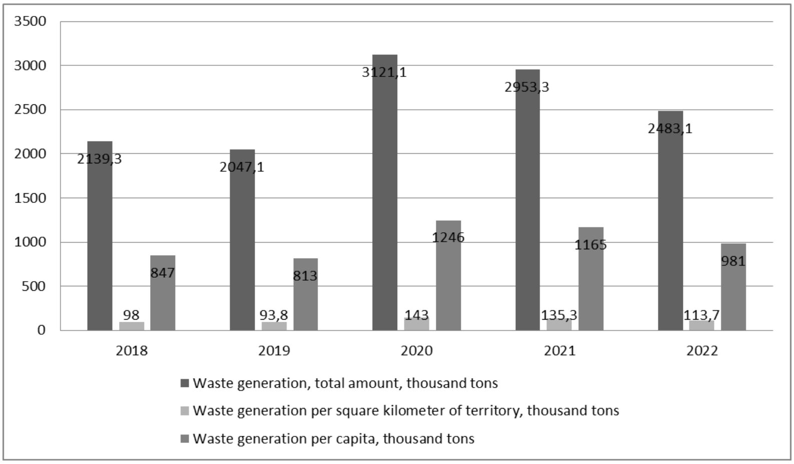

Fig. 3. Dynamics of the waste generation in Lviv Region in 2018–2022.

In collaboration with the Ministry of Environmental Protection and Natural Resources of Ukraine, the regional department has implemented the pilot project "Dispose Properly" in Lviv Region. This initiative allows environmentally conscious residents to dispose of used batteries in special safe containers for collecting chemical power sources. Notably, Lviv Region is among the first to implement such a project.

Throughout 2021, the electronic service "Ecomapa.gov.ua" successfully operated in Lviv Region and across Ukraine. This service enabled continuous monitoring and recording of unauthorized landfills and provided information on household waste disposal sites. It included an interactive map of Ukraine's landfills and a mobile application with an online reporting feature for detecting illegal dumping sites. In the region, 58 citizen reports submitted through the interactive map regarding illegal landfills were reviewed and subsequently addressed.

Waste Disposal Sites (WDS)

Waste Disposal Sites (WDS) are specially designated locations or facilities (landfills, complexes, pits, structures, subsoil areas, etc.) authorized for waste disposal by the relevant waste management authorities.

Each WDS has a special passport containing the name and code of the waste, its quantitative and qualitative composition, origin, technical characteristics, and information on control methods and safe operation. The passport is prepared by the WDS owner in accordance with the Instruction on the Content and Preparation of Waste Disposal Site Passports. WDS owners or, upon their authorization, specialized project organizations with the appropriate licenses conduct WDS inventory and develop passport projects.

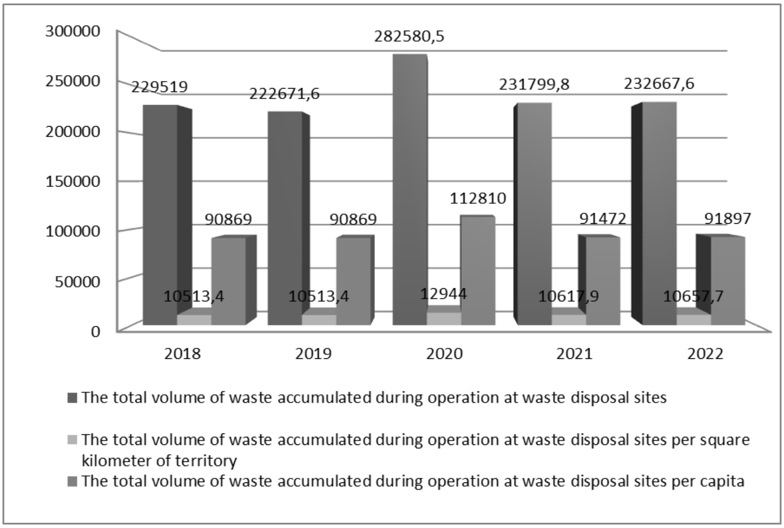

Fig. 4. Dynamics of the Total Volume of Waste Accumulated During Operation at Waste Disposal Sites in Lviv Region.

The data presented in Figure 4 indicate that the highest total volume of waste accumulated during operation at waste disposal sites in Lviv Region (including per square kilometer of territory and per capita) was observed in 2020.

General Dynamics of Waste Incineration in Lviv Region

Waste incineration is the process of burning solid, liquid, or gaseous waste at high temperatures. Incineration of waste (especially using the latest technologies) leads to the emission of toxic metals such as lead, mercury, dioxins, and furans. Other toxic substances are also released into the air, water, and soil.

Toxins present in emissions, slag, and fly ash (which accounts for up to 30% of the waste volume) at incineration sites can travel long distances, accumulate in soils and water, enter plant and animal tissues, and eventually reach the human body.

More than 90% of the waste that ends up at incineration plants and landfills can be recycled or composted. Burning these valuable materials to generate heat and electricity promotes consumption and hampers efforts to conserve natural resources.

Waste incineration negatively impacts climate change. Burning waste releases 1.355 kg of CO_2 per megawatt-hour of electricity produced. In comparison, coal-fired power plants emit 1.020 kg per megawatt-hour.

Recycling and composting can save five times more energy compared to the energy generated from waste incineration. Incineration requires large investments but provides very few jobs, meaning waste-to-energy plants create minimal employment.

On the other hand, reuse and recycling benefit the economy by creating ten times more jobs.

It is possible to incinerate unsorted waste as long as it does not contain hazardous substances. Typically, waste incineration plants are equipped with modern filtration systems that significantly reduce emissions. Waste incineration is a common practice in European countries. While incineration plants can handle any type of waste, recycling plants require waste to be sorted into two categories: organic and everything else. This necessitates the installation of additional containers in cities.

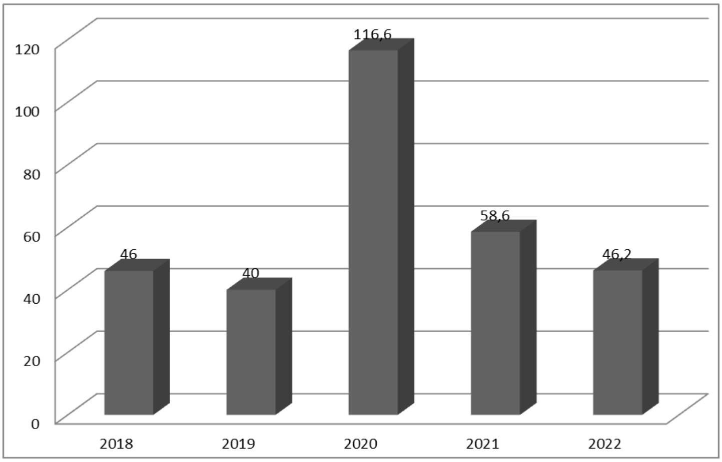

Fig. 5. Dynamics of Waste Incineration (thousand tons) in Lviv Region from 2018 to 2022.

The diagram presented in Figure 5 shows that the highest amount of waste was incinerated in Lviv Region in 2020, reaching 116.6 thousand tons. In 2021, the volume of incinerated waste was approximately half of that.

In accordance with the Cabinet of Ministers of Ukraine's directive No. 117-r dated 20.02.2019, "On the Approval of the National Waste Management Plan until 2030," and using the conceptual framework for developing the Waste Management Strategy for Lviv Region until 2030, the Department developed a Regional Waste Management Plan for Lviv Region until 2030 (hereinafter – the Regional Plan) during 2019-2020, in line with the Methodological Recommendations. The Regional Plan outlines a set of interrelated tasks and measures, synchronized in terms of timing and resource allocation, aimed at addressing key issues in waste management.

The Regional Plan will:

- Establish a foundation and select the optimal scenario for implementing a comprehensive waste management system in the region by 2030, with territorial division into clusters.
- Ensure the development of waste management infrastructure through land allocation for waste processing plant construction, creating a logistical model for waste facilities, modernizing existing facilities, and planning new ones while considering community financial capacity, tariff policies, and investments.

CONCLUSION

Solving the waste problem in the Lviv region, as well as reducing energy consumption, is one of the key conditions for ensuring the sustainable development of the city. Any civilized methods of waste processing cannot be covered solely by the revenue from selling the obtained raw materials.

Currently, the waste disposal tariff includes only the cost of waste collection and landfill burial. Therefore, changing the approach to waste management must be accompanied by a new principle of payment for its processing.

It is necessary to introduce a set of measures to improve waste management culture, including educational programs in schools and a gradual reduction in the use of plastic packaging.

The solution to the issue of safe handling of solid household waste in the Lviv region can be achieved through:

- the creation of modern waste sorting lines, landfills, and specialized enterprises for waste collection;
- preventing waste generation;
- preparing waste for reuse (sorted waste should be used as secondary raw materials);
- waste processing (which can be done in various ways, the most modern and widely used of which is mechanical-biological treatment).

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METHODLOGY FOR INTEGRATED ENVIRONMENTAL ASSESSMENT OF THE GEOLOGICAL ENVIRONMENT CONSIDERING THE ECOLOGICAL CONSEQUENCES OF MILITARY CONFLICT

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ABSTRACT

The proposed scientific study examines the methodology for integrated environmental assessment of the geological environment, considering the ecological consequences of military conflict. Addressing the environmental impacts of military conflicts is a pressing issue, as such conflicts often lead to ecosystem destruction, soil contamination, and the pollution of water resources and air.

Keywords: integrated assessment, environmental consequences, geological environment, military conflict, geoinformation system.

INTRODUCTION

Military conflicts can have serious consequences for the environment, especially the geological environment is subjected to excessive stress due to the activation of the factor of militarism. In addition, military conflicts often lead to serious environmental consequences, such as pollution of soils, water resources, air and loss of biodiversity. These consequences can have a negative impact on human health, ecosystems and sustainability of environmental recovery after hostilities. Environmental impact assessment is an important step in understanding the extent of damage and developing effective recovery strategies.

The purpose of this study is to develop a comprehensive methodology that will help to carry out an effective assessment of the ecological state of the geological environment, taking into account the environmental consequences of hostilities. The study is based on an integrated approach to working with geoinformation data, mapping the levels of pollution of atmospheric, lithospheric and hydrospheres. Special attention should be paid to assessing the levels of influence of the militaristic factor on the degradation processes of ecosystems and their possibility visual modeling.

MATERIAL AND METHODS

Writing a scientific article is an important and complex process. In our case, scientific research required the study of the following materials, the implementation of certain steps and the use of specific methods:

– literary review: analysis of literary sources, scientific publications and reports on a certain topic is carried out; previous studies and articles are analyzed in order to isolate still unexplored aspects of scientific problems;

– formulation of a research question hypothesis, which is focused on the processing of literary sources, synthesis of goals and assumptions of approaches to own research;

– comparison, analogy and abstraction as methods that allowed the transition from specific methodologies proposed by the International Committee of the Red Cross, the United Nations and the World Bank to an integral author's methodology;

– classification as a method that allowed to rank the advantages and disadvantages of each of the analyzed methods of environmental assessment due to military conflicts;

– logical-analytical method, which allowed to offer a sequence of strategic goals of the integrated environmental assessment of the geological environment and structure scientific research as a whole;

– graphic method, as a pictorial means of visual illustration, with the help of which visual schematic objects were created, allowing to visualize the practical results of the study;

– generalization, as a method used to form conclusions, the result of the study.

Theoretical analysis

We have analyzed methods for determining the environmental assessment of the geological environment, taking into account the environmental consequences of military conflict, proposed by the International Committee of the Red Cross (ICRC), the United Nations (UN) and the World Bank.

Methodology for conducting integrated environmental assessment after military conflicts, developed by the International Committee of the Red Cross (ICRC) (hereinafter - ICRC Methodology) (Fig. 1).

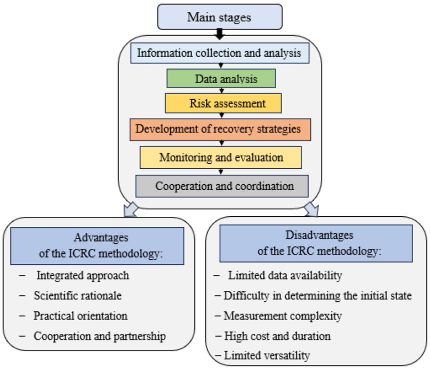

Fig. 1. Methodology for conducting integrated environmental assessment after military conflicts (ICRC).

The ICRC methodology is an important tool for understanding and managing the environmental consequences of hostilities. It helps to collect and analyze information, assess risks and develop recovery strategies, contributing to sustainable development and ensuring the safety of people and nature after war [1]; [2].

It should be noted that this ICRC Methodology is designed to restore environmental sustainability and improve living conditions in the affected areas. It serves as an important tool for identifying and assessing the environmental consequences of hostilities, as well as taking into account various aspects of environmental impacts and helping to collect, analyze and evaluate data to make informed decisions about ecosystem restoration.

The main objective of the ICRC Methodology is to assess the environmental damage that conflict may cause, as well as to establish the necessary measures to minimize this damage and restore ecological balance in the affected area. The use of this technique contributes to ensuring long-term restoration of natural resources, conservation of biodiversity and balanced development in areas affected by hostilities.

The main stages of the ICRC Methodology include:

− Information collection and analysis: comprehensive collection of information on the conflict and its consequences, namely potential sources of pollution, biodiversity loss and other environmental problems resulting from the conflict, is carried out. Data on military operations, use of weapons, damage to infrastructure, pollution by hazardous substances, natural resources, etc. are also added;

− Data analysis: the data obtained are analyzed in order to establish the extent of damage and identify priority problems that require immediate intervention;

− Risk assessment: risks to human and ecosystem health are assessed, allowing to identify the most critical aspects for further work;

− Development of recovery strategies: based on the data obtained and risk assessment, strategies for compensation of disturbances and restoration of the natural environment are developed. This may include infrastructure reconstruction, contaminated area cleanup, ecosystem restoration, including environmental measures, rehabilitation of water and soil sources, and other measures to ensure sustainable recovery.

− Monitoring and evaluation: after the implementation of recovery strategies, monitoring and evaluation of the effectiveness of its results after the war is carried out. This allows you to make adjustments and improve existing plans, helps to determine the effectiveness of the measures taken and the need for more thorough intervention;

− Collaboration and coordination: The important role of the methodology is to work with local groups, government bodies and international organizations to ensure coordination of efforts and maximum impact.

Advantages of the ICRC methodology:

− Integrated approach: The ICRC methodology is focused on a comprehensive assessment of the environmental consequences of military conflicts. It takes into account not only direct hostilities, but also the consequences of explosions, pollution of soil and water resources, destruction of ecosystems, etc. This allows you to get a complete picture of the environmental situation and develop effective measures to restore the environment;

− Scientific rationale: The ICRC methodology is based on scientific research and expertise in the field of geoecology and military conflicts. It uses modern methods of assessing environmental performance and modeling, which guarantees the objectivity and reliability of the results obtained;

− Practical focus: The ICRC methodology is designed for practical field application. It provides recommendations on priority measures for environmental restoration and protection of natural resources. This allows for efficient use of resources and rapid restoration of ecosystems.

− Cooperation and partnership: The ICRC methodology facilitates collaboration between different stakeholders such as military, environmentalists, NGOs, etc. This facilitates the exchange of experience and coordination of efforts to restore the environment and ensure sustainable development.

− The ICRC methodology has numerous advantages. It is scientifically based, contributes to the preservation of the natural environment and sustainable development after military conflicts, allows a comprehensive assessment of the environmental consequences of hostilities and the development of effective measures for environmental restoration [3], [4], [15].

Disadvantages of the ICRC methodology:

− Limited data availability: Conducting an integrated environmental assessment requires a large amount of data on the state of the environment, including pollution of soils, water resources, air, etc. However, in the zone of military conflict, data may be limited or not available at all, which complicates the assessment;

− Difficulty in determining the initial state: environmental assessment involves comparing the current state of the environment with the initial state before the military conflict. However, determining the exact initial state may be difficult due to the lack of reliable data before the conflict or changing environmental conditions during the conflict;

− Measurement complexity: Some indicators used to assess environmental status can be difficult to measure in a war zone. For example, measurements of background radiation or chemical contamination may require specialized equipment, or research may be hazardous to health;

− High cost and duration: it should be recognized that environmental assessment of the consequences of a military conflict is a complex and costly process. Measurement, analysis of data, preparation of reports and recommendations require significant financial and human resources. In addition, this process can take a long time, which can be problematic in case of emergencies;

− Limited universality: The ICRC methodology may be specific to certain types of military conflicts and regions, given the diversity of situations and contexts, limitations may arise.

− Given these shortcomings, it is important to constantly improve the methodology in order to provide a more accurate and effective assessment of the ecological state and restoration of the natural environment.

Methodology for assessing the environmental consequences of hostilities, developed by the United Nations (UN) (hereinafter - the UN Methodology) (Fig. 2)

The United Nations (UN) has developed a methodology for assessing the environmental consequences of hostilities. The methodology helps to identify potential risks to human health associated with the environmental consequences of hostilities, and take appropriate measures to avoid them. Similarly, attention is focused on assessing environmental impacts on the environment and further promoting the conservation of natural resources and biodiversity [5,6].

The main stages of the UN Methodology (Fig. 2):

− Information gathering: This phase involves the comprehensive collection and analysis of information on military actions and their impact on the environment. Aspects such as weapons, environmental risk zones, damage to infrastructure, levels of air, soil and water pollution are assessed;

− Impact analysis: at this stage, changes that have occurred in ecosystems and natural resources are assessed and documented. Assessment of the impact of hostilities on various aspects of ecology, such as air, water, soil, vegetation, wildlife, biodiversity and ecosystems;

− Risk assessment: at this stage, the impact of environmental impacts on human health, economy, social and cultural aspects is assessed. Explores potential impacts on the economy, livelihoods, access to drinking water, nutrition and more;

− Development of recommendations for recovery and damage minimization plans: at this stage, concrete measures are being developed to restore ecological balance and reduce pollution. The proposed measures may include restoring the landscape and ecosystems, cleaning up contaminated sites, increasing access to water, etc.;

− Cooperation and coordination: the last stage is cooperation with all important stakeholders, including local residents, military and civilian organizations, governments and other international organizations. This helps to ensure effective coordination, resource allocation and proper execution of planned activities.

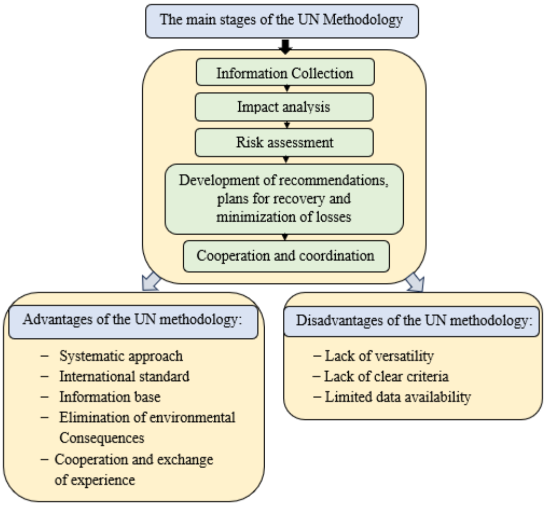

Fig. 2. Methodology for assessing the environmental consequences of hostilities (UN).

The methodology for assessing the environmental consequences of hostilities, developed by the UN, is an important tool for determining and quantifying the environmental impact of military conflicts. It is systematic, sets an international standard, provides access to information aimed at eliminating problems and promotes cooperation and exchange of experience. The proposed actions help ensure proper restoration of ecosystems, improvement of living conditions and contribute to sustainable development in the affected areas.

This UN Methodology has certain advantages that contribute to understanding and eliminating the negative environmental consequences of hostilities:

− Systematic approach: The UN methodology provides a systematic approach to assessing the environmental consequences of hostilities. It involves collecting and analyzing information on potential environmental risks, their impact on natural resources, ecosystems and human health.

− International standard: The United Nations methodology is an international standard for assessing the environmental consequences of hostilities. It is developed taking into account the best practices and experience from around the world, which allows to ensure the unity of approaches and results.

− Information base: The UN methodology provides access to a large amount of information and data on the environmental consequences of hostilities. This helps to understand the scale of the problem, identify priorities and develop effective strategies to reduce the negative impact.

− Addressing environmental impacts: The UN methodology aims to eliminate the environmental consequences of hostilities. It provides recommendations and tools to reduce the negative impact on nature and restore damaged ecosystems.

− Cooperation and exchange of experience: The UN methodology facilitates cooperation between countries and exchange of experience in assessing the environmental consequences of hostilities. This contributes to the improvement of methodology and effective solution of environmental problems.

The methodology for assessing the environmental consequences of hostilities, developed by the United Nations (UN), is an important tool for assessing the environmental impact of hostilities. It has numerous advantages that contribute to understanding and eliminating the negative environmental consequences of military conflicts. Deficiencies analysis allows us to determine how the most significant are lack of universality, lack of clear criteria and limited availability of data. They need attention and further Improvement:

− Lack of versatility. One of the shortcomings of the Methodology for assessing the environmental consequences of hostilities is its insufficient universality. The methodology was developed with a focus on certain types of hostilities and conflicts, and may not take into account the unique features of other situations. This can lead to incomplete or inaccurate environmental impact assessments in some cases.

− Lack of clear criteria. Another drawback of the Methodology for assessing the environmental consequences of hostilities is the lack of clear criteria for assessing the environmental impact. The lack of standardized and objective criteria can lead to subjectivity and inconsistency in estimates, which complicates data comparisons and decision-making.

− Limited data availability. Another disadvantage of the Methodology is the limited availability of data required for the assessment. An accurate assessment of environmental impacts requires a large amount of information, such as data on pollution, emissions, damage to ecosystems, etc. However, in many cases, such data may be inaccessible or incomplete, complicating the evaluation process [8], [9].

Further improvement of the Methodology can provide a more accurate and objective assessment of the environmental consequences of hostilities.

Methodology for conducting environmental assessment of the consequences of military conflicts within the framework of the project "Restoring Environmental Sustainability" implemented by the World Bank (hereinafter - the UK Methodology)

Environmental assessment of the consequences of military conflicts is an important step in determining the degree of damage and restoration of the geological environment after hostilities. Within the framework of the project "Restoration of Environmental Sustainability", implemented by the World Bank, a methodology for conducting an integrated environmental assessment of the geological environment, taking into account the environmental consequences of military conflict, was developed.

The GB technique includes the following steps (Fig. 3):

− Collection and analysis of primary data: at this stage, information is collected on military operations, the nature of damage, as well as on the environmental parameters of the geological environment.

− Determination of the degree of damage: based on the collected data, the degree of damage to the geological environment is assessed. Special methods and indicators are used to assess the impact of hostilities on natural resources, soils, water systems and other components of the ecosystem.

− Analysis of environmental impacts: at this stage, a detailed analysis of the environmental consequences of a military conflict is carried out. Changes in the ecosystem, the spread of pollution, the impact on biodiversity and other aspects are studied.

− Development of recovery measures: based on the results of the environmental impact analysis, the necessary measures for the restoration of the geological environment are determined. These can be measures for cleaning contaminated areas, soil reclamation, biodiversity restoration and others.

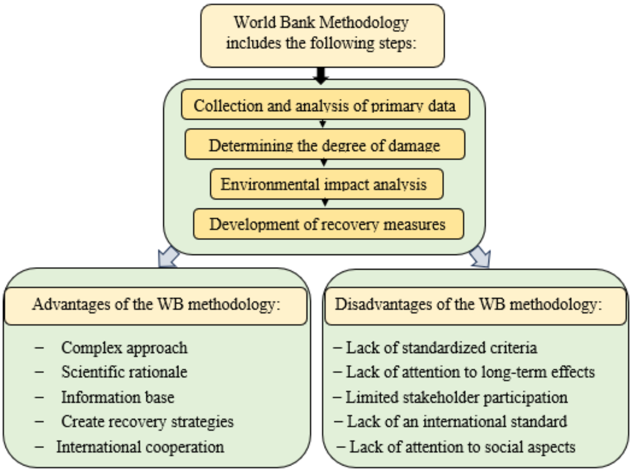

Fig. 3. Methodology for conducting environmental assessment of the consequences of military conflicts within the framework of the project "Restoring Environmental Sustainability" (World Bank).

The UK Methodology is an important tool for determining the degree of damage and restoring the geological environment after hostilities. These techniques help to understand the environmental impact of military conflicts and develop effective measures to restore its resilience. (Source: Environmental Resilience Restoration Project, World Bank.) [10] – [13].

The GB methodology for conducting such an assessment within the framework of the project "Restoring Environmental Sustainability" has several advantages:

− Integrated approach: The methodology takes into account a wide range of factors that affect environmental sustainability after military conflicts. It covers not only direct environmental impacts such as pollution of soils and water resources, but also direct consequences such as loss of biodiversity and destruction of ecosystems;

− Scientific rationale: The methodology is based on scientific research and expert environmental information. It uses up-to-date data and methods to carry out an objective assessment of the consequences of military conflicts;

− Information base: The methodology includes the creation of a comprehensive information database on the consequences of military conflicts. This allows you to collect, systematize and analyze a large amount of information that contributes to the effective planning and implementation of projects to restore environmental sustainability;

− Creating recovery strategies: The methodology helps to develop strategies and plans for restoring environmental resilience in areas affected by military conflicts. It allows you to take into account the peculiarities of local ecosystems and influence them in order to restore the natural and ecological balance;

− International cooperation: The methodology stimulates cooperation between different countries and international organizations in the field of restoring environmental sustainability after military conflicts. This facilitates the exchange of experience, resources and expertise to achieve better results in the restoration of nature and ecosystems.

This methodology is an important tool for the implementation of the project "Restoration of environmental sustainability" after military conflicts. It allows for a comprehensive assessment and planning of ecological system restoration, ensuring the sustainability and long-term environmental development [14].

Conducting an environmental assessment of the consequences of military conflicts is an important stage of the project "Restoring Environmental Sustainability". However, there are certain shortcomings in the Methodology for conducting such an assessment. Some of these include:

− Lack of standardized criteria: The Methodology may lack a clear set of criteria by which the consequences of military conflicts on the environment are assessed. This can lead to subjectivity and disparity in the evaluation results.

− Lack of attention to long-term consequences: The methodology can be aimed primarily at identifying and assessing the negative effects of military conflicts in the short term. However, it is also important to consider long-term consequences, such as pollution of water resources or destruction of ecosystems, which can have significant impacts on the environment and human health in the future.

− Limited stakeholder participation: The methodology may not involve sufficient participation and involvement of stakeholders such as local residents, academics, NGOs, etc. This can lead to a limited understanding of the situation and underestimation of some consequences of military conflicts.

− Lack of an international standard: The methodology may not meet international standards for environmental assessment of the consequences of military conflicts. This can make it difficult to compare evaluation results between different projects and regions.

− Lack of attention to social aspects: The methodology can focus mainly on environmental aspects, leaving aside the social consequences of military conflicts. However, it is important to take into account the impact of conflicts on the local population, their rights and living conditions.

The GB methodology has its drawbacks, but it is still an important tool for identifying and assessing the environmental impact of hostilities. Continued research and improvement of the Methodology can help reduce these shortcomings and improve the effectiveness of assessing the environmental consequences of military conflicts.

THE RESEARCH RESULTS AND DISCUSSIONS

The development of the Strategy for Integrated Environmental Assessment of the Geological Environment involves the following strategic goals:

Initial data collection**.** The first step is to collect initial data on the geological environment and characteristics of the military conflicts that have occurred in the area. This stage includes collecting data on the geological structure of the territory, studying the available geological maps. It is important to process information on the availability of natural resources, as well as data on pollution and damage to the geological environment obtained during previous environmental assessments. It is especially difficult to collect and systematize reporting documentation on military operations, including the use of weapons and equipment.

Determination of the environmental consequences of military conflict**.** The second strategic objective is to determine the environmental consequences that have arisen as a result of the military conflict. It involves determining the level of pollution of soil cover, precipitation and air due to the use of chemical and radiation weapons. Particular attention is focused on investigating the level of ecosystem damage and biodiversity loss. The possibility of environmental pollution due to the destruction of industrial infrastructure is being investigated.

Development of methods for assessing pollution and damage to the geological environment**.**

The third step is to develop methods for assessing pollution and damage to the geological environment. This may include:

− Identification of indicators of pollution and damage, such as the concentration of toxic substances in soil and water, or the area of damaged ecosystems;

− Development of methods for measuring and evaluating these indicators;

− Determination of safety limits for the geological environment and natural resources.

Identifying ways to restore and preserve the geological environment The fourth step is to identify ways to restore and preserve the geological environment after a military conflict. This may include:

− Development of plans for the restoration of contaminated areas and ecosystems;

− Use of soil and water purification technologies from toxic substances;

− Implementation of measures for the protection and restoration of biological diversity;

− Conducting training courses and disseminating information about the importance of preserving the geological environment.

Due to the significant environmental consequences arising from military conflicts, the development of a methodology for conducting an integrated environmental assessment of the geological environment is becoming an urgent task. In this case, we propose to develop our own methodology that will combine the approaches of the United Nations (UN) and the International Committee of the Red Cross (ICRC), and also takes into account the peculiarities of the project "Restoration of environmental sustainability".

Integrated environmental assessment of the geological environment, taking into account the environmental consequences of military conflict, is a complex process that requires a multidisciplinary approach and consideration of many factors. The stages of implementation of the technique are presented in sequence (Fig. 4).

Methodology of integrated environmental assessment of the geological environment taking into account the environmental consequences of military conflict

Step 1: Collection and analysis of information

1.1 Collect data on military conflicts:

− Locations of hostilities, scale and duration of the conflict;

− Types of weapons systems and ammunition used;

− Reports from military and civil society organizations on the consequences of the conflict.

1.2 Collect data on the geological environment:

− Geological maps, aerial photographs, satellite images characterizing the structure of soil cover and hydrogeological conditions of the study area;

− Information on the location of natural resources such as minerals, oil and gas fields.

Step 2: Identification of potential sources of pollution

2.1 Identify the types of possible contamination:

− Explosives;

− Chemicals from the ammunition depot;

− Odors, smoke and other emissions that may occur during hostilities.

Step 3: Environmental Impact Assessment

3.1 Air pollution assessment:

− Determining the amount of gas and particle emissions during the conflict (depending on the type of munitions used);

− The use of models to predict the spread of pollution in the air.

3.2 Assessment of water pollution:

− Identification of possible sources of groundwater and surface water pollution;

− Determination of the degree of solubility of substances in water and their possible potential for harmful effects on ecosystems.

Step 4: Assessing risks to human health

4.1 Assessment of public exposure to pollutants:

− Taking into account the physical proximity of the area to sources of pollution;

− Using models to determine possible concentrations of substances in air, water and soil.

4.2 Disease risk assessment:

− Using data on toxic properties of substances to determine potential health effects;

− Comparison with health safety levels established by relevant organizations.

Step 5: Development of minimization and remediation measures

5.1 Development of a pollution minimization plan:

− Identification of priority measures to reduce environmental risks;

− The choice of technologies and methods that will help minimize impact.

5.2. Development of a remediation plan:

− Establishment of measures to restore the environment after military conflicts;

− Calculation of resources (financial, human, technical) for successful implementation

Step 6: Verify implementation

6.1. Environmental monitoring:

− Determination of parameters that should be monitored to evaluate the effectiveness of implemented minimization and remediation measures;

− Regular measurements and data collection to update the environmental assessment.

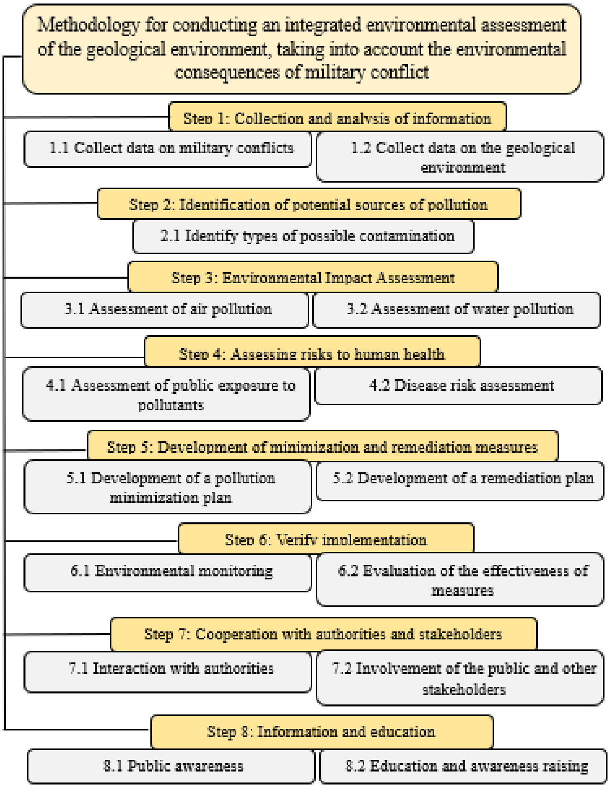

Fig. 4. Stages of Implementation of Integrated Environmental Assessment of Geological Environment, Considering the Environmental Consequences of Military Conflict.

6.2. Evaluation of the effectiveness of measures:

− Comparison of environmental indicators before and after implementation of measures to determine their effectiveness;

− If necessary, adjust the minimization and remediation plan.

Step 7: Cooperation with authorities and stakeholders

7.1. Interaction with authorities:

− Share with authorities the results of the assessment and recommendations for the implementation of policies and regulations aimed at environmental protection.

7.2. Involvement of the public and other stakeholders:

− Include the public, academics, nonprofits, and other stakeholders in the evaluation and decision-making process;

− Hold consultations and meetings to collect feedback and suggestions on minimization and remediation measures.

Step 8: Information and education

8.1 Public Awareness:

− Inform the public about the results of the assessment and measures taken to protect the environment;

− Provide access to information on risks and pollution minimization measures.

8.2 Education and awareness-raising:

− Organize educational activities and training on environmental issues and environmental impact assessment of military conflicts;

− Attract a wide audience to form an environmentally conscious community.

CONCLUSION

Methodology for Conducting Integrated Environmental Assessment of Geological Environment Considering the Ecological Consequences of Military Conflict. The methodology for conducting an integrated environmental assessment of the geological environment, taking into account the ecological consequences of military conflict, is an important tool for determining the extent of damage and the recovery of the geological environment after military actions. These methodologies help to understand the impact of military conflicts on the environment and develop effective measures for restoring its resilience.

The development of a methodology for conducting an integrated environmental assessment of the geological environment, with consideration for the ecological consequences of military conflict, is an important step in preserving natural resources and restoring ecosystems after war. This methodology will help determine the degree of pollution and damage to the geological environment, as well as develop effective measures for its restoration and conservation.

Developing a custom methodology for conducting an integrated environmental assessment of the geological environment, taking into account the ecological consequences of military conflict, is a complex task that requires combining approaches from the United Nations and the International Committee of the Red Cross (ICRC), as well as considering the specifics of the "Restoration of Ecological Resilience" project. The application of the above-mentioned methodologies can serve as a foundation for developing a unique methodology that will take into account the particularities of the geological environment and the ecological consequences of military conflicts.

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SYSTEMATIC ANALYSIS OF HYDROMETEOROLOGICAL ADAPTATION OF THE INTERZONAL GEOECOTONE «FOREST-STEPPE-STEPPE» OF UKRAINE IN THE CONTEXT OF GLOBAL CLIMATE CHANGE

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ABSTRACT

The issue of environmental management is an urgent problem for the development of communities and regions in Ukraine. In modern conditions, the issue of developing and implementing clear guidelines for short-, medium- and long-term development is becoming more relevant. They should primarily focus on the interests of the community. Thus, in order to coordinate all these issues in Ukraine, as well as in the countries of the European Union and North America, it is mandatory to take into account all possible threats to the environment. Minimization of negative impacts on the environment should be of key importance when implementing decisions on the long-term socio-economic development of territorial communities. Designing measures to adapt territories to climate change requires taking into account a number of climate parameters, including extreme ones, which need to be carefully reviewed due to the availability of extended observation series and climate change that has occurred. Since, as a rule, we are talking about using probabilistic and ensured indicators, it is advisable to determine them based on a full series of observations, rather than being satisfied with a 30-year observation period. According to climate data, the territory of the Haivoron and Zavalliv territorial communities is covered by aridization and desertification processes. There is a general clear trend of rising temperatures, which cannot be compensated for by an increase in precipitation in certain periods and, accordingly, an increase in the moisture coefficient.

As a result of climate change, in the context of a significant precipitation deficit and the prolongation of the low-water period in the region, which has already lasted for 15 years in a row, the issue of rational use of water resources is of particular importance. Taking into account the intense anthropogenic load on the water bodies of the Haivoron and Zavalliv territorial communities, it is advisable to carry out regular hydrological observations of the flow of the Southern Bug and its tributaries by arranging a hydrological post and conducting regular surveys of the state of water bodies.

Keywords: rational nature management, adaptation of the territory, climatic parameters, water resources, aridization and desertification, Haivoron and Zavalliv territorial communities, Haivoronskyi old industrial district.

INTRODUCTION

The issue of environmental management is an urgent problem for the development of communities and regions in Ukraine. In today's environment, the issue of developing and implementing clear guidelines for short-, medium-, and long-term development is becoming more urgent. They should focus on the interests of the community and not be hostage to political and bureaucratic interests. Thus, in order to coordinate all these issues in Ukraine, as well as in the countries of the European Union and North America, it is mandatory to take into account all possible threats to the environment. Minimization of negative impacts on the environment should be of key importance when implementing decisions on the long-term socio-economic development of territorial communities. In addition to these traditional components of the analysis, the Russian-Ukrainian war has increased the role of the security factor in all processes of territory development. The intense phase of Russian aggression has deepened the cornerstones of our country's development. For example, the destruction of the Kakhovka hydroelectric power plant dam has forced us to pay more attention to Ukraine's water sector, the peculiarities of adverse climate change, and the increase in anthropogenic pressure on the environment. All this requires an adequate response to reduce the risks of environmental degradation [21; 23].

Despite the degradation of many territories, it is worth highlighting those that are developing rapidly, or at least looking for ways to develop. In our opinion, these include the territory within the former Haivoron administrative-territorial district of Kirovohrad region (according to the reform of the administrative-territorial division of Ukraine, approved by the Resolution of the Verkhovna Rada of Ukraine No. 3650 of 17. 07.2020 «On the Formation and Liquidation of Districts»), which unites the Haivoron city and Zavalliv rural territorial communities and has the features and characteristics of both old-developed and old-industrial districts, forming the so-called Haivoron old-industrial district. This territory is a socio-geographical unit with a relatively low level of technological development of the industrial complex and excess production capacity, represented by large and medium-sized enterprises with outdated equipment, which played the role of city and village forming centers [17; 18].

Located in the west of the Holovanivsky district of Kirovohrad region, the Haivoron old industrial district borders on the Haisynskyi district of Vinnitsa region, the Podilsk district of Odesa region, and the Uman district of Cherkasy region. It belongs to the interzonal forest-steppe geoecotone of Ukraine, a territory rich in historical events and various natural resources, which, in fact, determined the trends of its development and current state. The uniqueness of the studied territory also lies in its location within the southern part of the West Prydniprovia denudation upland, which belongs to the South Podillia and South Prydniprovia upland regions of the Dniester-Dnipro forest-steppe region [17]. Within the Haivoron Old Industrial District, powerful industrial facilities have historically emerged and still exist today, which, despite the difficult economic conditions, have significant potential and are of great importance for the development of not only the area, but also our country as a whole.

The peculiarities of the landscape structure, the presence of various mineral resources and significant deposits of rare minerals within the Haivoron old industrial area are largely influenced by its proximity to various structures of the Ukrainian Shield [8; 18].

Not always well-thought-out economic development of the territory has led to fundamental changes in the properties and structure of natural components and landscape complexes, the formation of new, still insufficiently studied anthropogenic landscapes, and the aggravation of environmental and ecological problems. Accordingly, the modern knowledge of the nature of the Haivoron region should include the study of natural areas, historical features and consequences of its economic development, the current state of natural and anthropogenic components, and its landscape complexes [15; 23].

The territory of the Haivoron district has been explored for a long time, due to the development of mineral deposits, the construction of railways and highways, etc. Scientists and teachers of higher and secondary education institutions, as well as local historians, made a significant contribution to the study of the region. Today we can state that, from a geographical point of view, the Haivoron region has been studied in great detail [17]. However, despite the large number of publications, a coherent geographical or natural history image of the Haivoron region has not been formed until recently. Considerable attention is paid to climatic conditions, quality and quantity of water resources as an integral component of the interzonal geoecotone «forest-steppe-steppe» of Ukraine and the Haivoron old industrial area in the publications of such scientists as V. I. Vyshnevsky, Donich O.A., Melnyk S.V., Denysyk G.I., Sytnyk O.I., Kravtsova I.V., Nikolayevsky V.P., Kosovets O.O. and others. The authors (Denysyk G.I., 2012; Denysyk G.I., 2020; Sytnyk O.I., 2019; Sytnyk O.I., 2021; Sytnyk O.I., 2024; Nikolayevsky V.P., 2022; Vyshnevsky V.I., 2022; Melnyk S.V., 2023; Kosovets O.O., 2023; Rozhi T.A, 2023) highlights the landscape structure, climatic conditions, condition and main problems of water bodies of the territories with excessive anthropogenic load, which include the Haivoron old industrial area.

Object of research: hydrometeorological support for the adaptation of the territory of the Haivoron city and Zavalliv village territorial communities (Haivoron old industrial district) of Kirovohrad region to modern climate change.

The subject of the study is the systematization of information and analysis of the current state of climatic conditions and water resources use in the territory of the interzonal geoecotone «forest-steppe-steppe» of Ukraine within the Haivoron old industrial district.

The purpose of the study is to substantiate measures aimed at the rational use of water resources in the territory of the interzonal geoecotone «forest-steppe-steppe» of Ukraine within the Haivoron old industrial district.

METHODS AND EXPERIMENTAL PROCEDURES

The data presented in the article were obtained by analyzing archival, statistical and cartographic materials, as well as from our own field and analytical research. To analyze the current state of water resources of the territory of the interzonal geoecotone «forest-steppe-steppe» of Ukraine within the Haivoron old industrial area, we used the GIS packages SAS.Planet.Release and GoogleEarthPro, whose database made it possible to analyze the process of anthropogenization of the objects of the studied territory and determine the temporal patterns of their development.

THE RESEARCH RESULTS AND DISCUSSIONS

The current features of climate fluctuations on the globe are characterized by the redistribution of heat and moisture over its territory over time. Studies of changes in climate characteristics in space and time are carried out continuously in most countries, including Ukraine. The results of these studies are used in various models and forecasting schemes in many reports and guidelines. Climate change in Ukraine is manifested in an increase in air temperature, precipitation and evaporation. In general, there is a significant difference in temperature and humidity conditions in Ukraine between the decades of the late twentieth and early twenty-first centuries [21].The rate of global warming in Ukraine is generally higher than in Europe.

The report of the International Panel on Climate Change (IPCC), a United Nations body exclusively dedicated to the scientific aspects of climate change, presents five scenarios of climate warming. Under the first one (SSP1-1.9), from 2021 to 2040, the average surface temperature will be 1.5°C higher than the pre-industrial level, and in 2041-2060 and 2081-2100 - by 1.6 and 1.4°C, respectively. The second (SSP1-2.6), third (SSP2-4.5) and fourth (SSP3-7.0) scenarios are also based on the hypothesis that global warming is most likely to reach 1.5°C in 2021-2040, with differences in the estimates for 2041-2060 (1.7, 2.0, 2.1°C, respectively) and 2081-2100 (1.8, 2.7, 3.6°C). Finally, according to the fifth scenario (SSP5-8.5), the average global surface temperature will increase by 1.6°C in 2021-2040, by 2.4°C in 2041-2060, and by 4.4°C in 2081-2100 [21].

For the period of 2021-2100, the SSP2-4.5 scenario predicts an increase in annual air temperature (0.27 °C/10 years), an increase in the number of extreme high temperature events, and a decrease in the number of extreme low temperature events on average across Ukraine. Precipitation indices are characterized by positive trends, including an increase in annual precipitation and an increase in the number of extreme precipitation events. The most intense changes will be manifested in a decrease in the number of frosty days (-3.2 days/10 years), an increase in the number of summer and tropical nights (3.0 and 2.51 days/10 years, respectively), and an increase in annual precipitation (2.39 mm/10 years). Under the SSP5-8.5 scenario, a much sharper increase in annual air temperature (0.68 °C/10 years), an increase in the number of high temperature extremes, and a decrease in the number of low temperature extremes are projected. The biggest changes are observed in the increase in the number of tropical nights (7.9 days/10 years), decrease in the number of frosty nights (-7.78 days/10 years), increase in the number of summer nights (6.84 days/10 years) and increase in the percentage of warm nights (1.91%/10 years). Among the precipitation indices, the largest increase in extreme precipitation is projected for the number of days with heavy precipitation (0.16 days/10 years) and very wet days (0.96%/10 years). The largest differences between the scenarios are observed in the frequency of tropical nights and frosty days. The precipitation indices also show significant differences, in particular, the annual precipitation on average for Ukraine under SSP5-8.5 has a negative trend (-1.28 mm/10 years), while under SSP2-4.5 it is positive (2.39 mm/10 years). Under the SSP5-8.5 scenario, much stronger changes in very wet and extremely wet days are expected [21].

The calculated differences/deviations show that more intense climate change should be expected at the end of this century compared to its middle. For the period 2031-2060, the projected changes in precipitation and air temperature indices under both scenarios SSP5-8.5 and SSP2-4.5 are comparable. For the period 2071-2100, the SSP5-8.5 scenario provides for much stronger background changes in all temperature indices compared to SSP2-4.5. For precipitation indices in the period 2071-2100, the SSP2-4.5 scenario shows a larger background increase in annual precipitation compared to SSP5-8.5.

It is believed that the third scenario (SSP2-4.5) is the most likely and realistic. For the second scenario (SSP1-2.6) to come true, all countries must make more ambitious climate commitments as soon as possible [21].

Compared to the current climate norm, the average annual temperature is 1-2°C above normal every year. According to the National Academy of Agrarian Sciences of Ukraine, in recent decades, the boundaries of the country's natural and climatic zones have actually shifted 100-150 km to the north.

In recent years, vegetation conditions in the traditional northern steppe sub-zone (Dnipropetrovska, Kirovohradska and other regions) should de facto be classified as the southern steppe sub-zone.

The steppe region of Ukraine is gradually approaching the dry subtropics, which, for example, includes the territory of Greece. If the current trends in climate change continue in the next 20 years, there is a real danger that not only the steppe zone, but also more than half of Ukraine's arable land will be lost to intensive agriculture. Fluctuations in maximum temperatures during the growing season may require irrigation even for crops that did not need it before (e.g., wheat), which will lead to a significant increase in financial costs. At the same time, the effects of climate change and shifting climate zones on the agricultural sector may also be positive.

Among the consequences of climate change are the degradation and desertification of agricultural land, while changes in topsoil fertility and crop yields are observed. There are also changes in the microclimate of settlements and many health problems among the population due to the temperature of buildings and air in residential areas, which also creates difficulties for the existence of green spaces in them, etc.

In recent years, the duration of snow cover in winter has decreased significantly. Given this trend, it is believed that the period of «classic» winters is coming to an end. This period is being replaced by another one with the «winter season»[10].

Climate change is also affecting the flow regime in Ukraine. In particular, there is a decrease in flood peaks and an increase in lowland runoff, an increase in the number of thaws, a shift in the course and intensity of rains toward increased erosion hazards, and overgrowth and siltation of small rivers. At the same time, destructive floods due to intense rainfall are also observed [13; 17; 21]. Therefore, there is an urgent need to adapt territorial communities (urban and agricultural areas) to climate change. That is, to successfully address the issues of adaptation measures, it is necessary to have complete and comprehensive information on the course of hydrometeorological parameters of the territory and its structure [2; 23].

The Hydrometeorological Service already has experience in covering, preparing, and publishing a wide range of hydrometeorological information that can fully meet the needs of designing climate change adaptation measures. This includes the publication of climate reference books, the State Water Cadastre, the Climate Cadastre of Ukraine, as well as the work of scientists to summarize climate change in individual territories, etc. [2].

Taking into account the recommendations of the WMO, generalizations have recently been made for 30-year periods (1961-1990, 1991-2020). It is believed that 30-year periods more appropriately reflect the state of the climate of the territories. However, the 30-year series may not be sufficient to generalize extreme climate indicators, so it is recommended to use the entire series of observations.

Of course, the relevant conclusions about the territory of Ukraine can be made only on the basis of reliable and long-term data that are properly processed and analyzed. This extensive work was completed at the climatology department of the Boris Sreznevsky Central Geophysical Observatory. Similar to the previous edition of the Climate Cadastre of Ukraine, the new edition covers the period 1991-2020. The newly created Climate Cadastre of Ukraine is a comprehensive collection of information about the country's climate. It contains generalized results of observations at all 187 weather stations in Ukraine during 1991-2020. The collected data make it possible to establish spatial and temporal patterns of climate, to assess changes that have occurred over a long period of time, which is of great interest for many spheres of state life [2, 5].

In this regard, it is worth paying attention to the spatial and temporal features of changes in temperature and moisture conditions in the territory of the interzonal geoecotone «forest-steppe and steppe» of Ukraine. For example, for the Haivoron and Zavalliv territorial communities of Kirovohrad region, we have a number of representative observations of air temperature and precipitation made at the Haivoron weather station since 1924 (Tables 1-3) [17; 20].

The average monthly temperature and precipitation for 1961-1990 was used as the climatic norm until 2020 (Table 1). Taking into account the trends in temperature and precipitation, starting in 2021, new climatic norms were adopted, calculated according to each meteorological station (Table 2). Thus, the average annual temperature increased by 1.3 °C, and precipitation decreased by 27 mm (Tables 1, 2).

Table 1 − Average monthly temperature, precipitation and relative humidity at the Haivoron meteorological station for 1961-1990.

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
t °C	-5.1	-3.6	1.2	9.1	15.2	18.2	19.5	18.9	14.4	8.3	2.8	-1.6	8.1
Precipitation, mm	38.0	39.0	34.0	41.0	55.0	85.0	85.0	55.0	42.0	28.0	39.0	41.0	582.0

Table 2 − Average monthly temperature and precipitation at the Haivoron meteorological station according to the calculations of the climatic norm for 1991−2020.

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
t,°C	-3.0	-1.6	3.2	10.2	15.9	19.6	22.5	20.7	15.2	9.0	3.5	-1.3	9.4
Precipitation, mm	32.0	29.0	33.0	36.0	52.0	81.0	75.0	49.0	53.0	39.0	40.0	36.0	555.0

There is a downward trend in soil moisture. The simplest reason is that if annual precipitation varies (2019 - 536.7 mm, 2020 - 473.7 mm. 2021 - 649.5 mm, 2022 - 475.8 mm, 2023 - 454.1 mm), remaining approximately the same, but the temperature rises and evaporation increases. For example, as of July 2024, the dry soil layer was 60 cm, which is largely due to high temperatures (over 30 °C) for a long time. The ratio of precipitation to evaporation, which reflects the moisture (aridity) coefficient, affects natural ecosystems more than the absolute amount of precipitation alone.

The analysis of the results of meteorological observations for 1961-1990, 1990-2019, 2020-2024, taking into account the average temperature, precipitation, relative humidity, evaporation, and the accepted climatic norm, showed that the territory of the Haivoron and Zavalliv territorial communities is located within the subhumid zone of degradation and desertification and is characterized by moisture coefficients, respectively: 1.2, 1.0, 0.9 [17, 20].

Thus, we should not forget about the need to deploy irrigation systems. In short, new challenges mean new tasks. If we think about them in time, the Haivoron and Zavalliv territorial communities will be able to win a worthy place as centers of agricultural production in the new realities of management.

An integral component of hydrometeorological support is the mandatory and systematic provision of urgent and general hydrometeorological information, including the state of water bodies, to state authorities, local governments and the public. The territory of the Haivoronsky Old Industrial District has a fairly extensive river network, with the Pivdennyi Buh River and its tributaries flowing through its territory, which is one of the largest rivers in the Haivoronsky district and Ukraine as a whole. The distribution of rivers and the density of the river network are determined primarily by the peculiarities of the relief, climate, lithological composition of rocks and economic activity of the population [17; 19; 20].

As you know, according to I. Voyeikov: «rivers can be considered as a product of climate», which remains true today, since all other factors, united under the general name of landscape, can only partially affect the conditions of river nutrition without changing its basic character. This fully applies to the territory of the Haivoron and Zavalliv territorial communities. Rivers are fed mainly by rain, melted snow, groundwater and groundwater. The water regime is generally constant, with spring floods, summer and winter low water, and ice formations in winter (except in certain areas). However, spring floods have not always been pronounced in recent decades due to the fact that the permanent snow cover does not last long as a result of frequent thaws. Rain floods (minor increases in water levels) occur mainly in the summer after heavy rains or prolonged rains in the fall. As a result of the disruption of the precipitation regime, the level of groundwater and rivers has significantly decreased [13].

Table 3 − Extreme temperatures and frequency of adverse weather events at the meteorological station Haivoron.

No.	year	$t^0 \geq 30^0C$	max. t ºC	min. t ºC	thunder-storm	hail	fog	rainfall	Snow/ wet snow	rainlessness
1	2006	18	33.1	-27.6	28	1	33	47	10/2	8
2	2007	54	39.9	-18.0	30	1		58	5	40
3	2008	26	37.9	-18.7	27		31	68	6/4	11
4	2009	35	35.4	-20.0	32		33	62	7/1	20
5	2010	42	36.3	-27.0	46	1	39	66	/1	11
6	2011	28	33.5	-16.2	29	3	23	68	9/2	20
7	2012	58	33.5	-28.4	38	2	24	90	8/1	35
8	2013	24	33.4	-17.2	38	2	47	75	12	23
9	2014	23	35.2	-23.4	28	4	38	75	4	15
10	2015	47	37.0	-19.8	23	2	22	87	8/3	34
11	2016	39	35.2	-21.8	31	2	19	82	19/4	9
12	2017	40	37.4	-20.3	29	3	21	59	6/1	20
13	2018	31	33.5	-22.4	27	1	34	58	10/3	25
14	2019	47	35.4	-19.2	46	3	30	64	1/4	21
15	2020	53	35.0	-9.8	27		18	68	1/9	22
16	2021	31	34.1	-18.4	36	2	22	75	4/7	18
17	2022	26	35.4	-12.3	28		18	75	2/20	18
18	2023	33	37.2	-13.0	28		8	75	1/6	23
19	2024	15	35.1	-15.8						24

Due to this trend of shortening the duration of snow cover in winter, experts at the Borys Sreznevsky Central Geophysical Observatory note that the period of «classic» winters is coming to an end. This period is being replaced by another one with the «winter season» [10]. While 15-20 years ago it was believed that ice on all rivers formed, as a rule, in mid-December and melted mostly in March, in modern conditions, stable ice cover on rivers does not form or its duration is insignificant. Changes in climatic conditions also affect the flow regime.

At the beginning of the twenty-first century, due to warming, the role of air temperature as one of the main climatic factors increased. Particularly significant is the increase in air temperature during the winter hydrological season and its transition through 0°C into positive values, which leads to a decrease in water reserves in the snow cover before the start of the flood, as well as the depth of soil freezing and the formation of winter floods. Climate change has resulted in a decrease in maximum and annual runoff [10,13]. In particular, there is a decrease in flood peaks and an increase in low water runoff, an increase in the number of thaws, a shift in the course and intensity of rains towards increased erosion hazards, and overgrowth and siltation of small rivers. At the same time, there are devastating floods caused by intense rainfall. Therefore, there is an urgent need to adapt territorial communities (urban areas and areas of industrial and agricultural use) to climate change.

The geomorphological and climatic conditions of the territory of the Haivoronsky old industrial area, the formation of surface runoff, and the different intensity of erosion processes affect the amount of river sediment. Most of them get into rivers and reservoirs as a result of surface flushing of plowed river valley slopes. The formation of small riverbeds in modern conditions is characterized by an almost twofold increase in the volume of sediment and the particle size distribution of bottom sediments. This is due to increased soil washout as a result of changes in the use of agricultural land and a significant increase in the area of plowed land [19].

Despite the relatively large number of rivers, the Haivoron and Zavalliv territorial communities are insufficiently provided with local water resources, and hydrogeological conditions are not favorable for the formation of groundwater reserves, as the area is located in the Ukrainian crystalline massif zone. This is the reason why about 30% of the drilled wells are waterless, while others have low flow rates, which makes it possible to meet mainly the needs of agricultural production [22].

a)

b)

Fig. 1. Flooded quarry sites: a) Zavalliv graphite deposit;

b) Haivoron migmatite field.

In total, there are 89 artificial water bodies (ponds and reservoirs) on the Southern Buh River and its tributaries within the Haivoron Old Industrial District that regulate the flow of water. Their total area is 1091.4 hectares. A special place is occupied by reservoirs resulting from the flooding of the spent areas of quarries and the creation of tailing ponds for the treatment of waste from the concentrator (Fig. 1, 2).

Fig. 2. Takyrs and aeolian formations resembling arid morphosculpture arise with the drying of the solid phase of the tailings.

Accordingly, groundwater also plays an important role. Today, high-quality drinking, slightly mineralized groundwater reserves suitable for irrigation, expansion of the drinking water supply network and production of bottled water have been discovered within the study area. South of the Zavalliv graphite field, the Kirovgeologiya State Geological Enterprise's exploration and survey expedition No. 46 discovered radon healing waters in 1988 during geological survey work. Four wells in total produced more than 0.5 m3/hour of highly mineralized radon water. One of the natural monuments of local importance is the Ivankova Krynytsia spring, which covers an area of more than 2 hectares and is located in a large flat beam near the village of Kotivka.

Along with the presence of an extensive hydrological network, a number of negative factors worsen the ecological condition of water bodies. The rivers of the Haivoron region have experienced a significant anthropogenic load - their basins are areas of ancient settlement and plowing. During the twentieth century, the area of forests, especially on floodplains and terrace slopes, decreased, water quality deteriorated, and numerous environmental problems arose.

Most small rivers suffered particular damage in the 1960s and 1970s, when the riverbeds were straightened and dredged, which resulted in a qualitative change in their morphology and development conditions. These actions resulted in a change in the natural types of channel processes (meandering and floodplain multi-branching) and the processes of siltation began to prevail. It is worth emphasizing that anthropogenic impact on small rivers in modern conditions is one of the main factors that determines the formation of riverbeds, the amount of water flow, the nature of sediments, etc.

a)

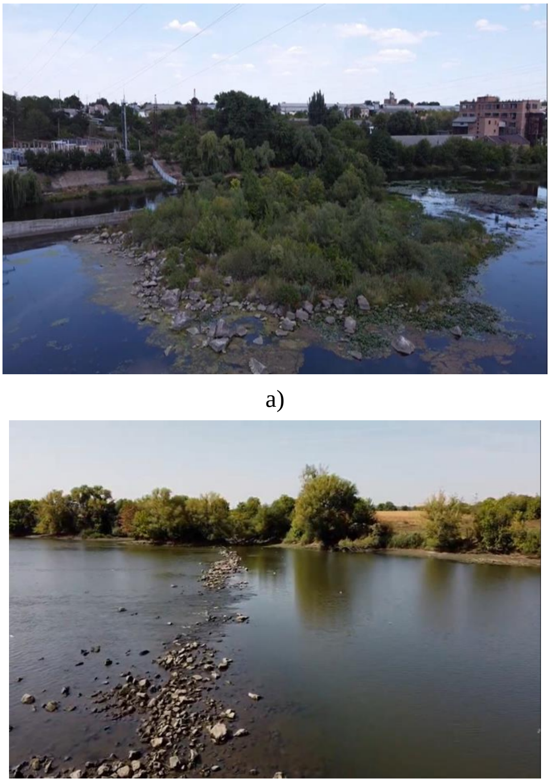
b)

c)

Fig. 3 (a, b, c) Changes in the course of the Southern Bug in the territory of the Haivoron and Zavalliv territorial communities as a result of the construction of hydroelectric power plants (HPP):
a) Haivoron HPP and the Haivoron reservoir; b) Berezivska (Savranska) HPP;
c) Salkivska HPP [16,18].

As a result of the construction of hydroelectric dams, new tracts of the lower reservoir reaches were formed, with the central channel or rapids as the paleolandscape basis. Depending on the mode of operation of hydroelectric power plants, their parameters, and the type of dams, these tracts have acquired different characteristics that are constantly changing. In particular, as a result of the construction of the Haivoron HPP, a reservoir was formed, the corresponding coastal morphosculpture began to form, and abrasive and accumulative processes developed (Fig. 3) [1; 17; 19].

In addition, as a result of anthropogenic development of the Southern Bug riverbed and its tributaries, artificial islands, derivation channels, technological embankments, reservoirs, and ponds were created, which significantly changed the nature of the currents, intensified or slowed down erosion processes, and led to the emergence of various previously uncharacteristic landforms (Fig. 4) [1; 18; 19].



a)

b)

Fig. 4 (a, b). Artificial landforms in the Southern Buh riverbed:

a) an embankment island created to prevent erosion of the river bottom during the discharge of water from the Haivoron HPP; b) a technological embankment used during exploration work near Zavallia.

Today, the problems of rational use, conservation and reproduction of water resources in the Haivoron Old Industrial District have become more acute and require immediate solutions. The permitting system for the planned use of water for irrigation is not working, there are no specialized organizations dealing with the construction and maintenance of reclamation systems, and the «Procedure for determining the size and boundaries of water protection zones and the regime of economic activity in them» is systematically violated. A large number of ponds are shallow and overgrown, turning into moisture evaporators [17; 19].

The Southern Bug River is subject to constant anthropogenic pressure; its water is used for technical and municipal needs, and for irrigation of fields. At one time, it was one of the cleanest rivers in Ukraine, but during the twentieth and twenty-first centuries, pollution from industrial emissions and the use of pesticides in agriculture led to a decline in fish stocks and the extinction of some species.

Since a significant amount of water is used for domestic needs, a large amount of chemical impurities enter water bodies in the reverse process, affecting the overall ecological state of the river and the organic world in it (Tables 4-6) [8, 9].

Table 4 − Concentration of chemical compounds entering the Southern Bug River within the city of Haivoron according to 2020 data.

Polluting substances, the discharge of of which is regulated	Actual concentration, mg/dm^3	Actual discharge, g/hour	Maximum permissible concentra-tions mg/dm^3	MPD (Maximum permissible discharge), g/ hour	MPD, recalculated in t/year
Ammonium nitrogen	7.7	112.34	0.5	15.74	0.137
BOC_5 (biological oxygen consumption)	70.5	1028.52	15.0	472.28	4.113
ChOC (chemical oxygen consumption)	205.0	2990.75	80.0	2518.80	21.939
Suspended solids	15.25	222.48	15.25	480.15	4.182
Petroleum products	0.1	1.46	0.05	1.57	0.014
Nitrates	90.2	1315.93	40.0	1259.40	10.969
Nitrites	4.58	66.82	0.23	7.24	0.063
Sulfates	109.8	1601.87	100.0	3148.50	27.423
Phosphates	19.0	277.19	2.145	67.54	0.588
Chlorides	134.4	1960.76	134.4	4231.58	36.857
Dry residue	1065.5	15544.58	1000.0	31485.00	274.233

Table 5 − Water quality assessment of the Southern Buh River within the Haivoron Reservoir in 2010-2020 by the CPI (combinatorial pollution index) method according to fishery MPC (maximum permissible concentration).

n=10; n′=8; M=80%; CPI =42; SCPI =4,2; quality class IV a - «very dirty»										
Indicator	[BOC_5]	[O_2]	[SO_4^{2-}]	[Cl^-]	[NH_4^+]	[NO_3^-]	[NO_2^-]	[Pmin]	SSAS	[ChOC]
N	41	41	41	41	41	41	41	41	41	41
N′	30	1	41	40	4	15	36	0	0	39
Hi	73.1	2.4	100	97.6	9.8	36.6	87.8	0	0	95.1
Evaluation indices	4	1	4	4	1	3	4	1	1	4
Ki	1.89	0.54	5.05	8.05	0.42	3.15	3.57	0.27	0.34	1.75
Evaluation indices	1	1	2	2	1	2	2	1	1	1
Evaluation points Si	4	1	8	8	1	6	8	1	1	4

Table 6 − Comparative assessment of the water quality of the Southern Bug River within the v. of Stavky in 2010-2020 by the CPI method according to fishery MPC standards.

n=10; n′=8; M=70%; CPI =31; SCPI =3,1; quality class III b - «dirty»										
Indicator	$[BOC_5]$	$[O_2]$	$[SO_4^{2-}]$	$[Cl^-]$	$[NH_4^+]$	$[NO_3^-]$	$[NO_2^-]$	[Pmin]	SSAS	[ChOC]
N	35	35	35	35	35	35	35	35	35	35
N′	29	3	0	0	7	1	31	0	1	17
Hi	82.8	8.6	0	0	20	2.9	88.6	0	2.9	48.6
Evaluation indices	4	1	1	1	2	1	4	1	1	3
Ki	2.21	0.72	0.33	0.13	0.57	0.4	32.4	0.27	0.36	1.2
Evaluation indices	2	1	1	1	1	1	3	1	1	1
Evaluation points Si	8	1	1	1	2	1	12	1	1	3

Given the growing negative impact of global climate change (warming, increased and uneven precipitation, flood risks), as well as the overregulation of small and medium-sized river flows in the Southern Bug basin within the Haivoron and Zavalliv territorial communities, we can expect the intensification of dangerous exogenous geological processes. Soon, the main problematic issue will be the study of the state of groundwater in the region and the problems associated with it. It is of great importance to assess the protective properties of the aeration zone, which is a natural protection of groundwater from pollution in natural and extreme conditions. Its characteristics determine the time of contamination penetration into the first aquifer from the surface, and the processes of sorption and ion exchange are carried out within it. The main natural indicators on which the estimates of the time of pollutant intrusion from the ground surface into groundwater are based are its thickness and lithological composition of the pore zone, which is largely modified as a result of anthropogenic load.

The study of critical infrastructure of hydro resources is also gaining special attention in the time of russian aggression. After the destruction of the Kakhovka hydroelectric power plant, there is an understanding of the development of a number of relatively transient short-term and long-term, mostly irreversible, environmental and technological hazards to the operation of critical infrastructure. The presence of three hydroelectric power plants on the Southern Buh River within the Haivoron old industrial area requires strict control over their condition.

During the observations in the 80s and 90s of the twentieth century, plants and animals characteristic of the Ukrainian steppe were rarely found in the area. Today, some species are widespread throughout the territory of the Haivoron territorial community.

On the example of the Haivoron territorial community, it can be argued that the boundaries of natural zones are shifting and, given the trends in temperature changes, it is reasonable to assume that the study area will eventually turn into a dry steppe [2].

CONCLUSION

Designing measures to adapt territories to climate change requires taking into account a number of climate parameters, including extreme ones, which need to be carefully revised due to the availability of extended observation series and climate change that has occurred. Since, as a rule, we are talking about the use of probabilistic and assured indicators, it is advisable to determine them based on a full series of observations, rather than being satisfied with a 30-year observation period.

Global climate change and the replacement of forest, forest-steppe and mainly steppe landscapes with field landscapes have led to significant regional changes in climatic conditions within the interzonal geoecotones of Ukraine. For example, within the interzonal forest-steppe geoecotone of Ukraine, the annual precipitation trend has been mostly negative for almost 60 years, and relative humidity has been decreasing. There is a general trend of temperature increase, which cannot be compensated for by an increase in precipitation in certain periods.

Accordingly, the humidification coefficient decreases. The territory of the geoecotone is covered by aridization processes. Altogether, this leads to the destruction of the unstable dynamic balance of landscapes in the transition zone of forest-steppe and steppe. Possible consequences may include a shift of the steppe boundary to the north, a change in the species composition of vegetation, a change in landscape structure, and a deformation of the configuration of the interzonal geoecotone boundaries. Field landscape studies confirm that these processes have already begun.

According to climate data, the territory of the Haivoron and Zavalliv territorial communities is covered by aridization and desertification processes. There is a general clear trend of temperature increase, which cannot be compensated by an increase in precipitation in certain periods and, accordingly, an increase in the humidification coefficient. The statistical analysis of the results of hydrometeorological observations shows that the territory of the Haivoron old industrial area is characterized by processes and phenomena similar to those observed throughout Ukraine: constant uneven precipitation, which is associated with abnormally wet periods with extremely severe droughts, especially in the last 15-20 years; the spread of drought phenomena that were not considered the norm for the study area. Thus, the fact of redistribution of average annual precipitation is undeniable. A steady decrease in precipitation in the winter-spring period cannot be fully compensated by an increase in precipitation in the summer-autumn period, which leads to the destruction of the dynamic relationship that once existed in the transitional zone of forest-steppe and steppe, to which the study area belongs. Possible consequences of temperature increase and redistribution of precipitation may also include: 1) shifting the boundaries of the steppe zone to the north and aridizing the territory of communities; 2) changing the species composition of vegetation; 3) changing the landscape structure of the territory, etc. Thus, the location of the Haivoronsky district within the interzonal forest-steppe geoecotone of the Right Bank of Ukraine and relative to the Voyeikov barometric axis, as well as local landscape features, contribute to the formation of climatic conditions that are unique to this district. Their further research is necessary for a more detailed understanding of the nature of the Haivoron district, rational use of natural resources, solving environmental problems and nature protection.

As a result of climate change, in the face of a significant precipitation deficit in the region and the prolongation of the low-water period, which has already lasted for 15 years in a row, the issue of rational use of water resources is of particular importance. After all, the lack of «high water» does not allow to flush riverbeds and accumulate the necessary amount of water. This has led to the catastrophic shallowing of the Southern Bug, whereas 10-15 years ago not everyone could swim across it, but now, in some places, it is possible to wade across (Fig. 5). The situation is very complicated and requires a deeper study and decisive action to improve the river's water content [3].

a)

b)

Fig. 5 (a, b). Shoaling of the Southern Bug River: a) near the narrow-gauge bridge across the river (the town of Haivoron); near the village of Zavallia [3; 17].

In addition, within the Haivoron old industrial area, the level of pollution of the Southern Bug is quite high, which indicates that its waters are unsuitable for the safe conduct of certain types of business. The dominance of nitrogen compounds, BOC_5 and ChOC is associated with significant organic pollution of the river by wastewater and limited self-purification capabilities due to significant water regulation. This is due to the significant level of anthropogenic pressure on the Southern Bug River basin and the associated wastewater discharge from enterprises and farms of various forms of ownership.

Taking into account the intense anthropogenic load on the water bodies of the Haivoron and Zavalliv territorial communities, it is advisable to carry out regular hydrological observations of the flow of the Southern Bug and its tributaries by arranging a hydrological post and conducting regular surveys of the state of water bodies.

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DETERMINATION OF TECHNICAL AND ECONOMIC INDICATORS OF LARGE-SCALE LOW-CARBON HYDROGEN PRODUCTION OPERATING NUCLEAR POWER PLANT UNITS IN UKRAINE

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ABSTRACT

The attainment of-zero carbon dioxide (CO_2) emissions by 2050, as outlined in IPCC Special Report on Global Warming of 1.5°C, has led to the extensive adoption of hydrogen as a new carbon-free energy carrier to decarbonize the economy. Hydrogen production through electrolysis plants near existing Ukrainian nuclear power enables large-scale in the short term can complement hydrogen production from renewable energy sources. Based on statistical data on the operation of NPP power from 2018 to 2021, the average annual utilization factors of the installed capacity of the power units were calculated, and the optimal electric power for the electrolysis plant was proposed. Considering the technological parameters of electrolysis plant, namely, the consumption of electric energy for the production of 1 kg of hydrogen at 52 kWh and the consumption of feed water at 22 liters, we obtained a total productivity low-carbon hydrogen amounting to 17417 kg per hour or 148 thousand tons per year. The Levelized Cost of Hydrogen (LCOH) produced from electricity by existing nuclear power plants is 3.12 \$/kg H_2, is 2.5 and 4.7 times lower than the corresponding costs for electricity from wind and solar power plants, respectively.

Keywords: low-carbon hydrogen, electrolysis, average annual installed capacity factor, nuclear power plant units, levelized cost of hydrogen.

INTRODUCTION

The world is confronted with an urgent global climate challenge to prevent the increase in global mean surface temperature (GMST) from exceeding 1.5°C above the pre-industrial average, which is likely to have serious consequences for human health and society [1,2]. Humanity is already 80% of the way to this threshold: GMST for 2018 – 2022 was approximately 1.2°C above the pre-industrial average [3]. In response to this challenge, most countries have agreed to reduce emissions in the Paris Agreement [4], with renewed national commitments at the Glasgow Climate Pact in 2021 [5]. Hydrogen is an energy carrier because it does not emit carbon when burned, and thus use does not directly contribute to greenhouse emissions [6]. Consequently, energy is poised to play a significant role in the decarbonisation of key sectors in modern societies, road and maritime, steel and chemical production, and heating and cooling buildings. By 2025, it is anticipated that countries with a hydrogen strategy for more than 80% of the global domestic product. International Energy Agency (IEA) has provided a roadmap for achieving net-zero emissions by 2050 indicating that approximately 530 million tons of hydrogen year will be needed worldwide This represents roughly the demand for hydrogen in 2020 which was around 90 million tons.

Hydrogen strategies are motivated by the necessity for low-carbon hydrogen production. Presently, approximately 96% hydrogen is generated through steam reform of methane or coal gasification [7]. These methods are unsustainable as they consume fossil fuels and produce substantial carbon dioxide emissions [12]. Carbon capture and storage (CCS) processes are well-established, but they reduce production efficiency and there is debate about the extent of uncontrolled methane emissions [13; 14]. While most attention has been paid to water electrolysis using renewable energy [15; 10], recent studies have also shown the feasibility of alternative low-carbon production routes using nuclear energy [16; 17].

Converting just 4% of current to electricity generated at nuclear power plants would carbon emissions by 60 tons per year. If all hydrogen were produced using nuclear energy, carbon dioxide emissions could be reduced by more 500 million tons per year.

Several countries are currently implementing or the possibility of producing hydrogen using nuclear power plants to help decarbonize their energy, industrial, and transport sectors. This also allows for increased returns from nuclear power plants, which will contribute to their increased profitability.

One of the key advantages of nuclear power is its capability to operate at very high-capacity utilization rates. This enables the large-scale production of carbon-neutral hydrogen, an emerging energy source with diverse applications. Hydrogen using nuclear energy economically viable compared to other energy sources in several significant ways:

- firstly, it is higher-quality production process, as nuclear energy has the highest efficiency in generating energy without greenhouse gas emissions;
- secondly, there is a potential for large-scale hydrogen production;
- third, the operating costs of nuclear plants are less susceptible to fuel price volatility compared to fossil fuel power plants. Consequently, a 50% increase in fuel costs results in only a ~5% increase in the total cost of nuclear electricity production, indicating that the economics of hydrogen production through nuclear power are more stable.

The «H2@Scale» initiative, launched by the U.S. Department of Energy in 2020, is examining the feasibility of developing nuclear power systems that simultaneously produce hydrogen and low-carbon electricity [18]. Among the numerous projects funded by the initiative, one will be implemented by three U.S. commercial electric utilities in collaboration with the Department of Energy's Idaho National Laboratory.

In the UK the non-profit «Energy Systems Catapult» developed a comprehensive model of the entire energy system, now includes the possibility of using advanced nuclear hydrogen production [19]. This model provides insights into the most cost-effective energy generation structure that can achieve net zero greenhouse emissions by 2050. The results indicate advanced nuclear reactors can be utilized to produce hydrogen alongside other technologies.

The French state-owned company «EDF» aims to increase profitability of nuclear power plants being constructed the UK by utilizing some of the energy from the second unit of Sizewell C power plant for electrolysis [20]. The modular nature of the electrolysis them to be used at the nuclear power plant, Hinkley Point C, as well. «EDF» plans to harness the excess capacity its nuclear plants during periods of overproduction to produce hydrogen through electrolysis.

The IEA's 2019 report "The Future of Hydrogen" indicates that the LCOH is contingent upon the number of operational hours of the electrolysis. When the electrolysis is utilized for 500 hours annually, hydrogen can be produced at an LCOH of approximately 4 \$/kg H_2. Conversely, operating the electrolysis for 8000 hours per year reduces the cost to 0.50 \$/kg H_2 [21]. The French company plans to install a 2 MW experimental electrolysis capable of producing 800 kilograms of hydrogen per day by 2035, the capacity could expand to 550 MW with a daily production of 220 tons. «EDF» anticipates the LCOH to be approximately 2.44 €/kg H_2 over a 20-year, electricity prices and technology costs.

Nucleareurope (formerly FORATOM) emphasizes the importance of utilizing all mature low-carbon energy sources, including nuclear power, which has the capability to produce hydrogen [22]. Nuclear power can supply both electricity and heat around the clock to facilitate efficient hydrogen production through various processes. Current nuclear power plants encounter challenges in operating within energy systems that have a growing proportion of variable renewable energy. Hydrogen offers the potential for energy storage and enhances the flexibility of these hybrid systems. Furthermore, hydrogen produced for external sale can serve as a valuable alternative revenue stream for nuclear power plants with surplus electricity.

High power factor: nuclear power plants generate electricity continuously, irrespective of weather and market. This makes them an ideal source of electricity for hydrogen production through electrolysis, ensuring maximum utilization over the entire lifetime of costly electrolysis. A reliable and stable power supply is crucial for large-scale hydrogen production.

Ukraine is among the countries with developed nuclear energy industry. In terms of the share of nuclear power generation in electricity production, Ukraine ranks fourth globally, France, Slovakia, and Hungary. Ukraine operates power units with a total capacity 13835 MW at four nuclear power plants: six at Zaporizhska NPP, four at Rivne NPP, three South-Ukraine NPP, two at Khmelnitsky NPP. Most the NPP power units are with VVER–1000 series reactors, which are similar in technical to foreign PWR reactors. As of end of 2021, twelve power units have completed their standard 30-year service life. The operating life of eleven of these has already been extended by 10 – 20 years, and a to extend the life of another unit is expected. In the medium term, the standard operating life of three additional nuclear power units will expire (Zaporizhska NPP – 6 in 2026, Rivne NPP – 4 and Khmelnitsky NPP – 2 in 2035). One of the priority tasks for the operating organization-operator of nuclear power plants, Joint Stock Company «National Nuclear Energy Generating Company «Energoatom» is to extend the operating life of power units to 60 for the majority power units.

According to operational data from the Ministry of Energy of Ukraine, electricity production in the United Energy System (UES) of Ukraine increased by 5.2% (7 billion 719.5 million kWh) in 2021 compared to 2020, reaching 156 billion 575.7 kWh. Last year (2021), Ukrainian nuclear power plants increased their electricity generation by 13.1% to 86 billion 2054 million kWh. Specifically, production at Zaporizhska NPP amounted to 35 billion 457.5 million kWh (+23.4% compared to 2020), South-Ukraine NPP – 18.626 billion kWh (–3.8%), Rivne NPP – 18 billion 827.3 million kWh (+10.3%), and Khmelnitsky NPP – 13 billion 294.6 million kWh (+20,5%). The share of nuclear power plants in the structure of electricity production in 2021 was 55.1% (in 2020 – 51.2%), thermal power plants, combined heat and power plants – 29.3% (35.2%), hydroelectric power plants – 6.7% (5.1%), block stations – 1% (1.2%), and renewable sources – 8% (7.3%). Thus, the main source of electricity production in Ukraine today is existing nuclear power plants, which is due not only to the available capacity of existing power units but also to the low cost of electricity production.

METHODS AND EXPERIMENTAL PROCEDURES

The purpose of the study is to determine the required capacity of electrolysis plants for the production of low-carbon hydrogen near existing nuclear power plant units in Ukraine, using analytical, thermophysical and technological analysis methods.

The research objectives of the study are calculating the utilization rate of installed capacities of operating units of Ukrainian nuclear power plants based on collected statistical data on the efficiency of operation existing nuclear power units for 2018 – 2021. Based on the results of the obtained coefficients and technological parameters of the operation of electrolysis plants, the required optimal capacity for the production of low-carbon hydrogen was determined and economic indicators were calculated.

THE RESEARCH RESULTS AND DISCUSSIONS

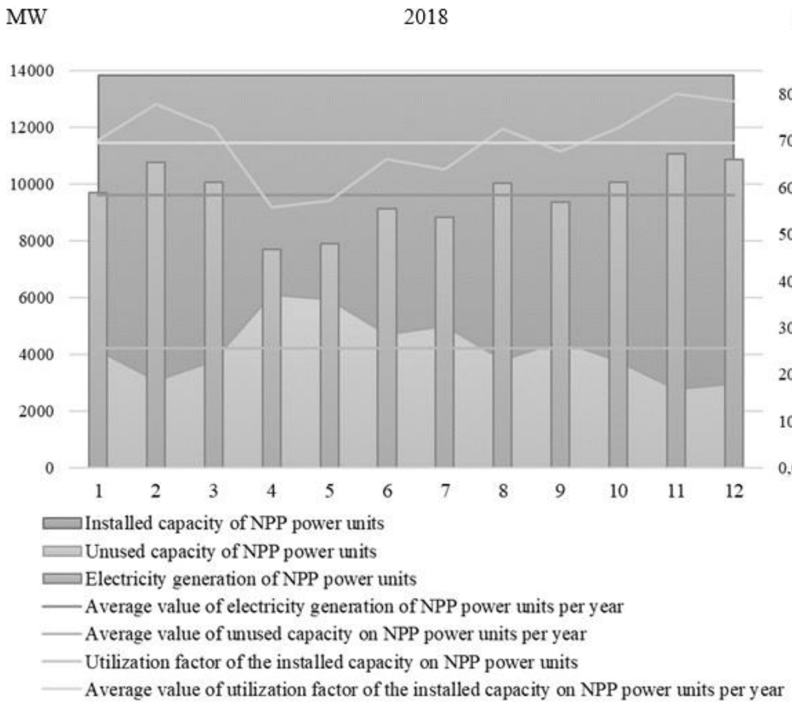
Based on dispatch information received from NPP «Ukrenergo» on the hourly operation of generating capacities of the United Energy System of Ukraine, the average annual utilization factor of the installed capacity of NPP power units was calculated for 2018 – 2021. The results of calculations of unused capacity and utilization factor of power units by month for 2018 – 2021, as well as the estimated average values of electricity production, unused capacity, and utilization factor of installed capacity per year at existing NPP power units are presented in Fig. 1.

Based on the dispatch information on the operation of existing nuclear power plant in Ukraine for 2018 – 2021, the average annual utilization rate of the installed capacity of NPP power units was calculated. It was 69.6% in 2018, decreased to 62.7% in 2020, and increased to 71.2% in 2021. The amount of free electricity that is not used in the Ukrainian energy market at existing NPP units ranges from 3983 MWh to 5156 MWh and can be used for the production of low-carbon hydrogen using electrolysis plants (Fig. 2).

To date, 15 units have been installed in at four existing nuclear power plants, 13 which are VVER – 1000 with an installed capacity of 1000 MWh. Therefore, it is advisable to install electrolysis plants with a capacity of 1 GW. Considering the average annual utilization rate of the installed capacity of NPP power units, such electrolysis plants can be installed in quantities of 3 – 4 units (i.e. with a total electric capacity of 3 – 4 GW).

Since Ukraine adopted an association agreement with the European Union in 2014, our state is obliged to implement documents that combating climate change, as well as developing environmentally friendly types electricity. «Green» hydrogen is an environmentally safe source of energy. During its combustion, steam is produced instead of carbon dioxide as occurs with other types of fuel. Compared to ordinary natural gas, hydrogen has a high level of energy intensity, making its use more economically profitable.

Hydrogen production Ukraine would address numerous issues, including political ones. By utilizing hydrogen fuel instead of natural gas imported from Russia, we could reduce our dependence on our neighboring country. Additionally, hydrogen production is necessary to avoid complications in international arena. For instance, the European Union may implement a carbon tax on products originating from Ukraine. Such sanctions can be imposed not only on our country but also on other states that neglect the environmental and fail to reduce carbon dioxide emissions. If Ukrainian products are to additional taxes, exporters will face significant challenges, the country will lose vital revenue.


MW
2018
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8000
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70,0
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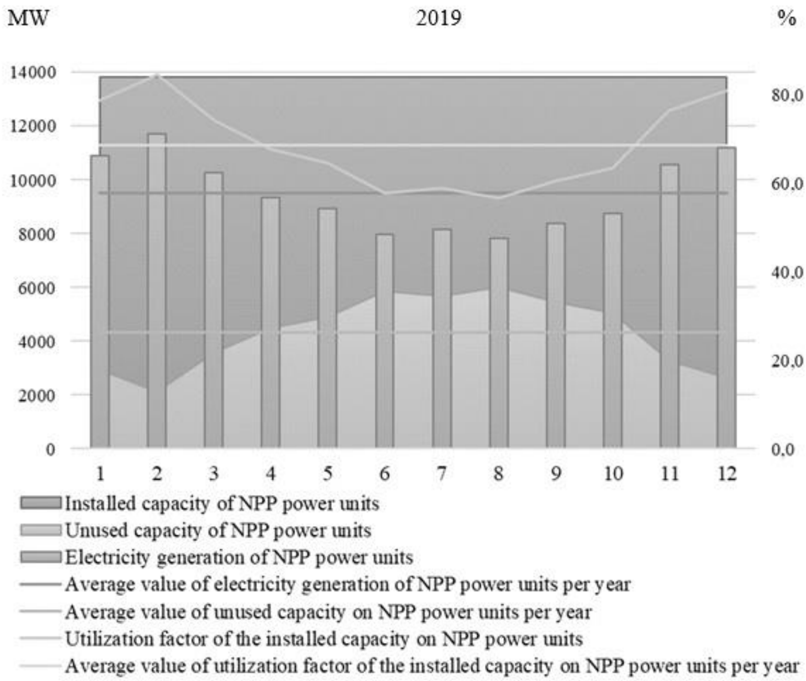
1 2 3 4 5 6 7 8 9 10 11 12
Installed capacity of NPP power units
Unused capacity of NPP power units
Electricity generation of NPP power units
Average value of electricity generation of NPP power units per year
Average value of unused capacity on NPP power units per year
Utilization factor of the installed capacity on NPP power units
Average value of utilization factor of the installed capacity on NPP power units per year


MW
2019
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10000
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6000
4000
2000
0
80,0
60,0
40,0
20,0
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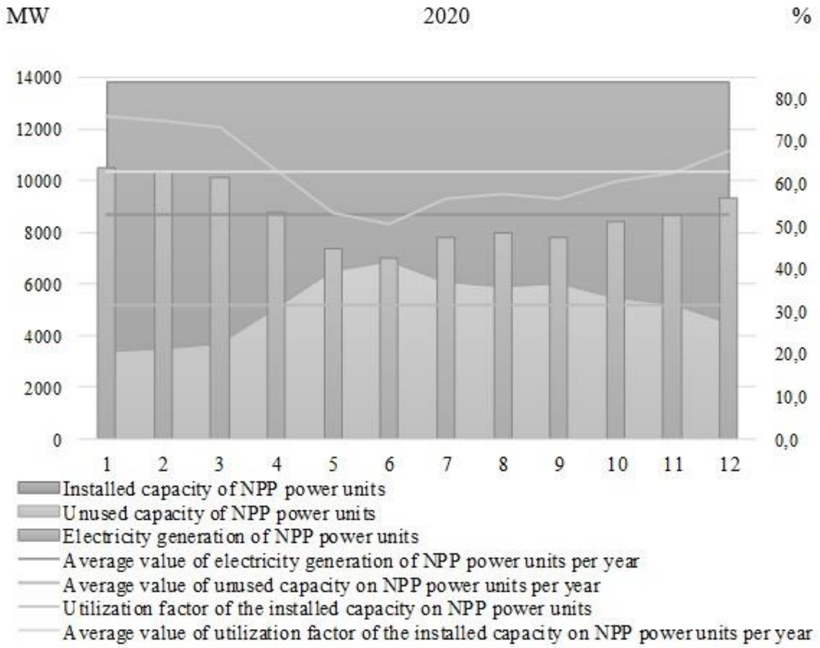
1 2 3 4 5 6 7 8 9 10 11 12
Installed capacity of NPP power units
Unused capacity of NPP power units
Electricity generation of NPP power units
Average value of electricity generation of NPP power units per year
Average value of unused capacity on NPP power units per year
Utilization factor of the installed capacity on NPP power units
Average value of utilization factor of the installed capacity on NPP power units per year



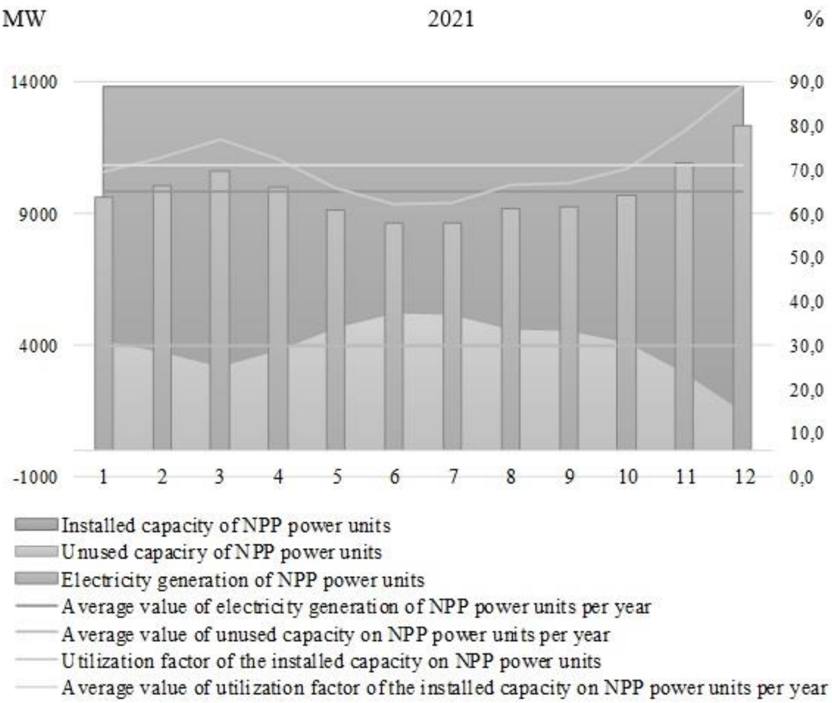


Fig. 1. Results of the operation existing power units at Ukrainian nuclear power plants from 2018 to 2021.

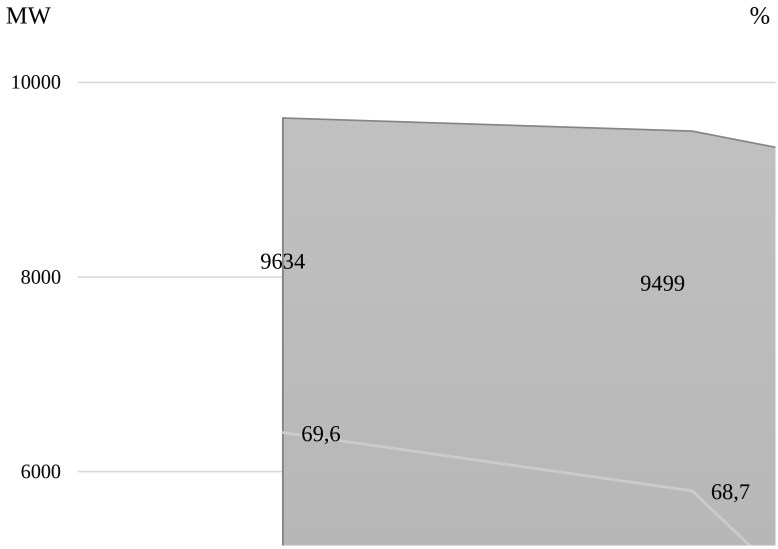


Fig. 2. Assessment of the unused capacity of existing nuclear power plant (NPP) units for the production of low-carbon hydrogen through electrolysis plants.

Even among supporters of clean technologies, there is no consensus on what kind of hydrogen be considered clean and one that does not harm the environment or exacerbate climate change. Hydrogen called «green» if the H_2 molecule obtained from ordinary water by electrolysis, and the electricity is derived from purely sources such as wind, solar or biomass. The mainponent of «green» hydrogen in is Germany, which has already nuclear energy and plans to phase out fossil fuels by 2045. Hydrogen obtained using electricity from nuclear plants is classified as «yellow». Advocates of nuclear argue that «yellow» hydrogen can be as clean as «green» hydrogen. The most powerful for «yellow» hydrogen the is France, where the majority of electricity is by nuclear power plants.

The electrochemical decomposition of water produce hydrogen and oxygen is a relatively straightforward involving two electrodes in an electrolyte connected to a direct current (DC) source. This fundamental of operation applies to all types of electrolysis, differing only in the type of electrolyte used. The most relevant technologies are alkaline water electrolysis (AWE), which operates with a liquid, polymer electrolyte membrane (PEM) cells, which use anomer, and high-temperature or solid oxide electrolysis (SOEC), which have a solid oxide electrolyte. Latter technology is the research stage and not will be further discussed. Table 1 shows the typical technical characteristics of AWE and PEM electrolysis technologies.

Table 1 - Key characteristics the primary technologies for low-temperature water electrolysis.

	AWE electrolysis	PEM electrolysis
Cathode (HER)	$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$	$2H^+ + 2e^- \rightarrow H_2$
Anode (OER)	$2OH^- \rightarrow ½ O_2 + H_2O + 2e^-$	$H_2O \rightarrow ½ O_2 + 2H^+ + 2e^-$
Charge carrier	OH^-	H^+
Electrolyte	Liquid electrolyte KOH	Acidic polymer membrane
Temperature range	60 – 90 °C	RT – 80 °C

Electrodes / Catalyst	Catalyst coated nickel substrates	Noble metals (platinum, iridium)
Typical current density	0.2 – 0.6 A/cm²	1.0 – 2.5 A/cm²
Technology Readiness Level (TRL)	8 – 9 (industrial mature)	7 – 8 (commercially available)
Typical pressure	atm. – 30 bars	atm. – 50 bars (350 bar)
System lifespan: (years)	20 +	10 +
Specific electrical energy demand	4.2 – 5.8 kWh/Nm³ H_2	4.5 – 6.8 kWh/Nm³ H_2
Capital expenditure (stack) minimum 1 MW	270 $/kW	400 $/kW
Capital expenditure (system) minimum 10 MW	500 – 1000 $/kW	700 – 1400 $/kW

Each technology has its own advantages and disadvantages. The general technical characteristics are provided in Table 2.

Table 2 − Advantages and disadvantages of AWE and PEM electrolysis.

	AWE electrolysis	PEM electrolysis
Advantages	▪ Mature, robust, and therefore, proven technology ▪ Multi-MW stacks enable systems with large capacities already today ▪ Potential to use earth abundant and inexpensive materials	▪ Very high-power densities ▪ Compact designs and small footprint ▪ Fast cold start-up time, fast load changing capabilities ▪ Suitable for high pressure operation ▪ Stacks in MW range available ▪ High intrinsic product gas purity
Disadvantages	▪ High material effort on system level by using highly alkaline liquid as electrolyte ▪ Low power densities and large footprint ▪ Additional effort for gas purity required ▪ Slow cold start-up time	▪ Use of expensive materials as titanium and critical platinum group metals (PGM) on cell level ▪ Long-term stability needs to be proven at MW-scale

Taking into account the existing advantages of electrolysis plants, both technological and cost, we will use the parameters of atmospheric alkaline electrolysis to calculate the technical parameters. The required of the electrolysis plant the level of 1 GW, we select a plant with a unit capacity of 100 MW. Therefore, to provide a total electrical capacity of 1 GW, 10 units of such plants necessary. Atmospheric electrolysis is composed standard modules utilizing proven technology essential for the low-carbon hydrogen production process, ensuring efficiency and reliability. The fundamental technological parameters of this module presented in Table 3.

Table 3 − Primary technical of an electrolysis plant with a capacity of 100 MW.

Specifications	Value
Net production rate	19400 Nm^3/h or 41.8 t/day
Production capacity dynamic range	1 to 100% of flow range
Power consumption at stack	4.4 kWh/Nm^3
Purity - with optional purification	from 99.99 to 99.998%

O_2 – content in H_2	< 2 ppm v
H_2O – content in H_2	< 2 ppm v
Delivery pressure	from 1 to 200 bar
Dimensions/footprint	depends on configuration
Ambient temperature	
Process room	from 2 to 40 °C
Rectifier room	from 2 to 35 °C
Electrolyte	25% KOH solution
Feed Water Consumption	1 l/Nm^3

The dimensions of the 100 MW electrolysis plant are illustrated in Fig. 3. The layout of the main equipment the atmospheric alkaline electrolysis plant is depicted in Fig. 4.

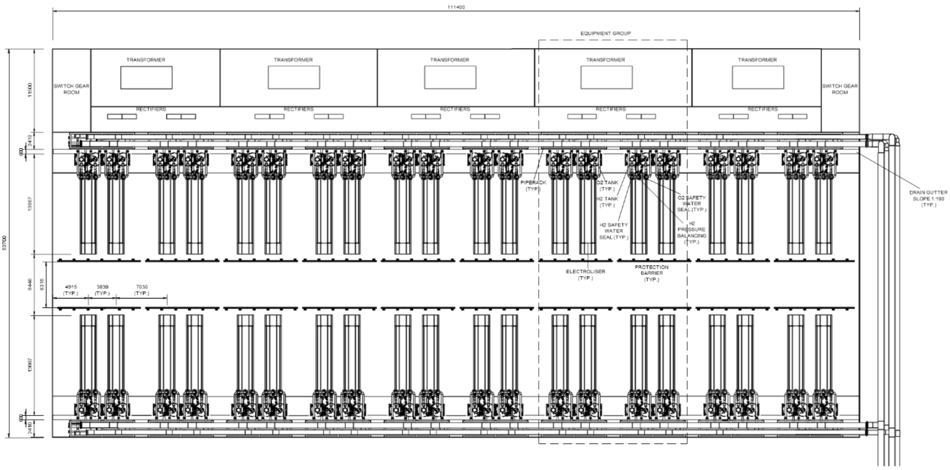


Fig. 3. Location of stacks in an atmospheric alkaline electrolysis plant with a capacity of 100 MW.

Hydrogen atmospheric alkaline electrolysis plant consists of standard modules of proven technology, critical for a hydrogen production process that is efficient, safe and reliable. The transformer and rectifier convert the AC voltage supply into DC current input at the required voltage. The electrolyser is of the filter press type with bipolar electrodes separated by non-asbestos diaphragms. Hydrogen gas is generated at the cathode and the oxygen gas at the anode. Electrolyte system consists of two gas separators and the electrolyte recirculation system. The electrolyte is recovered in the separators. then chilled and recycled into the cell block. The scrubber has three main functions: remove residual traces of electrolyte; cool down the hydrogen; feed water tank. The gas holder is a buffer tank installed between the electrolyser and the compressor or the process at site. If required, a compressor is installed to compress the gas from atmospheric pressure in the gas holder to the pressure required for the process or the storage vessel. Hydrogen generated in the electrolyser is a very pure gas, saturated with water, and its oxygen content doesn't exceed 0.2%. If higher purity is required, the last molecules of oxygen can be removed by catalytic reaction in a deoxidizer. The dryer will dry the gas to reach the suitable dew point. It consists of twin towers filled with a regererative desiccant to absorb the water. The optional gas storage provides a back-up solution or ensures the hydrogen make-up for batch applications with uneven gas consumption.

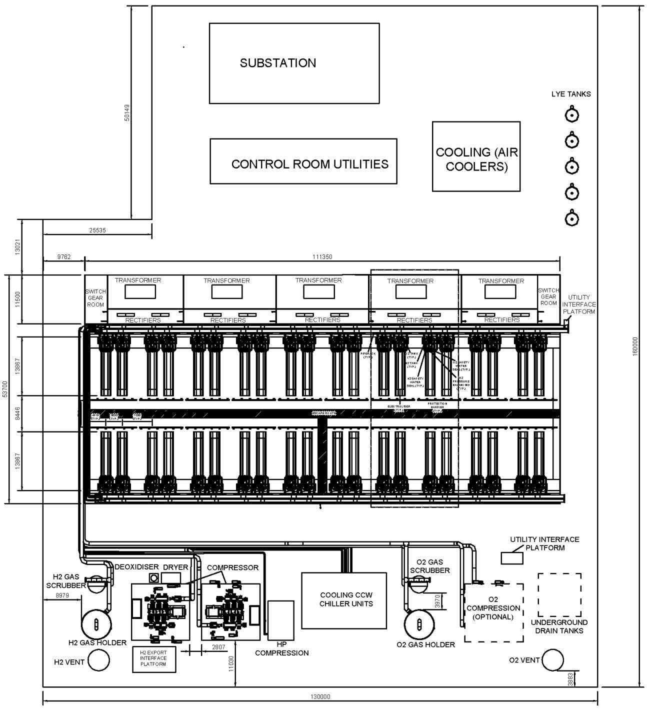


Fig. 4. Layout the main equipment an atmospheric alkaline electrolysis plant with an electrical capacity 100 MW.

To ensure the total of the electrolysis plant of 1 GW, it necessary to install blocks of 100 MW. The required area for the location of the electrolysis plant will be:

- length of 5 modules of 111.400 m, totaling 557.000 m;
- width of 2 modules of 53.700 m, totaling 111.400 m;
- total is 557.0 ×111.4 = 62 049.8 m^2 or 6.20 hectares.

Advantages of atmospheric alkaline electrolysis:

- large power range, including up 1 GW;
- optimal ratio between productivity and equipment location area;
- provides high pressure for storage and further use of hydrogen;
- highly efficient compared to otherer's.

The main material flows for hydrogen production at 1 GW electrolysis are depicted in Fig. 5.

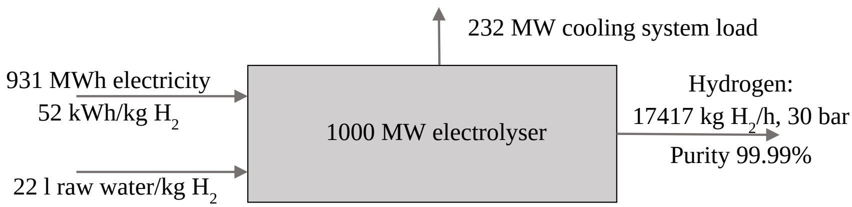


Fig. 5. Main material flows an atmospheric alkaline electrolysis plant with an electrical capacity of 1 GW.

To comprehend the economics of hydrogen production, it is essential to the differences in the structure of operating and investment costs according to the production method. «Grey» hydrogen necessitates less investment (30% of the total cost) compared «yellow» (40%) and «green» (45%) hydrogen, with more than 90% of its operating costs associated with the raw material which is a fossil fuel, such as methane. The of operating costs related to the production of «yellow» (60%) and «green» (55%) hydrogen is up to 80% of the cost of electricity. In the long term, these latter two production methods should share of the cost of production to 20% and 30% respectively, aiming to align with the cost structure of hydrogen. The cost of raw materials is predominant over 90% for fossil fuels in case of «grey» hydrogen and 80% for electricity with and «green» hydrogen with the remainder being divided between technical costs, labor costs and other operating costs.

In the short term, the cost of «grey» hydrogen is the lowest at around 1.6 €/kg H_2. However, low-carbon hydrogen technology needs to evolve to be cost-competitive, whether it is «green» hydrogen (4 to 6 €/kg H_2 – 2 to 3 €/kg H_2), «yellow» hydrogen (below 3 €/kg H_2 to below 2 €/kg H_2), or even «grey» hydrogen (with lower costs of CCS). «Grey» hydrogen is expected to increase in price, particularly due to rise CO_2 and natural gas prices.

Given the significant investment required to establish an electrolysis plant for producing low-carbon hydrogen it is essential to enhance the cost-effectiveness of electrolysis by extending their operational hours (a minimum threshold of 5000 hours per year and an optimal threshold of up to 8000 per year). However, this is hindered by the inefficiency of renewable energy sources, currently allowing for only 2000 to 4000 hours of use year. In this context, nuclear and hydroelectric power offer a dual: they are both controllable and predictable the year.

An analysis will be conducted to compare the technological, environmental, and cost indicators of low-carbon hydrogen production at an atmospheric alkaline electrolysis plant an electrical capacity of 1 GW. This analysis on the cost of electricity in Ukraine derived from renewable sources such as solar and wind (the «green tariff» effective 2024) and the cost of electricity at operational nuclear power plants in Ukraine (as 2024). The obtained data are presented in Table 4.

Table 4 − Comparison of technological, environmental and indicators of low-carbon hydrogen production at an atmospheric alkaline electrolysis plant with an electrical capacity of 1 GW.

Sources of electrical energy	Cost of electricity generation, \$/MWh [1]	Relative capacity factors of various electricity generation technologies in Europe, %	Annual low-carbon hydrogen production, thous. kg/year	Required area for capacity generation, ha [4]	CO_2 emissions during hydrogen production according to the life cycle of the installation, kg $CO_{2\,eqv.}$/kg H_2 [5]	Levelized cost of hydrogen (LCOH), \$/kg H_2
SPP	205.02	13 – 16% [2]	21466	12686	1.404 [6]	14.70
WPP	127.46	33 – 38% [2]	52556	34495	0.572 [6]	7.68
NPP	41.94	77 – 81% [3]	116955	337	0.624 [6]	3.12

[1] DLF Attorneys-at-Law. Ukrainian feed-in tariffs cut.
[2] Levelized Cost of Energy Analysis, Version 14.0
[3] World Nuclear Performance Report 2018
[4] STRATA – The footprint of energy: land use of U.S. electricity production
[5] IPCC 2014 Climate Change Report
[6] 3.38 kg $CO_{2\,eqv.}$/kg H_2 (current threshold) should be reduced to 3 kg (as specified in the EU taxonomy) by 2030, 2 kg by 2040 and 1 kg by 2050.

As shown in Table 4, the production low-carbon hydrogen from electric energy generated by operating nuclear power plant units advantages in terms of technological (productivity is twice as high as using electric energy from wind power plants (WPP) and five times higher compared to using electric energy from solar power plants (SPP)), environmental (the GHG content in the production of 1 kg H_2 is the lowest among all considered sources of electric energy production), and economic (the lowest price of producing 1 kg low-carbon hydrogen according to the levelized cost of hydrogen of LCOH which indicates the competitiveness of hydrogen produced; the lower the price, the greater income that can be obtained when selling it on the market) aspects. Thus, low-carbon hydrogen produced from electrical energy generated by operating nuclear power plants has undeniable advantages over hydrogen produced using electrical energy from renewable sources such as the sun and wind.

An analysis was conducted to enhance the profitability of the operating of the nuclear power plant with an electrical capacity of 1000 MW. This was achieved by comparing specific indicators in monetary terms regarding profitability in the current of electricity and the potential production of low-carbon hydrogen (Table 5).

Table 5 - Comparison of specific monetary indicators concerning profitability in the context of electricity production (current situation) and low-carbon hydrogen production.

Indicator	2013	2014	2015	2016	2017	2018	2019	2020	H_2 generation	Enhancing profitability
Volume of products manufactured of 1 GW (VVER–1000), million $	184.9	168.3	129.4	121.1	124.5	136.4	164.3	151.2	654.9	4.3
Net income of 1 GW (VVER–1000), million $	150.1	143.0	109.9	101.8	97.8	102.9	137.0	122.7	345.2	2.8

Based on the analysis of data over the past eight years from four Ukrainian nuclear power plants with a total installed capacity of 13835 MW (of 2021), an economic analysis was conducted on the specific performance for a typical power unit VVER–1000 with a reactor capacity of 1000 MW. The average amount of electricity in monetary terms produced by one unit an installed capacity of 1 GW is $155 million. The average net income the sale of electricity one power unit with an installed capacity of 1 GW is $127 million [23].

If a project is implemented to build an electrolysis plant with an electric capacity of 1 GW near an existing unit a similar capacity, the average of low-carbon hydrogen produced will be valued at $655 million, with an average net income from its sale amounting to $345 million. The implementation of this project by Joint Stock Company «National Nuclear Energy Generating Company «Energoatom» will enable the company to enhance specific performance indicators by increasing the volume of products produced and, consequently, income in monetary terms for a typical power unit VVER–1000 with a reactor capacity of 1000 MW compared to electricity production. Additionally, it will uniform loading of the power unit throughout year, thereby improving its operating conditions extending its life.

The introduction of hydrogen production near the existing typical power unit VVER–1000 with a capacity of 1000 MW will increase the production volume by 4.3 times and net income by 2.8 times compared to electricity production. Such low-carbon hydrogen production may be particularly relevant, considering Ukraine's commitments to the pan-European course on decarbonizing the economy, especially the energy sector, and from the perspective of enhancing the economic profitability of the Joint Stock Company «National Nuclear Energy Generating Company «Energoatom» in view of its corporatization.

CONCLUSION

Based on the dispatch information on the operation of existing nuclear power plant in Ukraine for 2018 – 2021, the average annual utilization rate of the installed capacity of NPP power units was calculated. It was 69.6% in 2018, decreased to 62.7% in 2020, and increased to 71.2% in 2021. The amount of free electricity that is not used in the Ukrainian energy market at existing NPP units ranges from 3983 MWh to 5156 MWh and can be used for the production of low-carbon hydrogen using electrolysis plants. 15 units have been installed in at four existing nuclear power plants in Ukraine, 13 which are VVER – 1000 with an installed capacity of 1000 MWh. Therefore, it is advisable to install electrolysis plants with an electrical capacity of 1 GW.

Considering the technological parameters of electrolysis plant, namely, the consumption of electric energy for the production of 1 kg of hydrogen at 52 kWh and the consumption of feed water at 22 liters, we obtained a total productivity low-carbon hydrogen amounting to 17417 kg per hour or 148 thousand tons per year. The Levelized Cost of Hydrogen (LCOH) produced from electricity by existing nuclear power plants is 3.12 \$/kg H_2, is 2.5 and 4.7 times lower than the corresponding costs for electricity from wind and solar power plants, respectively.

The introduction of hydrogen production near the existing typical power unit VVER–1000 with a capacity of 1000 MW will increase the production volume by 4.3 times and net income by 2.8 times compared to electricity production. Such low-carbon hydrogen production may be particularly relevant, considering Ukraine's commitments to the pan-European course on decarbonizing the economy, especially the energy sector, and from the perspective of enhancing the economic profitability of the Joint Stock Company «National Nuclear Energy Generating Company «Energoatom» in view of its corporatization.

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DESTRUCTION OF THE ICHTHIOFAUNA OF THE SOUTHERN BUH

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ANNOTATION

The work is dedicated to solving the environmental problems of the Southern Buh River, which arose as a result of the construction and operation of hydroelectric power plants and the search for ways to restore and preserve the lost ichthyofauna.

It has been established that decades of economic exploitation of the water resources of the Southern Buh basin have had a devastating impact on the biodiversity of ichthyofauna. Many valuable species have been destroyed.

The beginning of the degradation of the Southern Bug was the massive construction of hydroelectric power plants, which turned out to be a grandiose static-destructive pollution. The Southern Buh turned into a cascade of stagnant reservoirs, which completely changed and worsened the conditions for the existence of ichthyofauna species and led to their further disappearance.

The construction of hydroelectric power plants had a strong structural and operational impact on the river ecosystem of the Southern Buh and led to the violation of fundamental ecological laws: the law of the minimum of Y. Liebig , according to which the relative effect of a single environmental factor will be the stronger, the more this factor, in comparison with other environmental factors, will approach its quantitative minimum; the law of tolerance of Shelford , according to which the presence or prosperity of a population of any organisms in a given location depends on a complex of environmental factors, to each of which there is a certain range of tolerance (endurance) in the organism; from the law of feedback of human - biosphere interaction , first formulated by P. Dansereau, according to which any change in the natural environment caused by human economic activity "returns" and has undesirable consequences that affect the economy, social life and health of people.

The processes of destruction of the Southern Buh, caused by enormous overregulation and significant pollution, continue, which negatively affects its inhabitants, in particular, new representatives of the ichthyofauna are being added to the category of endangered and missing.

Proposed that will help stop the process of final destruction of the Southern Buh, restore its water resources, and recreate the lost ichthyofauna.

Keywords: Southern Buh, hydroelectric power plant, ichthyofauna, sturgeon family, environmental protection measures.

INTRODUCTION

Why is the thousand-year-old Southern Buh sick and its glorious inhabitants dying? The answer is obvious. The Southern Buh suffers most from economic activity.

In the Southern Buh basin, there are 6,582 small rivers with a total length of about 20,000 km, 11 medium-sized rivers with a total length of over 1,600 km, and 1 large river, the Southern Buh.

Large-scale economic development of the Southern Buh River began in 1929 with the commissioning of the first hydroelectric power plant and reservoir near the town of Pevmoysk . Since then , dozens of small hydroelectric power plants with a capacity of up to 10 MW have been built and are operating on the Southern Buh River (Table 1). The energy potential of the Southern Buh River is 27,735 MW [1]. Currently, due to significant overregulation and a huge number of artificial reservoirs in the catchment basin, the actual generated capacity of all small hydroelectric power plants fluctuates within 25-40% of the planned values. The procedure for assessing the environmental impact of economic activities appeared almost 50 years after the start of construction of the first hydroelectric power plants.

METHODS AND EXPERIMENTAL PROCEDURES

If you approach the dam of the Sabarivska HPP, you can see that the Southern Bug River is all green and blooming. There is a smell of blooming water in the air. The locks are completely closed at the Sabarivska HPP, the water in the river is stagnant (Fig. 1 and 2). At the Sabarivska HPP, the required level is maintained so that Vinnytsia is not left without water. When water is released from ponds in the Khmelnytskyi region, its level in the Southern Bug rises by a couple of centimeters every day. When the Sabarivska reservoir is filled with water above the norm, it is released through the dam so that the water does not stagnate. Every month, the water is taken for analysis. The water is absolutely suitable for drinking and household needs, assures the management of the Southern Buh Water Resources and Development Department [2]. However, the management does not dare to demonstrate the suitability of the water for drinking.

Table 1 − Small hydroelectric power plants on the Southern Buh River.

No. n/n	SHPP	Power, kW	No. n/n	SHPP	Power, kW
1	Ladyzhynska (current)	7500	9	Berezivska (current)	300
2	Sabarivskaya (current)	1050	10	Savranskaya (active)	450
3	Bratslavskaya (active)	400	11	Gayvoronska (current)	5700
4	Hlybochanska (active)	6130	12	Sutyska (current)	1400
5	Chernyatskaya (current)	1400	13	Pervomayskaya	600
6	Sandratska (current)	640	14	Kostyantynivska	400
7	Novokostyantynivska (active)	525	15	Mygiyskaya (active)	600
8	Shchedrivskaya (current)	640		Total	27735

A characteristic feature of the Southern Buh basin, which distinguishes it from other large rivers, is its very high degree of regulation. 16 reservoirs with a capacity of 316 million m ^{3} have been built on the bed of the Southern Bug River, which are used for the needs of hydropower, water supply and recreation. 170 reservoirs with a capacity of 578 million m ^{3} have been created in the basin , with a total water surface area of almost 30 thousand ha, and over 10 thousand artificial reservoirs (ponds), with a total area of over 56.4 thousand ha, and a total volume of 644 million m ^{3} , which is practically equal to the runoff in a low-water year of 95% of the supply. There is not a single small river or stream in the Southern Bug basin that would not be dammed by several dams of fish farming ponds. This increases the volume of evaporation and the level of water pollution. Water from fish ponds is discharged only during fish catching. As a result, the areas of small river and stream basins are practically removed from the area of the Southern Buh basin [2,3].

Fig. 1. The Southern Buh "blooms and smells" near the dam of the Sabarivska SHPP in Vinnytsia [2].

Fig.2. Result of eutrophication of the reservoir.

Every year, ecologists note a decrease in the water level of the Southern Buh River. The phenomenon of shallowing is especially evident in the area of the village of Mygiya, Pervomaisky district, which is known for the famous Buh rapids. The constant dark green color of the river water (see Fig. 3) indicates significant eutrophication in the middle and lower reaches of the Southern Buh. In addition, the Southern Buh is silting up, there is less fresh water, its quality is deteriorating, and the banks are overgrown with reeds. According to the Southern Management of the Southern Buh Basin, reservoirs located upstream take water for sanitary releases and thereby dehydrate the Southern Buh [4].

Fig. 3. Rapids near the village of Mygiya, Pervomaysky district, Mykolaiv region.

Analysis of data from the Ministry of Community and Territorial Development of Ukraine *(Table 2)* shows that 3,738 settlements in Khmelnytskyi, Vinnytsia and Mykolaiv regions, where more than 1.6 million rural residents live, lack centralized wastewater treatment [5]. In the regional centers of Khmelnytskyi, Vinnytsia and Mykolaiv, sewage treatment plants cover only half of the urban population.

Table 2 − No centralized sewage system [5].

No. n/a	Administrative territories	Population		Number of n/a, total			**There is no centralized sewage system.**		
		Urban population	Rural population	cities	town	villages	cities	town	villages

1.	Vinnytsia	799.385	746.031	18	29	1456		10	1451
2.	Volynska	539 179	492.242	11	22	1054	2	4	1029
3.	Dnipropetrovsk	2668.744	507.904	20	46	1372	1	13	1343
4.	Donetsk	3754.349	377.459	40	72	128		34	114
5.	Zhytomyrska	716,457	491.755	12	43	1613		8	1596
6.	Transcarpathian	465.904	787 887	11	19	579		2	563
7.	Zaporizhzhia	1306.231	381.170	14	22	914		11	896
8.	Ivano-Frankivsk	606.764	761.333	15	24	765		13	756
9.	Kyivska	1105.383	675 661	26	30	1126		5	1068
10.	Kirovohradska	591.944	341.165	12	27	991	1	9	985
11.	Luhansk	1859.590	276.323	12	24	497		15	494
12.	Lvivska	1534.040	978.044	44	34	1850	5	17	1839
13.	Mykolaivska	768.022	351.840	9	17	885			866
14.	Odesa	1597.062	780 168	19	33	1124		19	1110
15.	Poltava	867 201	519.777	16	20	1810		3	1773
16.	Rivne	548.088	604.873	11	16	999		1	978
17.	Sumy	741.430	326.817	15	20	1458		8	1445
18.	Ternopil	473.727	564.968	18	17	1023	1	7	1017
19.	Kharkiv	2158.121	500 340	17	61	1673	1	22	1636
20.	Kherson	631.317	396 596	9	31	658		12	588
21.	Khmelnytskyi	720 752	533.950	13	24	1414		9	1402
22.	Cherkasy	678 682	513.455	16	15	824		10	810
23.	Chernivtsi	390.551	511.081	11	8	398	2	1	398
24.	Chernihiv	649.063	342.231	16	29	1465	1	15	1454
	Ukraine	30 735929	13 521035	406	683	26076	14	248	25611

Most regional departments of ecology and natural resources in their annual regional reports on the state of the environment shyly avoid information on the number and condition of sewage treatment plants. The unsatisfactory condition of outdated sewage treatment plants and the lack of storm sewers increases the anthropogenic load on the Southern Bug basin. As a result, natural aquatic ecosystems have been completely transformed into anthropogenic water bodies, which in the process of their evolution have turned out to be completely unsuitable for the existence of aboriginal sturgeon species of ichthyofauna.

The ichthyofauna of the Southern Buh includes 75 species of fish. The main species of fish are: bullhead, crucian carp, carp, roach, rudd, pike, perch, bream, flatfish, grass carp, silver carp, catfish, and pike perch. In the upper reaches The Southern Bug is inhabited by carp, bream, crucian carp, tench, roach, bream, rudd, chub, bream, roach, crucian carp, crucian carp, pike, perch, ruff, bream, loach, and bullhead. In the middle reaches, in addition to the above-mentioned fish, there are also bream, roach, pike perch, catfish, and burbot. In the lower reaches, the fish population is replenished with bream, which has been very rare recently. Some migratory and semi-migratory fish enter here from the Dnieper-Buh estuary and the Black Sea - beluga, sturgeon, stellate sturgeon, tyulka, herring, rudd, ram, shemaya, bream, roach, eel, pike perch and some others. However, they do not rise above the village of Oleksandrivny due to the presence of a dam [6].

The creation of reservoirs disrupts the centuries-old conditions of life and reproduction of ichthyofauna. The increase in the intensity of eutrophication in artificial reservoirs on rivers is evidence of a constant influx of untreated wastewater, which affects the change in the species and quantitative composition of ichthyofauna. The fact of a reduction in the number of species of ichthyofauna of the Southern Bug is obvious. First of all, species of ichthyofauna disappear, the existence of which becomes unbearable and impossible with the deterioration of hydrophysical, hydrochemical, hydrobiological and microbiological indicators of river water.

RESEARCH RESULTS AND DISCUSSION

The Southern Buh, along the Stopich, was considered one of the richest rivers in fish. Fishing was the most important branch of all the industries of the lower Cossacks and supplied them with the most used product for food and trade, and the Southern Bug River was considered one of the best places for fishing. In Buza, Inhul, and the estuaries, Cossacks caught sterlet (*Acipenser ruthenus*), stellate bream (*Acipenser stellatus*), Black Sea beluga (*Huso ponticus*), Russian sturgeon (*Acipenser gueldenstaedtii*), European catfish (*Silurus glanis*), common bream (*Abramis brama*), roach (a transitional form *of Rutilus rutilus*), and Black Sea flounder (*Platichthys flesus luscus*). But during the 20th century The Southern Bug was dammed by several dams, which practically crippled the river and turned it into a series of continuous reservoirs-sedimentation basins, which gradually become polluted and silted up, which creates unsuitable conditions for the life of representatives of the ichthyofauna [6]. Hydroelectric dams not only block the way for migrating fish to spawning grounds, but also affect the spawning grounds themselves (Fig. 4).

Migratory sturgeons, for example, lay their eggs in places of fast flow on a rocky or pebble bottom, to which they stick. Large reservoirs absorb most of such places, silt them up and make them useless as spawning grounds. When rivers are backed up, silting of the soil occurs, and spawning grounds under such conditions lose their significance. The path to the spawning grounds of migratory fish is often quite long and difficult. The spawning grounds of some species are located in the upper reaches of rivers, far from the estuary. The fish that go from the sea to the lakes to spawn include: sturgeons - beluga, sturgeon, stellate sturgeon; sterlet, sturgeon-thorn, Black Sea herring; some cyprinids, for example, bream or pike, etc.

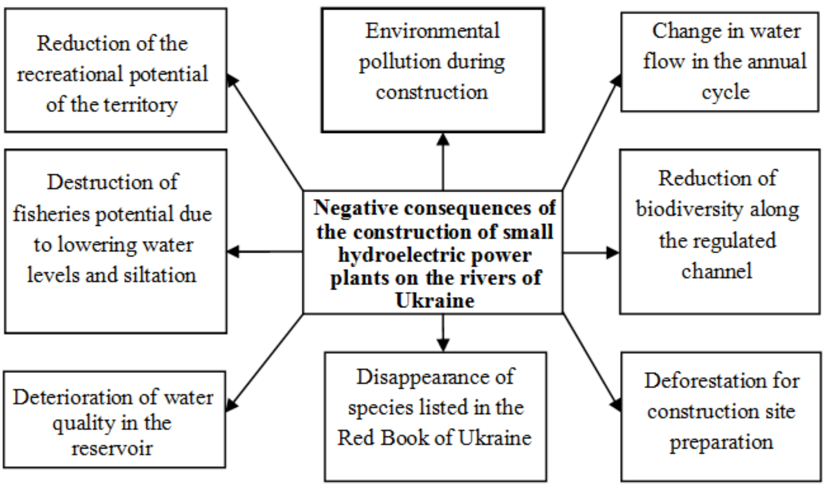


Fig. 4. Negative consequences of the construction of small hydroelectric power plants.

Let's analyze which representatives of the ichthyofauna we have lost by creating unbearable conditions for their spawning and existence. Sturgeon – ancient family freshwater fish, What appeared 200-250 million years ago. According to paleontological studies, the human race appeared about 2.8 million years ago, and Homo sapiens, in general, is only 160 thousand years old. However, the youngest species in the Earth's biosphere - Homo sapiens, in less than 100 years, managed to almost completely exterminate the sturgeon family, which was an ornament of the hydrosphere and which had practically no natural enemies, except for humans. The ethical question remains unanswered: "Why did the biological species Homo sapiens (*Homo sapiens*) decide that it has the right to decide which biological species are useful for the Earth's biosphere and which are not useful, which species should be preserved and which can be mercilessly destroyed, violating fundamental ecological laws."

The destroyed natural distribution areas of sturgeon fish are presented in (Fig. 5). The sturgeon family that lived in the rivers of Ukraine includes: beluga, Russian sturgeon, stellate sturgeon, sterlet and thorn sturgeon.

Beluga (*Huso huso*) is the largest freshwater fish on Earth (Fig. 6) and a valuable commercial fish. In Ukraine, this species was previously considered a separate subspecies - the Black Sea Beluga. The population of the beluga is very low, therefore the conservation status of the species is endangered [7-9]. Beluga is a migratory demersal-pelagic fish that lives permanently in the sea, and enters rivers to spawn. In the Black Sea basin, the beluga made spawning migrations to large rivers: the Danube (more than 2000 km from the mouth), the Dnieper, the Southern Bug, the Dniester and the Pioni. The life span of the beluga is up to 100 years. It reaches sexual maturity later than other sturgeon species: males at 12-14 years of age, females at 16-18 years of age. The interbreeding interval is 4-5 years.

Spawning migrations occur twice a year: in spring (second half of March - April, at a water temperature of 4–5°), and in autumn (September - November) - spawning in the spring of the following year. Males become sexually mature at the age of 12–14 years with a length of over 120 cm, females at 16–18 years with a length of over 150 cm. The greatest body length is over 5 m, weight 1000 kg (usually individuals up to 2.5 m and up to 200–300 kg are caught), life expectancy up to 100 years. Spawning from late April to early June at a water temperature of 8–17°C in deep places with a fast current and rocky or sandy-pebble soil. Fecundity 360 thousand - 7.7 million eggs. Caviar is bottom, sticky. After spawning, the adults, and later the juveniles, drop into the sea. The fry consumes crustaceans, worms, insect larvae, and fish fry; adults feed mainly on fish.

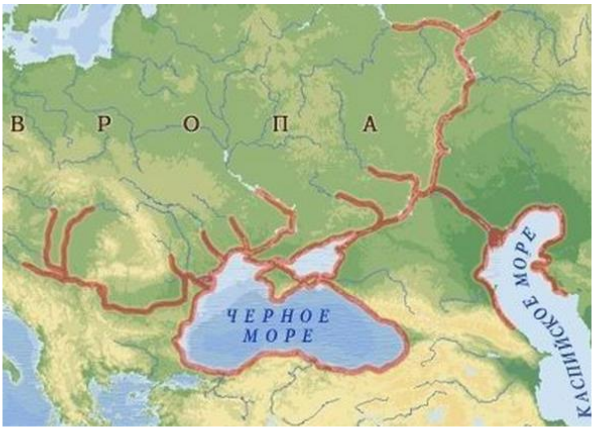


Fig. 5. Destroyed natural habitats of sturgeon fish.

Fig. 6. Beluga – the king fish. Completely destroyed in the Southern Buh River.

The main part of the Black Sea population of beluga goes to spawn in the Danube, Dnieper, Dniester and Southern Bug. In the first half of the 20th century. was a commercial fish almost on the entire sea coast. In the Dnieper, large individuals (up to 300 kg) were caught between the modern Dnieper and Zaporizhia, and extreme measures were noted in Kiev and higher: on the Desna, beluga reached the village of Vyshenki, and on the Sozh - to Gomel, where in the 1870s an individual weighing 295 kg was caught. In the Danube, in the past the species was quite common and rose to Serbia, and in the distant past it reached the city of Passau in eastern Bavaria. Along the Dniester, beluga spawning was noted near the city of Soroki in northern Moldova and above Mogilev-Podilskyi. Along the Southern Bug, beluga rose to Voznesensk (northern Mykolaiv region). In nature, beluga hybridizes with sterlet, stellate sturgeon, barbel and sturgeon [7-9]. The largest beluga ever caught is shown in (Fig. 7).

Fig. 7. The largest beluga ever caught weighed 1571 kg and reached 7.2 m long.

The disappearance of the beluga occurred as a result of changes in the hydrological, chemical, and biological regimes of water bodies caused by hydraulic engineering construction, water pollution, and overfishing. Beluga is found singly near the shores of the Crimean Peninsula, somewhat more often in the Danube and near its mouth. It has virtually disappeared in the lower reaches of the Dnieper, the Southern Bug, and the Dniester, as well as in the Northern Donets [8].

The construction of the hydroelectric power plant has negatively affected the entire family of Ukrainian sturgeons: Black Sea beluga, Russian sturgeon, stellate sturgeon, sterlet and sturgeon thorn.

The Russian sturgeon (*Acipenser gueldenstaedtii*) is a migratory bottom-dwelling fish that lives permanently in the sea and enters rivers to spawn (Fig. 8). The conservation status of the species is vulnerable [8, 9]. The Russian sturgeon is a valuable commercial fish, the number of which has been steadily declining over the past 25–30 years. It enters the Danube in small numbers, occasionally the Dnieper, occasionally the Dniester estuary, and practically does not enter the Southern Buh, Northern Donets, and the rivers of the Northern Azov Sea [8-11].

The Russian sturgeon has a long, spindle-shaped, thick body. The greatest length is over 2 m, weight over 100 kg, in catches there are individuals 1.3–1.6 m long and weighing about 30–40 kg; life expectancy is over 50 years. The upper third of the body is dark gray, brownish, often almost black, the sides are grayish, milky gray with a bluish cast, occasionally greenish, the belly is yellowish or milky white.

The disappearance of the Russian sturgeon is associated with changes in the hydrological, chemical, and biological regimes of water bodies caused by hydraulic engineering construction; water pollution, and overfishing [8].

The stellate sturgeon (*Acipenser stellatus*) is a migratory bottom fish that is common near the northern shores of the Sea of Azov, along the Crimean Peninsula, and in the northwestern part of the Black Sea (Fig. 9). The number of stellate sturgeons has been steadily declining since the end of the 20th century. It is very small in Ukraine and was the object of fishing for valuable black caviar. There are hybrids of stellate sturgeon with sturgeon, stellate sturgeon, and sterlet. Conservation status of the species: vulnerable [8, 9].

Now in small numbers it enters the Danube, occasionally singly into the Dnieper and Dniester estuaries, and practically does not enter the Dniester, Southern Bug, Dnieper, and rivers of the Northern Azov region.

The stellate sturgeon has an elongated, spindle-shaped body. The antennae are short, not fringed. The snout is xiphoid, long, its length is more than 60% of the head length. The greatest length is up to 220 cm, weight - up to 80 kg, usually individuals up to 150 cm long and weighing 25–30 kg are caught; life expectancy is about 30 years. The upper third of the body is dark, grayish-blue or almost black, the sides are whitish or silvery gray, the belly is yellowish or milky white.

The stellate sturgeon lives permanently in the sea, and enters rivers twice a year to reproduce: in the fall (from late September to late November) and in the spring (from March to late April - early May). The disappearance of the stellate sturgeon occurred as a result of changes in the hydrological, chemical, and biological regimes of water bodies caused by hydraulic engineering construction, water pollution, and overfishing [8].

Sterlet (*Acipenser ruthenus*) is a valuable commercial fish, the economic value of which has been lost due to its small number (Fig. 10). Conservation status of the species: endangered. Since the second half of the 20th century, its number and range have sharply decreased. In Ukraine, it was found in the main channel and in large tributaries of all large rivers. It has disappeared in the Northern Donets, Southern Buh and in most of the Dnieper and Dniester basins. It is now noted in the lower Danube and the Middle and Upper Dniester basins, and may be in the Dnieper Reservoir.

Sterlet has an elongated, spindle-shaped, low body. The lower lip is interrupted in the middle, the antennae are fringed. The greatest length is up to 1–1.2 m, weight up to 16 kg, usually fish up to 40–60 cm long and weighing 0.4–1 kg were caught in the traps, life expectancy is about 30 years. The upper part of the body is dark, grayish-brown, often with a greenish or bluish sheen, the sides are grayish, steel-silver, the belly is yellowish or milky-white.

The disappearance of sterlet occurred as a result of changes in the hydrological, chemical, and biological regimes of water bodies caused by hydraulic engineering construction, water pollution, and excessive fishing [8, 9].

Sturgeon Sturgeon (*Acipenser nudiventris*) is a migratory bottom fish that lives in the sea and enters rivers to spawn (Fig. 11). Conservation status of the species: extinct. Sturgeon is a valuable object of fishing, in Ukraine it was found in the Black Sea off the coast of the Crimean Peninsula (Kara-Dag massif, Karkinitskaya Bay) and in marine waters near the mouths of the Dnieper, Southern Bug, Dniester and Danube. In the first half of the 20th century. it was found singly, since the 1960s it has not been caught.

Fig. 8. Russian sturgeon.

Fig. 9. Sevryuga.

Fig. 10. Sterlet.

Rice. 11. Sturgeon thorn.

The sturgeon has a long, spindle-shaped, tall and massive body. The greatest length is over 2 m, the mass is over 40–70 kg (individuals weighing 8–10 kg were more common), and the lifespan is over 30 years. The upper third of the body is dark gray, sometimes almost black, with a dark blue or brown cast, the sides are light gray, the belly is milky or dirty white. Spawning occurs from late April to late May at a water temperature of 10–15°C, in sections of rivers with a fast flow and hard, pebble or sandy soil [8-10]. The disappearance of the sturgeon is due to changes in the hydrological, chemical, and biological regimes of water bodies caused by hydraulic engineering construction; water pollution and overfishing [8].

In the Red Book of Ukraine, representatives of the sturgeon species are listed as endangered or extinct [8]. The terms endangered or extinct are inaccurate and even cunning. Ukrainian sturgeons did not disappear on their own, since there are no natural reasons for their disappearance. Ukrainian sturgeons were destroyed as a result of a combination of man-made anthropogenic factors: the construction of hydroelectric power plants and countless artificial ponds on tributaries, the constant discharge of untreated wastewater and the creation of unsuitable conditions for the existence of sturgeon species. Current water quality indicators of the Southern Bug do not meet necessary indicators of water quality to ensure the normal functioning of the sturgeon family. The destruction of representatives of the sturgeon species in the Southern Bug was only the first stage of the extinction of the aboriginal ichthyofauna. The second stage of the destruction of the natural ichthyofauna is currently underway, associated with increased pollution of river water and a gradual deterioration of living conditions. Species for which living conditions have significantly deteriorated have become rare. On the verge of extinction are less demanding ichthyofauna species compared to sturgeon, which are presented in (Fig. 12-14).

Common bluegill (*Ballerus ballerus*) is a fish of the cyprinid family (Fig. 12) . Commercial fish. Length up to 30 cm (sometimes more), weight up to 1 kg (most often 200 - 300 g). The body of the bluegill is compressed laterally and more elongated in length than that of the bream. It is widespread in rivers and large lakes of the basins of the Baltic, Caspian, Black and Azov seas. Due to significant pollution of the Southern Bug, the bluegill is small in number [8-13].

Chekhonia (*Pelecus cultratus*) is a fish from the cyprinid family (Fig. 13). Commercial fish. The only species of the genus Chekhonia (Pelecus). Up to 35 cm long, weight - 300-400 g, sometimes more. Distributed in the basins of the Black and Azov Seas, as well as in the Caspian and Aral Seas and the waters of their basins. Chekhonia is very demanding on breeding conditions. It spawns in places with significant water flow speeds, in areas with a densely sodden bottom, for two to three days, depending on the water temperature. Due to significant pollution of water bodies - on the verge of extinction [8].

The bream, bream, also bream *(Rutilus frisii*) is a species of fish of the genus bream of the cyprinid family (Fig. 14). The species is listed in the Red Book of Ukraine [8]. In general, it is a large fish, the body length reaches 70 cm, and the weight is 6 kg. It has a slender, rolled, elongated body, covered with small scales. The bream is common in the basins of the Black and Azov Seas, as well as in the southern part of the Caspian Sea. The bream feeds in desalinated areas of the sea, and returns to rivers to spawn. The fish got its name because of its strong pharyngeal bones and powerful teeth, which can easily bite through large mollusk shells. In the recent past, it was common in many rivers of Ukraine, and in the lower reaches of the Southern Bug it was considered a commercial fish. Due to the regulation of river flows and pollution of their waters, the number of this species has significantly decreased, it has become a rare and at the same time a disappearing fish. Fish that constantly live in fresh waters, which cannot reach the mouths of rivers, where the food base is much richer, grow more slowly. There is a need for protection and even artificial breeding of the wrasse. Without this, it may disappear. One of the measures aimed at preserving the wrasse is a ban on its fishing [8- 10].

Introduction to the Far East ichthyofauna. Fish farming is of great importance in solving the food security of Ukraine. Thanks to the artificial introduction of representatives into reservoirs Far Eastern ichthyofauna: white amur (*Ctenopharyngodon idella*), amoupian shrew (*Pseudorasbora parva*), white (*Hypophthalmichthis molitrix*) and variegated (*Aristichthys nobilis*) silver carp, acquired industrial meaning and actively are used in fish farming by growing them in polyculture with carp - a traditional fish farming facility.

Grass carp (*Ctenopharyngodon idella*) is a species of fish of the genus *Ctenopharyngodon* , family *Cyprinidae* (Fig. 15) . It is a large and fast fish, can reach a length of 1-2 meters, and weigh 33 kg or even more. Grass carp has an elongated body shape flattened on the sides, sharp teeth are designed for grinding vegetation. The fish has rather large scales, with a dark color. Grass carp usually lives in freshwater reservoirs of Asian rivers. Acclimatized in many countries of Asia, Europe, America, Africa. Grass carp is an industrial fish cultivated in pond farms, where breeding is completely artificial with the use of hormonal stimulation of maturation of mature fish, incubation of eggs in devices. It is used in canals as a natural land reclamation to combat overgrowth. Currently, fish are actively bred in freshwater reservoirs of Ukraine [8; 10].

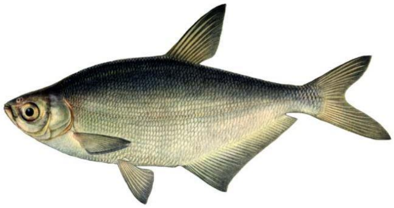


Fig. 12. Common bruise.

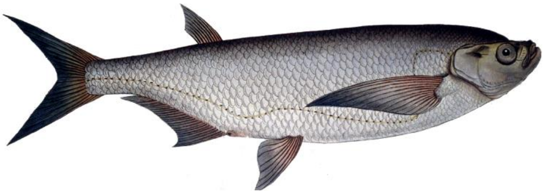


Fig. 13. Chekhonya.

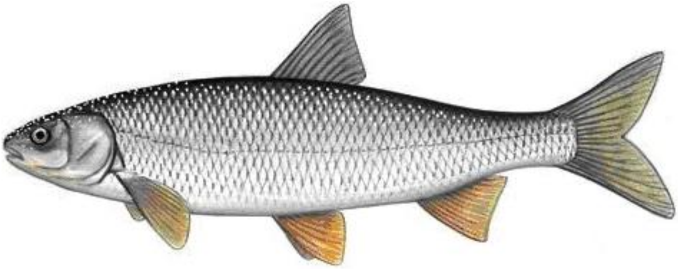


Fig. 14. Vyrozub, also vyrezub.

Amur roach (*Pseudorasbora parva*) is a species of fish of the genus *Pseudorasbora* , family *Cyprinidae* (Fig. 16). A small fish, similar to its peers of the grass carp. The roach has an elongated body, medium-sized scales. The body length reaches 5-9 cm, rarely 12 cm. The roach is a schooling fish that prefers calm, clean water bodies. It mainly inhabits rivers, lakes, bays and ponds. Non-fishery fish. In pond farms it is a mass waste fish. It is used in fishing as a live bait for catching predators [8-10].

Silver carp (*Hypophthalmichthys molitrix*) is a species of fish of the genus *Hypophthalmichthys* , family *Cyprinidae* (Fig. 17, 18). The body of the silver carp is quite high, moderately long, the head is wide. Silver carp is a large, schooling fish that can reach more than 1 m in length and a body weight of 40 kg. The fish lives in ponds with a weak current [8,10].

Fig. 15. White amur.

Fig. 16. Amur chebachok.

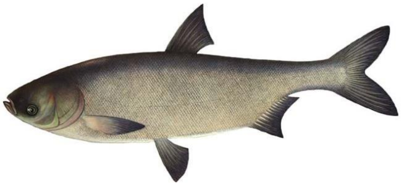


Fig. 17. White silver carp.

Fig. 18. Variegated silver carp.

Herbivorous grass carp and silver carp are introduced into reservoirs Southern Bug from goal increase their fish productivity, and Amur little girl imported accidentally (example) random full acclimatization). However, due to the constant significant increase in pollution of the water area, fish production is not increasing.

Migration of ichthyofauna occurs in order to find the most optimal conditions for existence, food base and spawning. For the vast majority of fish, hydroelectric dams pose a serious threat. If migration routes are artificially blocked by hydroelectric dams, the natural population completely dies.

Sturgeon, which are forced to make long upstream migrations to spawn, are at particular risk. In fact, almost 50% of fish die when passing through hydroelectric power plants. Fish die not only because they physically collide with turbine blades, but also because of the rapid decompression or pressure changes created by them. When passing through hydroelectric power plant turbines, fish are observed to suffer mechanical and biological damage, as well as abnormal behavior. Visual examinations of the body, as well as the results of autopsies of dead fish, revealed the following main types of injuries: bulging eyes, lacerations and cuts, damage to the body's integuments, gas bubbles in the muscles of the back, on the gills, fins and in blood vessels, hemorrhages in the eyes, in the bases of the fins, muscles, abdominal organs and in the brain, barotrauma of the swim bladder, rupture of the walls of the swim bladder, respiratory arrhythmia.

Some dead fish showed discoloration of the body, while others, on the contrary, had increased pigmentation. In most cases, the fish showed hemorrhages in the tissues and organs. The nature of the injuries largely depends on the size of the fish's body. In small fish, the swim bladder was most severely damaged, and in large ones, in addition, there was a violation of the body's integuments, muscle rupture , and a fracture of the spine. In dead fish, the following are observed: cut wounds, damage to the trunk, and the absence of body parts (Fig. 19).

Fig. 19. Photo of fatal injuries of dead fish that are forced to go to spawning through hydroelectric dams.

In Ukraine, to prevent fish from entering hydroelectric power plant turbines, barbaric electric fencing devices are used to scare away fish (Fig. 20). As a result, fish receive electrical injuries, the consequences of which have not yet been studied. The use of electric barrier devices is possible only after conducting additional studies of fish behavior in electric fields.

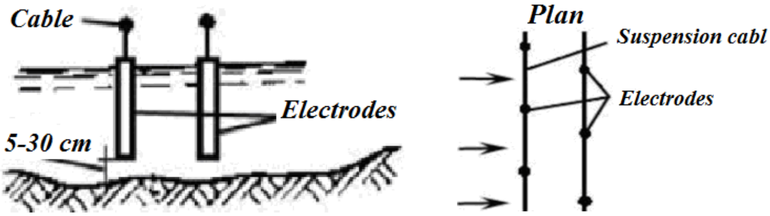


Fig. 20. Electric barrier devices.

Rivers are the only, comfortable, natural habitats for representatives of river ichthyofauna. Any change in the natural, hydrological regime of a river is necessarily reflected in the conditions of existence of the species that inhabit it. The transformation of rivers into a continuous cascade of reservoirs with a slowed-down flow leads to: an increase in the level of water pollution; changes in the temperature regime; an increase in the eutrophication process; silting of the riverbed; stopping migration routes, destruction of natural spawning grounds and food base for representatives of ichthyofauna.

Rising temperatures significantly affect the inhabitants of lakes and artificial reservoirs:

- up to 26°C - no harmful effects are observed;

– 26-30°C - inhibition of fish life;

- above 30°C - harmful effect on biocenoses;

– 34-36°C - fish and some species of other organisms die.

To cool the heat exchange equipment of Ladyzhynska TPP, river water is taken from the Ladyzhynska reservoir in the amount of 1.955 billion m^3/year, of which 1.170 billion m^3/year are repeatedly discharged into the reservoir. In addition, it should be noted that the river water intake by Ladyzhynska TPP for cooling needs is 5–6 times higher than the natural inflow of the Southern Bug River, and during low tide the corresponding imbalance increases to 16–18 times. In such a situation, the Ladyzhynska reservoir becomes an integral part of the single reversible circulation water supply system of Ladyzhynska TPP. Excessive use of water resources of the Ladyzhynska reservoir has led to the complete destruction of representatives of ichthyofauna (Fig. 21, 22).

Fig. 21. Death of 45,750 representatives of the ichthyofauna of the Ladyzhyn Reservoir in September 2023.

Fig. 22. The discharge of a large amount of harmful substances into the Ladyzhyn Reservoir on October 4, 2023 led to the instant death of 3,000 Red Book sturgeons and belugas weighing over 9 tons.

The problem of fish migration was first addressed in 1909 by the Belgian scientist G. Denil, who proposed the design of a fish pass [1]. The baffles were arranged in such a way as to create a reverse flow at the walls and bottom, which in turn slows down the main flow. The fish pass in this case can be installed on a relatively steep slope, usually with a height to length ratio of 6/1, and maintain a maximum speed of less than 1.21 m/s. These models of fish passes are effectively used in places where there is little space [1; 14; 15] .

To create normal conditions for the migration of representatives of ichthyofauna in developed countries, fish-friendly turbines and fish feeders are used at hydroelectric power plants (Fig. 23).

The general consequences of hydraulic engineering construction can be divided into the following types:

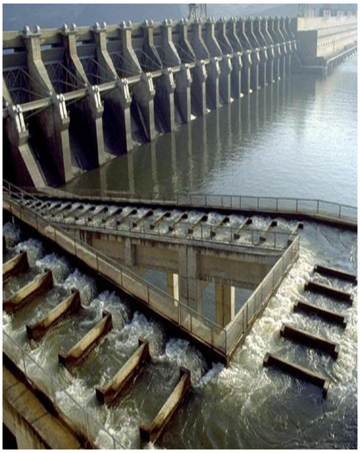
1) morphometric – change in the definition and length of coastlines, redistribution of depths, change in the surface area of the water mirror;

2) hydrophysical – increase and decrease in water content, redistribution of water flow in space and time, change in flow velocity, change in water exchange and temperature regime;

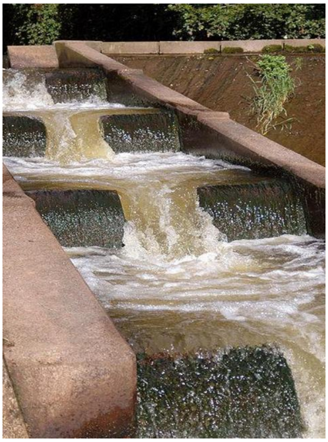
3) hydrochemical – change in total mineralization and ionic content, change in gas (oxygen) regime, increase in the content of organic and biological substances;

4) toxicoecological and radioecological: increased content of heavy metals, pesticides, radionuclides, increased biotest indices;

5) hydrobiological and bioproductive: changes in flora and fauna, including the reduction of rare, valuable and important economic species, the development of harmful species, the appearance of water blooms, overgrowth and waterlogging, deterioration of self-purification conditions.



John Day Hydroelectric Power Plant Fish Hopping on the Columbia River.



A small fish pass on the River Otter in the UK.

Washington state in the USA Fish pass with restored natural relief on the Rhine River in Germany.

Fig. 23. Fish-eating animals [1].

CONCLUSIONS

All the static and destructive changes in the Southern Buh and the rivers of Ukraine, carried out for the sake of obtaining "**cheap**" kilowatts of electricity, ultimately led to the destruction and loss of valuable natural species of ichthyofauna. During the construction of small hydroelectric power plants, no one thought about the environmental consequences, so a number of environmental mistakes were made that led to a catastrophic increase in the mortality of the ichthyofauna of the Southern Buh. The destroyed sturgeon ichthyofauna of the Southern Bug turned out to be a living bioindicator that demonstrated the complexity of environmental problems that arose as a result of hydraulic engineering construction and excessive economic use of water resources. Most of the fish that disappeared from the Southern Buh are migratory fish that lived in the Black Sea basin, and "passed" into the rivers to spawn. These are beluga, Russian sturgeon, stellate sturgeon, sterlet, sturgeon, blue sturgeon, Chekhonya, vyrozub, ramanya, etc. These fish almost ceased to exist in the Southern Buh and Dniester rivers due to the construction of hydroelectric dams, which prevented the fish from passing through to spawn.

The ecological mistakes made in nature management that led to the destruction of the Southern Buh sturgeon family must be corrected. Ecologists and environmentalists are obliged to create conditions for the restoration and revival of the destroyed ichthyofauna of the Southern Bug. To restore the lost ichthyofauna of the Southern Buh and Ukrainian rivers, the following priority measures must be taken:

1) to carry out reconstruction and construction of new waste water treatment plants and to stop discharging wastewater without treatment;

2) to build fish passage channels and create conditions for the migration of migratory fish species through hydroelectric dams;

3) clear silted reservoirs and riverbeds, and establish spawning grounds for migratory fish species;

4) prohibit the use of electric barrier devices at hydroelectric power plants that cause electrical injuries to larvae and young fish;

5) replace conventional hydro turbines of hydroelectric power plants with fish-friendly turbines ;

6) conduct an inventory of infrastructure facilities in the sanitary protection zone of the water body and achieve compliance with the requirements of the Water Code of Ukraine;

7) increase the number of artificially grown fry of valuable fish species and stock clean reservoirs with fish.

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PROSPECTS OF THE BIOMETHANE INDUSTRY FOR THE CENTRAL REGION OF UKRAINE

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ABSTRACT

Ukraine is experiencing a significant energy shortage as a result of military operations. The solution to the problem is the development of the domestic biomethane industry, which, under favorable conditions, can produce up to 30% of the carbon-neutral analogue of natural gas for domestic consumption. Ukraine has a powerful agricultural sector of the economy, the waste of which is the main raw material for the production of biomethane. The paper analyzed the capabilities of the regions of the Central region of the country as prospects for the construction of biomethane plants. The Cherkasy region was chosen as the object of research. Cherkasy region is one of the energy-deficient regions of Ukraine, in which the electricity deficit in 2021 was approximately 2 billion kWh. The energy potential of the region's agriculture was calculated based on statistical data on the gross harvest of the region's leading agricultural crops and waste coefficients. It was determined that up to approximately 10% of the total need for primary energy carriers in the region can be met through primary plant waste.

The problems of the development of the biomethane industry are the seasonality of the formation of primary plant waste, which necessitates the need to combine waste sources from both crop and livestock farms. At the current stage of the industry's development, domestic biomethane plants operate mainly on primary livestock waste, the capacity of which does not allow for the formation of gas in significant industrial volumes. To inject biomethane into the GTS distribution network, it must meet the requirements for natural gas. Thus, the development of domestic biomethane production on an industrial scale also requires the construction of appropriate infrastructure. In the European Community, biomethane production is supported by the subsidy policy of the governments of the countries. In Ukraine, a decision has been made at the legislative level to prioritize the development of the biomethane industry, but the issue of financing has not been resolved. For rapid development, the industry requires significant investments that are absent from the country's military budget. The prospects of the biomethane industry depend on attracting foreign investors. The best region for investment in the biomethane industry is the Central region of the country.

Keywords: Biomethane, plant waste, livestock waste, waste volumes, energy potential.

INTRODUCTION

The current transformation in the choice of energy carriers in the energy sector of Ukraine is associated with the rejection of the use of natural gas of Russian origin and the association with EU countries. Green energy is developing rapidly in Europe. Today, in the energy balance of the European Community countries, 20% of energy is obtained from renewable sources, among which the share of bioenergy is more than half. The most promising substitute for natural gas is biomethane, which in its chemical and physical properties is practically no different from natural gas. According to the European Commission's plan, by 2030 the EU intends to increase biomethane production to 35 billion cubic meters per year, and by 2050 - to 100-180 billion m3 [1]. In European countries, biomethane is currently used mainly locally. The production of significant volumes of biomethane allows the use of high-pressure gas transmission systems, where biogas is supplied with natural gas parameters. This makes biomethane available for integration into existing gas infrastructure without additional costs for new networks.

The raw material base for biomethane production consists of various organic materials, among which agricultural waste is mainly used in the technologies. Ukraine is a powerful agrarian country with significant volumes of residual products in the agricultural sector, which potentially creates significant raw material resources for the production of biogas and biomethane. Prospects for rapid development of the biomethane industryopens up new opportunities for Ukraine, which, thanks to the presence of large areas of agricultural land, raw materials and a developed gas transmission system, can become a powerful supplier of renewable gases.In February 2023, Ukraine and the EU signed a Memorandum of Understanding on Strategic Partnership in the Field of Renewable Gases, Biomethane, Hydrogen and Other Synthetic Gases [2]. Priorities in the development of domestic biomethane production are enshrined at the legislative level. In 2024, a customs clearance procedure came into force in the country, which allowed the export of biomethane under a temporary ban on the export of natural gas [3]. The potential for biomethane production in Ukraine for the next few years is up to 10 billion m³/year, which allows us to completely abandon the import of natural gas for the country's needs. Biomethane can be produced both for domestic consumption (supply to the gas network with subsequent use for the production of electricity and/or heat, or as motor fuel for vehicles), and potentially for export to European countries. Thus, the development of the biomethane industry is of strategic importance for the recovery and further development of the domestic economy [3].

At the state level, the economic feasibility of biomethane production requires the construction of biomethane plants in regions with significant volumes of cheap organic raw materials and a developed gas distribution system infrastructure. The most promising for the development of the biomethane industry in our country is the combination of several sources of raw materials for the production of biogas in significant volumes with its subsequent use in gas distribution systems (Figure 1). Such a distribution of the components of biomethane production and transportation will allow producing significant volumes of produced biogas and supplying it under pressure to the country's gas distribution system, which will ensure the energy needs of different regions of the country [4].

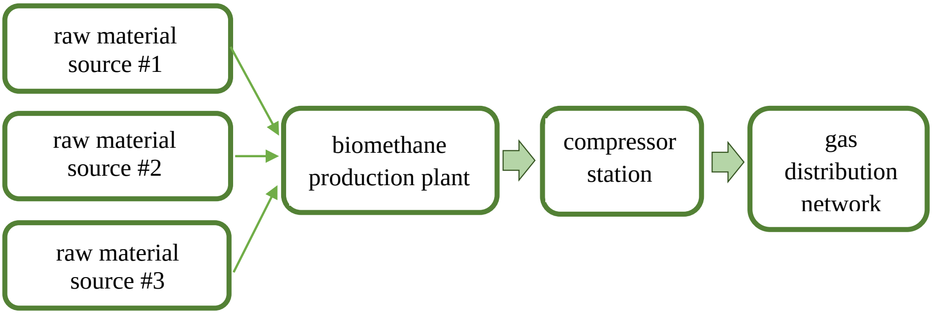

Fig. 1. Approximate scheme for building biomethane production at the regional level.

The construction of biomethane plants should be carried out taking into account the possibility of providing cheap types of raw materials, which determines the linking of projects to the objects of raw material sources. The geography of the location of domestic operating biomethane plants indicates their linking to livestock farms and sugar factories. The prospects for using primary plant waste as raw materials for biomethane production require a detailed assessment to determine the opportunities of different regions of Ukraine for the development of this bioenergy industry.

Military actions and their consequences have led to limited use of agricultural land in the south and east of Ukraine. Agricultural enterprises in the central region of the country have suffered much less, but have increased risks of growing grain crops due to climate change, which provokes prolonged droughts and unfavorable conditions for plant development. Assessment of the prospects for the development of the biomethane industry in certain central regions of the country is extremely relevant for the formation of strategic plans for the recovery and further development of the country's energy sector.

METHODS AND EEXPERIMENTAL PROCEDURES

The assessment of the energy potential of primary agricultural waste in the Central regions of Ukraine was made on the basis of statistical data on the gross harvest of agricultural crops, taking into account waste coefficients (the ratio of dry mass of above-ground residues to the mass of the harvested crop with field moisture). The waste coefficient in crop production is for wheat - 1.0; barley and other cereals - 0.8; rapeseed - 2.0; corn for grain - 1.5; sunflower - 2.0 [5]. The energy use coefficient depends on the ratio of grain yield and cattle and pig population on livestock farms. The analysis of the prospects of livestock farming for the development of the domestic biomethane industry took into account statistical data on livestock farming.

RESEARCH RESULTS ANDDISCUSSIONS

The central region of Ukraine historically consists partly of Dnipropetrovsk, Kirovohrad, Vinnytsia, Poltava and Cherkasy regions. The natural zone of this part of the country is a forest-steppe, characterized by a continental climate with little snow in winter and moderately humid summer. Such climatic conditions create the most favorable conditions for the development of the domestic agricultural sector. In a regional context, the volume of agricultural waste generation depends on the industrial specialization of a particular region (industrial or agricultural), the development of entrepreneurship in the region, etc. According to the annual estimated volume of agricultural waste generation in Ukraine, five groups of regions can be distinguished [6]:

Group I – Poltava and Vinnytsia regions;

Group II – Dnipropetrovsk, Chernihiv, Cherkasy, Kirovohrad, Kharkiv and Kyiv regions;

Group III – Sumy, Khmelnytskyi, Odesa, Zaporizhia, Zhytomyr, Ternopil and Mykolaiv regions;

Group IV – Kherson, Donetsk, Lviv, Volyn, Rivne and Luhansk regions;

Group V – Ivano-Frankivsk, Zakarpattia and Chernivtsi regions.

Today, biomethane production in Ukraine is mainly associated with the use of primary livestock waste. Their estimated volume is almost 50 million tons. Cattle waste accounts for 62%, pig farming – 35%, poultry farming – 3%. The largest volumes of livestock waste generation are observed in Khmelnytskyi, Vinnytsia and Poltava regions [6,7]. In a regional breakdown, about 54% of the total livestock population is kept mainly in farms of all categories in the regions of Central Ukraine (Table 1) [8].

Table 1 – Regions of Ukraine with the largest number of livestock kept in all types of farms.

Region of Ukraine	Number of thousand cattle
Khmelnytskyi	198.2
Poltava	168.5
Vinnytsia	145.7
Ternopil	124.9
Cherkasy	121.1

The leaders in terms of the number of farm poultry in all categories of farms are Kyiv (27.4 million heads), Vinnytsia (27.0 million heads) and Cherkasy (24.4 million heads) regions.[9].

Theoretically calculated volumes of biogas depending on the types of livestock (Table 2) indicate the prospects for developing the biomethane industry in the Central region.

The share of crop waste in biogas production is still insignificant, although livestock waste is inferior to crop waste in volume. The total estimated volume of crop waste in Ukraine in 2019 was over 127 million tons. Crop production in Ukraine is one of the most important sectors of the agricultural sector, which has a significant impact on the country's economy. Grain crops, in particular corn and wheat, are key export products that provide foreign exchange earnings and contribute to the development of agriculture. Military actions have led to significant damage to domestic infrastructure related to wheat transportation. Corn remains the leading crop in the Ukrainian agricultural sector. The sown areas under it occupy approximately a third of the total area of grain crops. A significant share of the grown corn is directed to meet the needs of domestic livestock. It is clear that the predominant share of plant waste is corn waste (42%), sunflower (24%), and wheat (22%). Cherkasy and Poltava regions are leaders in growing corn and sunflower seeds. As for winter wheat, the first place is occupied by the Odessa region. Powerful agricultural production determines the formation of significant volumes of primary plant waste. The largest estimated volumes of plant waste are observed in the regions of the steppe and forest-steppe zones of Ukraine (Poltava, Vinnytsia, Kirovohrad, Cherkasy regions), the smallest - in the regions of the Carpathian region (Transcarpathian, Chernivtsi, Ivano-Frankivsk) (Figure 2) [6]. A significant impact on the dynamics of production of the main agricultural crops in Ukraine is exerted by military operations and a change in the structure of sown areas with the orientation of agricultural enterprises to the cultivation of profitable grain crops and oilseeds

Table 2 – Possible volumes of biogas from primary waste in livestock farming [10].

Primary livestock waste	Biogas output Nm^3/t	Methane content, %
Cattle manure (flush system)	15-18	55-68
Cattle manure (litter)	42-50	55-58
Chicken manure (without litter)	90-100	58-60
Chicken droppings (litter)	150-160	58-60
Pig manure (flush system)	25-28	60-65
Horse manure (unlittered)	60-63	60-65

Source: table of biogas yield from 1 ton of substratehttps://ac-group.in.ua

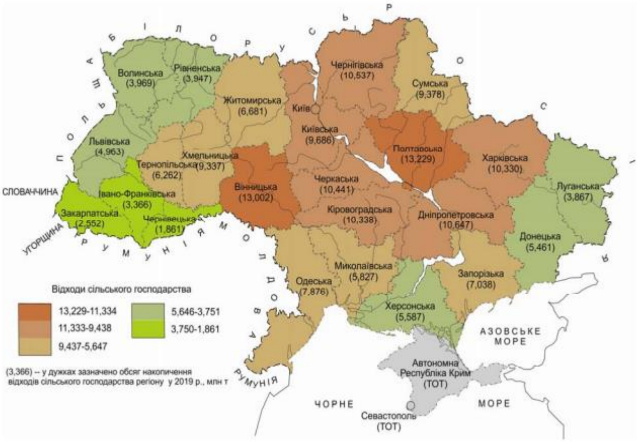

Fig. 2. Volumes of agricultural waste by regions of Ukraine [6].

To assess the prospects of the biomethane industry based on crop waste, Cherkasy region was chosen as a model object, which is the geographical center of the country and occupies a leading place in the domestic agricultural sector. The area of agricultural land in Cherkasy region occupies approximately 1.5 million hectares, of which almost 87% is arable land. The agricultural sector involves 573 enterprises and 1416 farms [11]. In the structure of agricultural production, crop production accounts for 62%, livestock production for 38%. The leading crop among cereals is winter wheat, technical crops are sugar beets and sunflower. Among the livestock sectors, meat and dairy cattle breeding stands out. Cherkasy region differs from other regions in its high level of production of grain, sugar beets, sunflowers, vegetables and potatoes and meat and dairy livestock farming. In total, 9 production types of agricultural farms have been identified on the territory of Cherkasy region. The basis of their formation is grain farming, growing industrial oilseeds, and meat and dairy cattle breeding [12]. Grain crops dominate the structure of crop production in Cherkasy region (Figure 3).

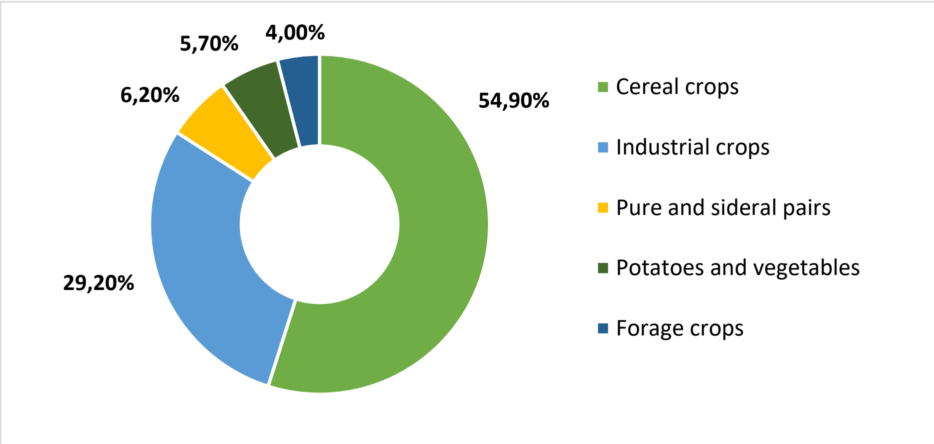

Fig. 3. Structure of crop crops in Cherkasy region in 2019.

Cherkasy region is among the top five regions of Ukraine in terms of grain yield. In the structure of production of the main agricultural crops across all categories of farms in Cherkasy region, winter wheat, grain corn, and sunflower predominate (Table 3)[13].

Table 3 – Production of main agricultural crops in Cherkasy region.

Leading agricultural crops	Gross collection, thousand tons		
	2019	2020	2021
Wheat	1083.0	797.8	1228.9
Barley	222.9	192.8	228.6
Corn for grain	3190.8	1650.8	3634.5
Sunflower	673.7	568.8	810.2
Soy	218.9	99.5	193.7
Rapeseed and colza	142.9	36.5	54.5

Corn waste has the greatest energy potential among agricultural crops in Cherkasy region. Sunflower waste is in second place - the economically feasible potential of sunflower stalks in 2021 was almost 610 thousand tons. Grain waste is in third place (Fig. 4).

Corn and sunflower stalks are not considered good raw materials for fuel production, as they require additional drying, which increases the cost of fuel. Another problem is the lack of balers on farms for baling the stalks of these crops, which leads to additional costs for its collection. Traditionally, in the agricultural farms of the region, straw is a valuable resource for livestock, where it is used as feed and bedding for farm animals. Primary crop waste in the fields can be plowed as organic fertilizers, protect vegetable beds in winter from frost, etc. As an energy resource, straw in the farms of the region is used mainly in private households and is not widely used. Sunflower and corn stalks are practically not used for energy needs, as they require additional efforts and capital investments to obtain effective fuel. So far, the problem of accelerated wear of heating boilers remains due to the risk of increased corrosion when burning straw. Biofuel from crop waste is characterized by a high content of sulfur and chlorine compounds, the release of which provokes technological problems in the operation of equipment. Staying straw in field conditions for a certain time improves its chemical composition, but increases humidity, which reduces energy efficiency. Thus, to obtain high-quality biofuel from primary crop waste, it is necessary to store straw in closed warehouses for a long time.

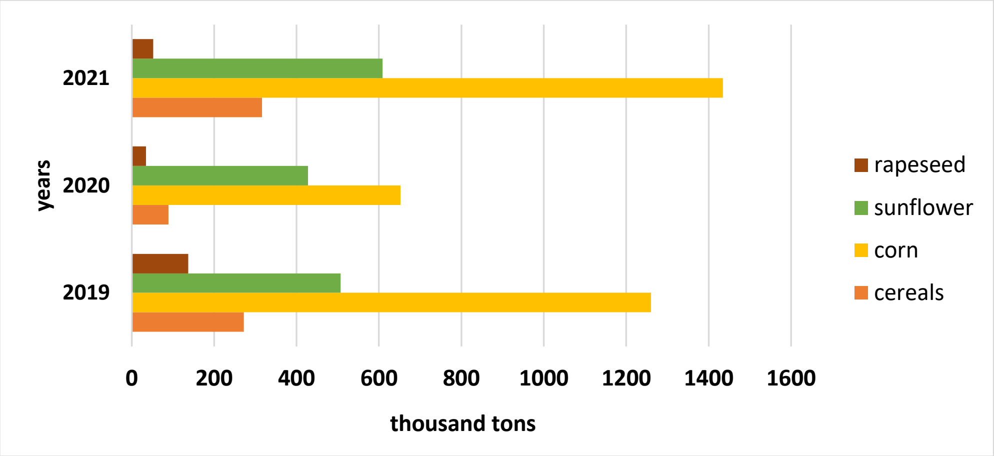

Fig. 4. Energy potential of leading agricultural crops in Cherkasy region for 2019−2021.

The total volume of waste in the calculations is considered to be the theoretical biomass potential of certain plant crops, which can be significantly affected by weather conditions, primarily the level of precipitation. The volume of straw of grain and leguminous crops that can be used for energy purposes depends on the level of development of livestock farming, since primary plant waste is primarily used as bedding and roughage for cattle and pigs. The needs of livestock farming in straw are calculated at the rate of 0.9 t per head of cattle and 0.365 t per head of pigs per year. It is believed that only half of the straw free from livestock needs can be used for energy production. The conversion of the energy potential of primary grain waste into the equivalent of conventional fuel is presented in Table 4.

Table 4 – Energy potential of grain straw in Cherkasy region in terms of conventional fuel equivalent.

Indicator	2019	2020	2021
Economic energy potential grain straw million tons	2.18	1.2	2.41
Calorie equivalent for straw	0.4777	0.4777	0.4777
Fuel equivalent million tons	1.04	0.57	1.15
Caloric equivalent for gas	1.14	1.14	1.14
Gas equivalent, million m3	0.9	0.5	1.0
Caloric equivalent for coal	0.627	0.627	0.627
Coal equivalent	1.7	0.9	1.8

Thus, primary waste of grain and leguminous crops in Cherkasy region under favorable weather conditions for growing grain crops (2021) can yield approximately 1.15 million tons of energy (1 million m3 of gas, or 1.8 million tons of coal). Thus,Crop waste can satisfy approximately 10% of the total need for primary energy carriers in Cherkasy region for electricity production. Thus, processing only crop waste to solve the electricity deficit in the region is not cost-effective. Biomethane production on a combined basis of crop and livestock farms in the region may be more economically feasible and of interest to potential investors. The best promising energy opportunities are the remains of grain and leguminous crops and manure with bedding for cattle. In the Cherkasy region, livestock farming is carried out in 175 farms of the region, including cattle kept in 160 farms (cows - in 149 farms) and pigs - in 122 farms. Thanks to investments, modern farms have been built and are increasing their capacity, on which a significant number of cattle (cattle) are kept. Primary livestock waste, together with crop residues, can be transported to biomethane production enterprises. AndExisting biogas plants must be technically configured to produce biomethane.

Analysis of the opportunities for the development of biomethane production in Cherkasy region shows the prospects for the development of the industry for the Central region of Ukraine. However, there are also significant obstacles. A significant factor restraining the development of domestic biomethane production is the high cost of biomethane production even with the availability of free raw materials. According to the estimates of the Bioenergy Association of Ukraine, by the fall of 2024, the cost of biomethane that is economically profitable for producers is 800-900 euros per 1000 cubic meters, depending on the raw materials and capacity of the plant. At the same time, the cost of natural gas today is significantly lower - 300 euros per 1000 cubic meters. [15]. For producers, even under the ban on natural gas of Russian origin, it is much more profitable to use fossil fuels than to enrich biogas into biomethane. The development of the industry can only be stimulated by the possibility of exporting the produced biomethane to European countries. For this, its certification by audit companies that have a license for this type of activity from the European Commission is necessary.

Another factor influencing the increase in domestic biomethane production is the need to ensure adequate biomethane transportation capacity through main and distribution gas pipelines. It is known that 47% of biomethane plants currently operating in Europe are connected to the gas distribution network, and 20% to the gas transportation network [4,14]. Several branches of the state gas transportation system pass through the central regions of Ukraine. For example, one of the gas pipelines of the gas transportation system of Ukraine (GTS) passes through the territory of Cherkasy region (Figure 5). The gas distribution system of the region combines several compressor stations and an extensive distribution system that can be used for pumping and transporting the produced biomethane.

Fig. 5. Scheme of the gas transportation system of Ukraine.

Technically, the volume of biomethane supply to the network depends on gas consumption in the area of connection of the biomethane plant. In the Central regions of Ukraine, natural gas consumption falls in the summer. In the spring-summer period, the volume of primary crop waste is also the lowest. If the connection point of the biomethane plant is located in an area of low consumption, it is necessary to solve the problem of increasing the volume and pressure when feeding into the gas distribution system. The solution to this problem can be different: liquefaction of part of the biomethane for its further transportation by road, connection to networks with higher pressure (for example, to main gas pipelines). Also, at the border of the gas distribution system and the gas transportation system (GTS), reverse compressors can be installed, which will allow transferring excess gas from gas distribution to gas transportation networks. These technical solutions will require additional capital investments by the producer, which will increase the cost of produced biomethane [15].

For the export of Ukrainian biomethane to European countries, according to the requirements of the European Union, it is necessary to enter data on the raw materials - the source of origin of this biogas. EU Directive 2023/2413 (RED III) on the promotion of the use of energy from renewable sources, according to which the EU database on renewable gases is created - Union data base (UDB) began operating in the fall of 2024. According to RED III, evidence of sustainability of all batches of biomethane exported to the EU, including data on raw materials, is required to be entered into the database. Currently, there is a requirement for third countries that national biomethane registers must be connected to the UDB. Ukraine does not yet have its own such register, and the only effective mechanism for exporting domestic biomethane remains evidence of sustainability, based on a voluntary sustainability certification scheme. Resolving export barriers in cross-border trade in biomethane, as well as the prospects for the development of the industry, largely depend on the decisions of the European Union institutions.

CONCLUSION

The rising cost of energy resources and their depletion, the worsening energy crisis in the world and in Ukraine stimulate the use of alternative fuels, among which the most promising is the use of biomethane obtained from organic agricultural waste.

Ukraine has a powerful agricultural sector and is one of the leading countries in the production of grain and leguminous crops, while a significant amount of primary plant waste (mainly straw) is generated. However, in our country only 1% of plant biomass is used as an energy resource. Domestic biomethane plants operate mainly on livestock inputs and secondary plant waste.

The central region of Ukraine is characterized by the most favorable conditions for the development of crop production. Cherkasy region was chosen as a model region to determine the prospects for the development of the biomethane industry in the central regions of the country. Cherkasy region is among the top five regions of Ukraine in grain crop production. In the region, the largest volumes of straw are produced by crops such as corn (1st place), sunflower and winter wheat. The energy potential of primary agricultural waste in Cherkasy region depends on the size of the sown areas, the yield of grain and leguminous crops, weather conditions and the development of livestock farming. The economic potential of grain and leguminous straw can satisfy up to 10% of the energy needs of the region. The development of livestock farming, in particular dairy farms and the cooperative use of waste from agricultural farms in the region is promising for the construction of biomethane plants in the experimental area.

Today, corn and sunflower stalks in the region's farms remain mostly in the fields after harvest, despite their significant volumes and the prospect of using them as energy resources for local communities. Straw is used mainly in private households and is not widely used. The lack of interest of owners of large farms in collecting and further selling straw from these crops as an energy resource is explained by several factors. Most farms do not have balers for baling corn stalks, and additional collection costs increase the cost of waste. Another problem is technological: burning straw provokes an increased corrosion risk for heating boilers due to the high content of alkali metals, sulfur compounds and chlorine in biomass. Also, the quality of straw as a biofuel is largely determined by its humidity, so the construction of closed warehouses is recommended for storing biomass.

A limiting factor for increasing biomethane production in Ukraine is the high cost after purification, which makes its use on the domestic market unprofitable. The export potential of domestic biomethane is high when using the Ukrainian GTS and undergoing voluntary certification. The resolution of export barriers in cross-border trade in biomethane, as well as the prospects for the development of the industry, largely depend on the decisions of the European Union institutions.

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