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Assessing the indicators of the effectiveness of the strategic environmental directions of sustainable development of Ukraine in war conditions

Andrii Terebukh[1], Oksana Roik[1*], Natalia Pankiv[1], Halyna Ilnytska-Hykavchuk[1], Yaroslava Moskvyak[1], Larysa Teodorovych[1], Bohdana Koshova[1], Mariia Lushchyk[1]

[1] Department of Tourism, Lviv Polytechnic National University, 2/4 Karpinskoho St., Building 1, Lviv, 79000, Ukraine
* Corresponding author's e-mail: oksana.r.obervan@lpnu.ua

ABSTRACT

The article examines the methodology for assessing the effectiveness of strategic environmental directions for sustainable development in wartime through integral assessment, which provides a comprehensive picture of the impact of military actions on the ecological situation in Ukraine. The methodology is based on the fuzzy analytic hierarchy process (FAHP), which considers the uncertainty and complexity of processes characteristic of wartime conditions. The obtained results can be utilised for developing adaptive sustainable development strategies that address the specific challenges faced by Ukraine during military actions.

Keywords: sustainable development, multi-criteria analysis, resource management, strategic environmental directions, fuzzy analytic hierarchy method, integral assessment, environmental processes.

INTRODUCTION

Sustainable development is a fundamental concept of modern society, ensuring the harmonious coexistence of humans and nature through the integration of economic, social, and environmental aspects (Weitz et al., 2018). This concept becomes particularly significant in wartime conditions when military actions exert a substantial negative impact on the environment and socio-economic development (Hariram et al., 2023). In Ukraine, where the war creates additional challenges for ecological stability, the development and implementation of strategic environmental directions to ensure sustainable development is an urgent task (Renaud et al., 2022; Safranov et al., 2024).

Sustainable development is one of the key concepts in modern society, ensuring the harmonious coexistence of humanity and nature through the integration of economic, social, and environmental aspects (Ly et al., 2023). In wartime conditions, these aspects become especially relevant as military actions have a substantial negative effect on the environment and socio-economic development (Hariram et al., 2023). The development and implementation of effective strategic environmental directions become a critically important task for ensuring sustainable development in Ukraine.

The relevance of the study lies in the need to develop tools that ensure sustainable development during wartime, taking into account the specific challenges faced by Ukraine. In this regard, the purpose of this article is to model eco-economic processes to assess the effectiveness of strategic environmental directions for sustainable development in Ukraine. The application of multi-criteria optimisation methods, including the use of weighting coefficients for each indicator, enables a comprehensive evaluation of the effectiveness of strategies and the selection of the best paths for achieving sustainable development goals (Alrasheedi et al., 2020; Ziolo et al., 2021).

An analysis of contemporary scientific works and studies on the subject of sustainable development demonstrates a wide range of approaches and methods used to ensure the harmonious integration of economic, social, and environmental components of societal development. A significant number of scientific papers focus on sustainable development in the context of achieving the United Nations Sustainable Development Goals (SDGs) and adapting these goals to national conditions in the face of global challenges such as climate change, resource depletion, and social inequality (Weitz et al., 2018; Renaud et al., 2022).

In the context of the war in Ukraine, where ecological challenges become particularly acute, research aimed at modelling eco-economic processes to evaluate the effectiveness of strategic environmental directions is of particular importance (Hariram et al., 2023). In this context, studies analysing the impact of military actions on the environment and the potential for ecosystem restoration post-war are crucial. For instance, the research by (Biermann et al., 2017) emphasises the importance of developing adaptation strategies during wartime, considering the need to conserve natural resources and minimise negative environmental impacts.

Recent research in the field of sustainable development focuses on various aspects of integrating economic, social, and environmental components, especially in times of crises and conflicts. An important aspect is the development and implementation of effective strategies that ensure sustainable development, taking into account specific challenges, particularly during wartime.

Modelling and evaluating the effectiveness of sustainable development strategies are key topics in contemporary studies. Alrasheedi et al. (2020) propose a novel approach to assessing the green economy through the application of extended interval intuitionistic fuzzy models. This approach allows for a comprehensive consideration of various criteria and provides balanced solutions to achieve sustainable development. Such a methodology can be adapted to evaluate strategies during wartime, where it is necessary to respond swiftly to changes in environmental and economic conditions.

Ziolo et al. (2021) emphasize the importance of environmental sustainability policies in the European Union, which could be adapted for Ukraine, where military actions exacerbate environmental issues. Weitz et al. (2018) advocate for a systematic approach to prioritizing the SDGs, highlighting the need for contextual strategies tailored to national conditions, which is crucial for Ukraine in war condition. Hariram et al. (2023) stress the integration of socio-economic and environmental aspects into sustainable development models, a vital consideration during wartime when social and environmental crises are frequent.

Renaud et al. (2022) examine synergies and trade-offs between development goals, proposing adaptive strategies for global challenges like climate change and resource depletion. Such approaches are essential for Ukraine.

Biermann et al. (2017) focus on the importance of developing adaptation strategies under wartime conditions, considering the need to preserve natural resources and minimize negative environmental impacts. These approaches may be beneficial for Ukraine, where environmental issues are intensified by the ongoing war. Research by Hariram et al. (2023) also highlights the significance of integrating socio-economic and environmental aspects into sustainable development models. This emphasizes the importance of considering all components of sustainable development to ensure long-term environmental sustainability.

Pyliavskyi et al. (2021) explore pathways for improving the green economy and environmental protection, which is relevant for analyzing sustainable development strategies during wartime. They provide valuable tools for evaluating the effectiveness of environmental strategies. The implementation of innovative strategies for wastewater treatment (Tulaydan et al., 2017, Malovanyy et al., 2021), solid waste disposal (Tymchuk et al., 2021, Nahursky et al., 2022), and gas purification (Pospelov et al., 2020, Manidina et al., 2021) is promising.

Furthermore, the study by Safranov et al. (2024) examines the ecological component of sustainable development potential for industrial-urban agglomerations, which is important for Ukraine, where military actions affect the environmental situation in cities and industrial areas.

Therefore, contemporary academic works demonstrate a wide range of approaches to ensuring sustainable development amidst global and local challenges. Modelling eco-economic processes, including the application of multi-criteria optimization, is an essential tool for evaluating the effectiveness of strategic directions for sustainable development in Ukraine during wartime.

MATERIALS AND METHODS

The research includes the development of models for assessing the effectiveness of strategic environmental directions. In this context, modelling and evaluation of the effectiveness of strategic environmental directions for sustainable development use multi-criteria optimization methods. The primary objective of the methodology is to systematically determine and analyze the indicators that reflect the effectiveness of environmental strategies at the regional level in the context of military actions. The research begins with the creation of an input indicator matrix, which incorporates information about various aspects of ecological, economic, social, and institutional development in the regions of Ukraine. This matrix consists of data corresponding to the number of regions and the indicators that characterize effectiveness.

Following this, the indicators are standardized based on the ratio of actual values to reference values, facilitating easier comparisons. Standardized values are introduced and calculated using a formula where a reference value of 5 points is employed. The study involved a panel of 95 experts from various regions of Ukraine, ensuring a comprehensive and geographically diverse perspective. The selection of experts was based on several key criteria, including their professional experience in relevant fields. Each expert had a minimum of five years of experience in their respective domain, ensuring the reliability and depth of the insights provided. The inclusion of experts from different regions allowed the study to capture regional variations in eco-economic and institutional conditions, which are crucial for understanding the broader implications of the strategic environmental directions of sustainable development. The diversity of expert backgrounds also facilitated a multi-faceted analysis, incorporating both theoretical and practical perspectives on the challenges and opportunities facing the strategic environmental directions of sustainable development.

To assess the effectiveness of strategic environmental directions, index models are utilized. The indices for the components of effectiveness are calculated by taking the arithmetic mean of the standardized indicators for each group of indicators across regions.

The integral assessment of effectiveness is computed by summing the indices of the components of effectiveness, allowing for the derivation of an overall indicator for each region.

Furthermore, to identify the intervals of indicator values, the concept of the "Golden Ratio" is applied. This facilitates the establishment of criteria for categorizing regions into effectiveness levels, specifically low, medium, and high.

In conclusion, the proposed methodology offers a comprehensive approach to evaluating strategic environmental directions for sustainable development amidst wartime conditions, enabling the identification of key issues and the formulation of recommendations aimed at enhancing ecological effectiveness in Ukraine.

The multi-criteria analysis methods, particularly the fuzzy analytic hierarchy process (FAHP), gain significant importance, as they account for the complexity and uncertainty of eco-economic processes (Saaty et al., 2012; Jha et al., 2020). This method not only aids in evaluating the current situation but also in formulating strategies for the future, which is critically important in the context of limited resources and instability caused by war (Tung et al., 2017; Liu et al., 2021).

Methodological approaches to evaluating the effectiveness of environmental strategies often rely on multi-criteria methods, enabling a comprehensive consideration of various aspects of sustainable development. The fuzzy analytic hierarchy process, in particular, is one of the most effective tools for modelling complex eco-economic processes under conditions of uncertainty (Chen et al., 2016, Zijp et al., 2015). This approach allows for the consideration of the influence of various factors and subjective assessments on decision-making, which is vital for adapting strategies in the context of military conflict.

Significant contributions to the methodological framework of sustainable development research have been made by scholars focused on minimizing the negative impact of anthropogenic factors on the environment through the implementation of innovative technologies. For instance, the research by (Kuo et al., 2019) highlights the necessity of applying modern approaches to natural resource management and implementing sustainable practices in the industrial and agricultural sectors of the economy.

Thus, the literature review indicates the need for further development of research in the field of sustainable development, especially in the context of war, where traditional approaches require adaptation to new conditions. The application of multi-criteria optimization methods and the fuzzy analytic hierarchy process allows for effective evaluation and implementation of strategic environmental directions, which are crucial for ensuring sustainable development in Ukraine during wartime.

The aim of this article is to model eco-economic processes to assess the effectiveness indicators of strategic environmental directions for sustainable development in the context of war. To achieve this goal, the fuzzy analytic hierarchy process is employed, allowing for the consideration of multi-criteria aspects and uncertainties inherent in such complex processes (Saaty et al., 2012, Chen et al., 2016). The research utilizes expert assessments to develop models that provide an effective tool for evaluating and managing eco-economic processes (Li et al., 2019, Wang et al., 2020).

In wartime conditions, it is essential to ensure the effective use of resources and adapt strategies to changing circumstances in order to achieve long-term sustainable development goals (Lebel et al., 2014, Kluza et al., 2024). A significant contribution to the methodological framework of sustainable development research has been made by the work of (Malovanyy et al., 2020), which focuses on minimizing the negative impact of anthropogenic factors on the environment through the implementation of innovative technologies. These studies highlight the necessity of applying modern approaches to natural resource management and implementing sustainable practices in the industrial and agricultural sectors of the economy.

Thus, research on modelling eco-economic processes and assessing the effectiveness indicators of strategic directions is crucial for developing adaptive strategies that address contemporary challenges and ensure sustainable development in Ukraine during wartime.

RESULTS AND DISCUSSION

Contemporary approaches to assessing the effectiveness of strategic environmental directions involve the integration of ecological, economic, social, and institutional indicators, allowing for a comprehensive analysis and the development of more effective measures to achieve sustainable development (Ly et al., 2023, Zhang et al., 2016).

According to research, evaluating ecological indicators can significantly influence the success of sustainable development strategies. The importance of considering all aspects, from pollutant emissions to social indicators such as the level of environmental awareness among the population, is emphasized in the literature (Villamayor et al., 2023, Hariram et al., 2023). The analysis of the interconnections between different sustainable development goals demonstrates the necessity of employing multi-criteria methods for optimizing resources and achieving strategic environmental objectives (Weitz et al., 2018, Renaud et al., 2022).

In the wartime context that Ukraine currently faces, these methods not only enable the assessment of the current state of ecological and economic systems but also forecast the effectiveness of various development scenarios. This capacity allows for the adaptation of strategies to changing conditions, ensuring the best balance between ecological and economic goals (Vakal et al., 2020, Kluza et al., 2024). Thus, modelling eco-economic processes is an essential tool for developing and implementing sustainable development strategies during wartime, facilitating effective adaptation and recovery.

For an adequate assessment of the effectiveness of strategic directions for sustainable development, it is crucial to consider ecological, economic, social, and institutional aspects. The selection of indicators is based on their ability to reflect the real state and dynamics of changes in the respective areas. Choosing such indicators ensures a comprehensive approach to evaluating the effectiveness of strategic environmental directions for sustainable development in Ukraine during wartime. They allow for the consideration of various aspects of sustainable development and the adaptation of strategies to variable conditions (see Table 1).

Thus, we obtain a matrix of input indicators that will characterize the effectiveness level of strategic environmental directions for sustainable development. The matrix of input indicators will have the following form (Zijp et al., 2023, Roik et al., 2023, Terebukh et al., 2023):

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1k} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2k} & \cdots & x_{2n} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ x_{i1} & x_{i2} & \cdots & x_{ik} & \cdots & x_{in} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ x_{w1} & x_{w2} & \cdots & x_{wk} & \cdots & x_{wn} \end{bmatrix} \quad (1)$$

where: w – represents the number of regions, n – represents the number of indicators characterizing the effectiveness level of strategic environmental directions in the country, x_{ijk} –is the value of the i indicator for the k component in the j region.

Table 1. Components and Indicators of the effectiveness of strategic environmental directions for sustainable development in Ukraine during wartime

Component	Indicators	Rationale
Ecological	Reduction of harmful substance and greenhouse gas emissions (x_{1kj})	Emissions of harmful substances and greenhouse gases impact climate change and air quality. Reducing these emissions is critical for improving the ecological situation.
	Indicators of air and water quality (x_{2kj})	Air and water quality directly affect public health and ecosystems. Quality indicators help monitor changes and implement necessary measures.
	Level of soil pollution and reduction of waste (x_{3kj})	Soil pollution and large amounts of waste negatively affect ecosystems and public health. Reducing these indicators contributes to the preservation of natural resources.
	Restoration and conservation of biodiversity (x_{4kj})	Biodiversity is key to the resilience of ecosystems. Restoring and conserving biodiversity supports ecological balance and ensures the resilience of natural systems.
Economic	Gross domestic product (GDP) per capita (x_{5kj})	GDP per capita is a primary economic indicator of welfare. An increase in this indicator signifies economic growth and an improved standard of living.
	Investments in green technologies and renewable energy (x_{6kj})	Investments in green technologies promote a transition to a sustainable economy and reduce negative environmental impacts. Renewable energy decreases dependence on fossil fuels.
	Number of jobs created in the field of clean technologies (x_{7kj})	Jobs in green technologies contribute to economic development and reduce unemployment while supporting ecological sustainability.
Social	Level of environmental awareness among the population (x_{8kj})	A high level of environmental awareness fosters responsible attitudes towards nature and supports ecological initiatives at the community level.
	Access to clean water and sanitation (x_{9kj})	Access to clean water and sanitation is fundamental for healthy living and prevents the spread of water-related diseases.
	Quality of life and health of the population (x_{10kj})	Indicators of quality of life and health reflect the overall well-being of the population and serve as indicators of the success of strategic environmental initiatives.
Institutional	Effectiveness of environmental legislation and its implementation (x_{11kj})	Effective environmental legislation is the foundation for ensuring compliance with environmental norms and standards. Its implementation is crucial for sustainable development.
	Level of cooperation among government, business, and civil society on sustainable development issues (x_{12kj})	Cooperation among all sectors of society is essential for the effective implementation of sustainable development strategies. Synergy of efforts promotes the achievement of common goals.
	Availability and effectiveness of state and international programs supporting environmental initiatives (x_{13kj})	Support programs are vital for financing and implementing environmental projects. Their effectiveness determines the success of practical implementation of environmental strategies.

In the next stage of the study, standardized indicator values are determined based on the ratio of actual indicators to their reference values. Since there are no specific standards for individual properties, the reference value of the indicator (5 points) is used as the basis for comparison, and the overall score reflects the degree of deviation from the reference values (Zijp et al., 2023, Roik et al., 2023, Terebukh et al., 2023):

$$z_{ij} = x_{ij} / x_{max} \tag{2}$$

where: z_{ij} – is the standardized value of the iii-th indicator in the j region, x_{ij} –is the value of the i indicator, representing the evaluation of the effectiveness of strategic environmental directions for sustainable development in the j region, x_{max} – is the reference value of the indicator, representing the evaluation of the effectiveness of strategic environmental directions for sustainable development at the regional level.

As a result, we obtain a matrix of standardized values of indicators for evaluating the effectiveness of strategic environmental directions for sustainable development in the country. This matrix will have the following form (Zijp et al., 2023, Roik et al., 2023, Terebukh et al., 2023):

$$Z = \begin{bmatrix} Z_{11} & Z_{12} & \cdots & Z_{1k} & \cdots & Z_{1n} \\ Z_{21} & Z_{22} & \cdots & Z_{2k} & \cdots & Z_{2n} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ Z_{i1} & Z_{i2} & \cdots & Z_{ik} & \cdots & Z_{in} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ Z_{w1} & Z_{w2} & \cdots & Z_{wk} & \cdots & Z_{wn} \end{bmatrix} \tag{3}$$

The calculations for standardized indicators and the integral assessment of the effectiveness of strategic environmental directions for sustainable development at the regional level, considering the impact of military actions, are presented in Table 2.

The obtained matrix of standardised values allows for the calculation of the indices for individual components of the effectiveness of strategic environmental directions for sustainable development at the regional level under the impact of military actions, using the formula (Zijp et al., 2023, Roik et al., 2023, Terebukh et al., 2023):

$$I_{kij} = \frac{1}{n}\sum_{j=1}^{n} z_{ij} \quad (4)$$

where: I_{kij} – represents the indices of the individual k components of the effectiveness evaluation for the group of i indicators in the j region, z_{ij} – is the normalised i indicator of the k component in the j region, n – is the number of indicators for the k component of the effectiveness evaluation at the regional level.

The calculation of the integral assessment of the effectiveness of strategic environmental directions for sustainable development at the regional level, considering the impact of military actions, is carried out using the formula (Zijp et al., 2023, Roik et al., 2023, Terebukh et al., 2023):

$$I_{ESIj} = \frac{1}{n}\sum_{j=1}^{n} I_{kij} \quad (5)$$

where: I_{ESJj} – is the integral assessment of the effectiveness of strategic environmental directions for sustainable development in the j region, and n is the number of components characterising the level of effectiveness of strategic environmental directions at the regional level.

An I_{ESIj} value of 0 indicates a critical state of the system, characterised by a state of danger due to the reduction in the effectiveness of strategic

Table 2. Standardized indicator values for the integral assessment of the effectiveness of strategic environmental directions for sustainable development at the regional level

Region	Components of the integral assessment of the effectiveness of strategic environmental directions for sustainable development:												
	Ecological (I_{1ij})				*Economic I_{2ij}*			*Social I_{3ij}*			*Institutional I_{4ij}*		
	x_{1kj}	x_{2kj}	x_{3kj}	x_{4kj}	x_{5kj}	x_{6kj}	x_{7kj}	x_{8kj}	x_{9kj}	x_{10kj}	x_{11kj}	x_{12kj}	x_{13kj}
Vinnytsia	0.85	0.71	0.67	0.68	0.82	0.66	0.69	0.73	0.70	0.83	0.74	0.70	0.71
Volyn	0.89	0.85	0.82	0.80	0.77	0.71	0.72	0.75	0.84	0.83	0.83	0.73	0.75
Dnipropetrovsk	0.56	0.48	0.63	0.54	0.53	0.50	0.47	0.57	0.51	0.53	0.51	0.49	0.52
Donetsk	0.29	0.28	0.22	0.22	0.26	0.26	0.24	0.29	0.24	0.26	0.23	0.25	0.26
Zhytomyr	0.83	0.68	0.71	0.66	0.76	0.65	0.67	0.73	0.66	0.75	0.71	0.68	0.69
Transcarpathia	1.00	0.91	0.86	0.93	0.77	0.86	0.84	0.90	0.93	0.88	0.93	0.85	0.89
Zaporizhzhia	0.36	0.43	0.37	0.33	0.42	0.39	0.35	0.39	0.44	0.39	0.41	0.38	0.43
Ivano-Frankivsk	1.00	0.96	0.92	0.97	0.87	0.94	0.92	0.97	0.95	0.97	0.98	0.91	0.93
Kyiv	0.86	0.71	0.73	0.69	0.89	0.72	0.75	0.83	0.85	0.73	0.83	0.84	0.76
Kirovohrad	0.80	0.62	0.67	0.65	0.75	0.64	0.66	0.69	0.70	0.65	0.69	0.67	0.70
Luhansk	0.22	0.21	0.21	0.23	0.22	0.22	0.24	0.23	0.24	0.22	0.24	0.22	0.23
Lviv	1.00	0.93	0.89	0.96	0.89	0.91	0.92	0.95	0.96	0.95	0.97	0.91	0.94
Mykolayiv	0.71	0.64	0.66	0.62	0.70	0.63	0.64	0.68	0.65	0.69	0.67	0.66	0.66
Odesa	0.77	0.69	0.73	0.71	0.69	0.70	0.71	0.69	0.72	0.71	0.69	0.68	0.72
Poltava	0.73	0.67	0.70	0.65	0.75	0.66	0.67	0.69	0.68	0.69	0.68	0.67	0.70
Rivne	0.89	0.82	0.82	0.84	0.83	0.83	0.82	0.84	0.85	0.86	0.86	0.85	0.84
Sumy	0.58	0.53	0.54	0.51	0.55	0.53	0.54	0.54	0.53	0.54	0.53	0.52	0.55
Ternopil	0.92	0.84	0.84	0.87	0.83	0.84	0.82	0.85	0.87	0.87	0.86	0.83	0.87
Kharkiv	0.43	0.45	0.43	0.41	0.45	0.43	0.44	0.42	0.44	0.45	0.44	0.44	0.43
Kherson	0.40	0.37	0.38	0.36	0.39	0.38	0.38	0.39	0.38	0.39	0.38	0.37	0.38
Khmelnytsk	0.82	0.77	0.78	0.79	0.82	0.76	0.77	0.79	0.81	0.79	0.78	0.76	0.79
Cherkassy	0.75	0.69	0.72	0.67	0.73	0.68	0.70	0.72	0.71	0.73	0.70	0.69	0.71
Chernivtsi	0.86	0.83	0.82	0.84	0.84	0.83	0.85	0.85	0.83	0.84	0.85	0.84	0.84
Chernihiv	0.55	0.51	0.50	0.53	0.54	0.50	0.52	0.54	0.51	0.52	0.51	0.51	0.52

environmental directions at the regional level under wartime conditions. The calculations for the indices of individual components and the integral assessment of the effectiveness of strategic environmental directions for sustainable development at the regional level, considering the impact of military actions, are presented in Table 3.

To determine the intermediate states that will characterize the evaluations of the integral effectiveness of strategic environmental directions for sustainable development at the regional level, we use the formula of the so-called "golden ratio" (Golden Ratio Calculator, 2022). The essence of this ratio is a proportional relationship close to 0.618:0.382. The patterns of the "golden ratio" are widely present in living nature, manifesting in the harmonious structure of organisms, including humans. This indicates that the application of the principles of the "golden ratio" for determining states appears natural.

To establish the intervals for evaluating the integral effectiveness of strategic environmental directions for sustainable development, we derive the following quadratic equation (Golden Ratio Calculator, 2022):

$$x^2 + ax - a^2 = 0 \quad (6)$$

Solving this equation allows us to find x_1 and x_2:

$$x_{1,2} = -\frac{a}{2} \pm \sqrt{\frac{a^2}{4} + a^2} \quad (7)$$

where: $x_1 = 0.383$; $x_2 = 0.854$.

Therefore, the states of the integral indicator for assessing the integral effectiveness of strategic environmental directions for sustainable development at the regional level, within the interval from 0 to 1, are illustrated in Figure 1. According to the application of the "Golden Ratio", the intervals for assessing the integral effectiveness of strategic environmental directions for sustainable development are divided into three categories.

Table 3. Calculation of the integral assessment of the effectiveness of strategic environmental directions for sustainable development at the regional level (I_{ESIj})

Region	Components of the integral assessment of the effectiveness of strategic environmental directions for sustainable development				I_{ESIj}
	I_{1iJ}	I_{2ij2}	I_{3ij3}	I_{4ij4}	
Vinnytsia	0.73	0.72	0.75	0.72	0.73
Volyn	0.84	0.74	0.81	0.77	0.79
Dnipropetrovsk	0.55	0.50	0.54	0.51	0.52
Donetsk	0.25	0.25	0.26	0.25	0.25
Zhytomyr	0.72	0.69	0.71	0.69	0.70
Transcarpathia	0.93	0.82	0.90	0.89	0.88
Zaporizhzhia	0.37	0.39	0.40	0.41	0.39
Ivano-Frankivsk	0.96	0.91	0.96	0.94	0.94
Kyiv	0.75	0.79	0.80	0.81	0.79
Kirovohrad	0.68	0.68	0.68	0.69	0.68
Luhansk	0.22	0.23	0.23	0.23	0.23
Lviv	0.94	0.91	0.95	0.94	0.94
Mykolayiv	0.66	0.66	0.67	0.66	0.66
Odesa	0.73	0.70	0.71	0.70	0.71
Poltava	0.69	0.69	0.69	0.68	0.69
Rivne	0.84	0.83	0.85	0.85	0.84
Sumy	0.54	0.54	0.54	0.53	0.54
Ternopil	0.87	0.83	0.86	0.85	0.85
Kharkiv	0.43	0.44	0.44	0.44	0.44
Kherson	0.38	0.38	0.38	0.38	0.38
Khmelnytsk	0.79	0.78	0.80	0.78	0.79
Cherkassy	0.71	0.70	0.72	0.70	0.71
Chernivtsi	0.84	0.84	0.84	0.84	0.84
Chernihiv	0.52	0.52	0.52	0.51	0.52

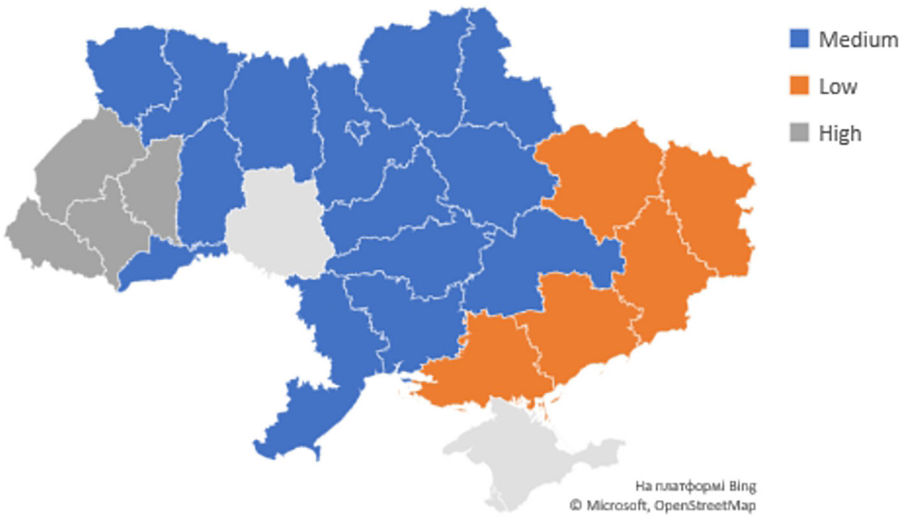

Figure 1. Grouping of regions by the level of integral assessment of the effectiveness of strategic environmental directions for sustainable development at the regional level

The first category represents a low level of effectiveness, which includes regions where the value of the integral indicator is less than or equal to 0.383. This suggests that these regions are currently in a state where the effectiveness of strategic environmental directions is inadequate, indicating a need for additional efforts and resources to enhance sustainable development. Examples of regions within this category include Donetsk, Luhansk, Zaporizhzhia, Kherson, and Kharkiv.

The second category corresponds to a medium level of effectiveness, comprising regions where the indicator value lies between 0.383 and 0.854. This indicates that some progress has been made in implementing strategic environmental measures; however, there are still opportunities for further improvement. Regions classified within this group are Vinnytsia, Volyn, Dnipropetrovsk, Zhytomyr, Kyiv, Kirovohrad, Mykolaiv, Odesa, Poltava, Rivne, Sumy, Khmelnytskyi, Cherkasy, Chernivtsi, and Chernihiv.

The final category represents a high level of effectiveness, covering regions where the indicator value exceeds 0.854. This denotes a high degree of success in implementing strategic environmental directions for sustainable development. Regions such as Transcarpathia, Ivano-Frankivsk, Lviv, and Ternopil fall into this category.

This classification provides a precise framework for identifying regions that require greater allocation of resources and efforts to improve the effectiveness of strategic environmental directions for sustainable development. The Figure 2 presents the average values of the integral components for assessing the effectiveness of strategic environmental directions for sustainable development, classified into three levels: low, medium, and high effectiveness of strategic environmental directions for sustainable development in Ukraine.

For regions with a low level of effectiveness, the average values of the integral indicators are approximately 0.33 for the ecological component (I_{1ij}), 0.34 for the economic component ($I2_{ij}$), 0.34 for the social component (I_{3ij}), 0.34 for the institutional component (I4ij), and 0.34 for the integral effectiveness score (I_{ESIj}). This suggests that these regions have a significantly insufficient level of effectiveness in implementing strategic environmental measures.

The medium level of effectiveness shows average values of around 0.71 for the ecological component (I_{1ij}), 0.70 for the economic component (I_{2ij}), 0.71 for the social component (I_{3ij}), 0.70 for the institutional component (I_{4ij}), and an integral score (I_{ESIj}) of 0.70. These values indicate a moderate performance in strategic environmental efforts, reflecting some progress yet leaving room for further improvement.

In contrast, the high level of effectiveness has notably higher average values, with the ecological component (I_{1ij}) at 0.93, the economic component (I_{2ij}) at 0.87, the social component (I_{3ij}) at 0.92, the institutional component at 0.91, and an overall integral score (I_{ESIj}) of 0.90. These values signify a substantial level of effectiveness in achieving the goals of strategic environmental development, demonstrating effective implementation

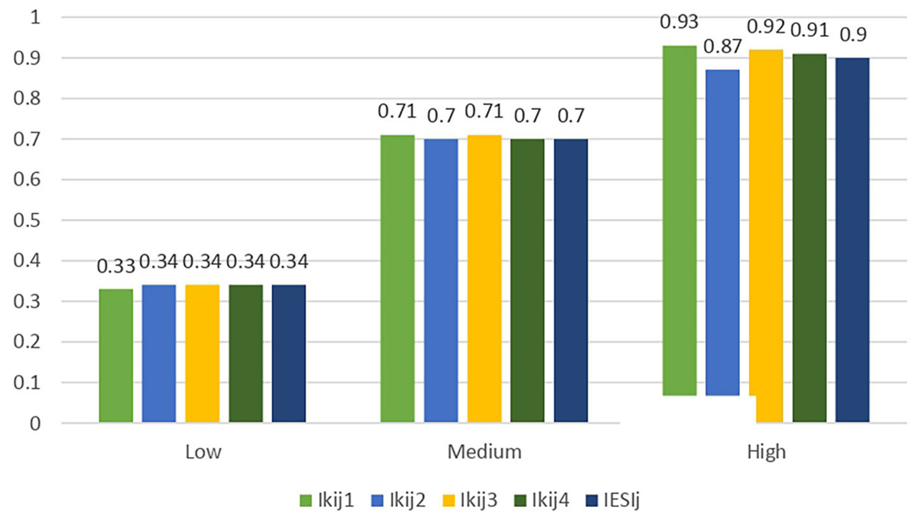

Figure 2. The average values of the integral components for assessing the effectiveness of strategic environmental directions for sustainable development

and progress towards sustainable development. The justification for this study lies in the growing urgency to address the challenges of sustainable development in Ukraine, particularly in war conditions and post-war recovery. As Ukraine faces significant environmental pressures, the need for strategic planning and evaluation of environmental processes becomes critical.

This research contributes to this need by developing a model based on the fuzzy analytic hierarchy process (FAHP), which allows for a more precise evaluation of strategic environmental directions. The FAHP method is particularly suited to address the complexity and uncertainty inherent in environmental decision-making, where multiple criteria and expert judgments must be considered simultaneously (Saaty and Vargas, 2012; Jha et al., 2020). Traditional methods may not fully capture the nuances of such complex systems, especially when external factors such as conflict and socio-economic instability are present. By incorporating fuzzy logic, the study enhances the accuracy and reliability of evaluating environmental priorities, making it a valuable tool for policymakers. Furthermore, the model's hierarchical structure provides a systematic approach to breaking down the strategic goal of sustainable development into specific sub-objectives and tasks. This structured approach ensures that various dimensions of environmental sustainability, such as emissions reduction, air and water quality, soil pollution control, and biodiversity restoration, are assessed in an integrated manner. Such a comprehensive evaluation is essential for Ukraine's sustainable development, as it seeks to align its environmental strategies with international standards and EU directives during its European integration process.

In addition, the study fills a gap in current literature by applying the FAHP method specifically to Ukraine's context, considering the impact of war and the need for recovery-oriented strategies. The findings of this research are expected to provide actionable insights for decision-makers, contributing to the development of informed and effective environmental policies aimed at long-term sustainable growth. Thus, the study not only advances academic knowledge in the field of eco-economic modelling but also serves as a practical framework for the evaluation and implementation of strategic environmental initiatives in Ukraine.

In the proposed model, the analysed indicators are evaluated through pairwise comparisons to determine their importance at each level of the hierarchy. At the second level, sub-goals are compared in terms of their impact on achieving the main strategic objective. Moving to the fourth level, the importance of strategic tasks is assessed to determine their contribution to achieving the sub-goals. A nine-point scale of preference is suggested for comparing two strategic factors (see Table 4).

The prioritisation of the effectiveness indicators of strategic environmental directions, described verbally, is subsequently transformed into triangular fuzzy numbers. The results are recorded in the form of a pairwise comparison matrix (Saaty et al., 2012, Jha et al., 2020):

Table 4. Nine-point preference scale for pairwise comparison of the effectiveness indicators of strategic environmental directions for sustainable development

Importance preference	Definition	Fuzzy value strength of importance
Equivalence	Equal importance for achieving the goal	$\tilde{1}$ = (1, 1, 1)
Poor	One element is slightly more important than the other	$\tilde{3}$ = (1, 3, 5)
Strong	One element is significantly more important than the other	$\tilde{5}$ = (3, 5, 7)
Very strong	One element is much more important than the other	$\tilde{7}$ = (5, 7, 9)
Absolute	One element is indisputably more important than the other	$\tilde{9}$ = (7, 9, 9)
Intermediate values between adjacent statements	If the evaluator has no clear stance on comparing two elements, intermediate values are used	$\tilde{2}$ = (1,2,4); $\tilde{4}$ = (2, 4, 6); $\tilde{6}$ 6 = (4, 6, 8); $\tilde{8}$ = (6, 8, 9)
Transitivity of evaluations	If the *i* element is assigned one of the above levels in comparison to the *j*, the *j* element is assigned the reciprocal value relative to the *i*	Reciprocal values of the above values

$$\tilde{A} = \begin{bmatrix} \tilde{1} & \widetilde{x_{12}} & \cdots & \widetilde{x_{1(\cdot)}} \\ \frac{\tilde{1}}{\widetilde{x_{12}}} & \tilde{1} & \dots & \widetilde{x_{2(\cdot)}} \\ \vdots & \vdots & \cdots & \vdots \\ \frac{\tilde{1}}{\widetilde{x_{1(\cdot)}}} & \frac{\tilde{1}}{\widetilde{x_{2(\cdot)}}} & \dots & \tilde{1} \end{bmatrix} \tag{8}$$

where: (•) – denotes n for operational goals, p_k for tasks (k = 1, 2, …, n), and m for scenarios, $\tilde{x}_{ij} = (l_{ij}, m_{ij}, u_{ij})$ $i, j = 1, \dots (\bullet)$, $\tilde{x}_{ij}$ represents the strength of importance of the i strategic factor over the j factor, averaged using the geometric mean of pairwise comparisons made by experts. Moreover, $\tilde{x}_{ij} = \tilde{I}/\tilde{x}_{ij}$ $(1/u_{ij}, 1/m_{ij}, 1/1_{ij}$ ma $\tilde{x}_{ij} = \tilde{I}(1,1,1)$ (Saaty et al., 2012, Jha et al., 2020) (see Table 5).

Table 3 presents the pairwise comparison matrix for various indicators across the ecological,

Table 5. Construction of the pairwise comparison matrix for each group of indicators

Ecological component				
	Reduction of emissions	Air and water quality	Soil pollution and waste reduction	Biodiversity restoration
Reduction of emissions	1	5	3	7
Air and water quality	1/5	1	1/3	3
Soil pollution and waste reduction	1/3	3	1	5
Biodiversity restoration	1/7	1/3	1/5	1

Economic component			
	GDP per capita	Investment in green technologies	Jobs created in eco-friendly technologies
GDP per capita	1	3	5
Investment in green technologies	1/3	1	3
Jobs created in eco-friendly technologies	1/5	1/3	1
Social component			
	Environmental awareness	Access to clean water and sanitation	Quality of life and health
Environmental awareness	1	3	5
Access to clean water and sanitation	1/3	1	3
Quality of life and health	1/5	1/3	1
Institutional component			
	Effectiveness of legislation	Level of cooperation	State and international support programs
Effectiveness of legislation	1	3	5
Level of cooperation	1/3	1	3
State and international support programs	1/5	1/3	1

economic, social, and institutional components of sustainable development. The results indicate that "Reduction of Emissions" is perceived as the most critical ecological factor, emphasizing its importance in improving environmental outcomes. In the economic context, GDP per Capita" is highlighted as essential, reflecting its strong correlation with job creation in eco-friendly sectors. Socially, "Environmental Awareness" is prioritised, suggesting that fostering sustainability within communities is crucial for enhancing public health and access to resources. Finally, the institutional component underscores the importance of effective legislation and cooperation among stakeholders in implementing environmental policies. Overall, the findings reveal the interconnectedness of these indicators and provide a framework for policymakers to allocate resources effectively and enhance the impact of strategic environmental directions in Ukraine. At the third stage, the pairwise comparisons are verified for consistency using the inconsistency index (Saaty et al., 2012, Jha et al., 2020):

$$CR = CI/RI \times 100\% \quad (9)$$

where: $CI = (\lambda_{max} - n)/(n - 1)$ – is the consistency index, where λ_{max} – is the maximum or principal eigenvalue of the comparison matrix A_1, n – is the number of rows (or columns) in the matrix A, RI – is the average random inconsistency index calculated from a randomly generated matrix of size $n \times n$ (see Table 6).

The inconsistency ratio CR should not exceed 10%. If the pairwise comparisons in matrix A consisting of the values m_{ij} are consistent, then the pairwise comparisons in the fuzzy relation matrix A will also be consistent (Sylkin et al., 2020). Once the pairwise comparisons are verified, local and global priority values can be computed (Step 4). These are calculated as follows (Sylkin et al., 2020, Saaty et al., 2012):

1) Compute the fuzzy sum for each row of the fuzzy comparison matrix A and normalise them using operations with fuzzy numbers:

2) $$\widetilde{Q_i} = (l_i, m_i, u_i) = \frac{\sum_{j=1}^{P_k}(l_i, m_i, u_{ij})}{\sum_{i=1}^{P_k}\sum_{j=1}^{P_k}(l_i, m_i, u_{ij})}$$

$$i = 1, 2, \dots, P_k; k = 1, 2, \dots, n \quad (10)$$

3) Calculate the degrees of possibility that $Q_i > Q_g$ $(i, g = 1, 2, \dots, P_k, i \neq g)$, using the following formula:

$$V(\tilde{Q}_i \geq \tilde{Q}_g) = hgt(\tilde{Q}_i \cap \tilde{Q}_g) = \begin{cases} 1, for\ m_i \geq m_g \\ 0, for\ l_g \geq u_i \\ \frac{l_g - u_i}{(m_i - u_i) - (m_g - l_g)} \end{cases} \quad (11)$$

where: hgt – is the height of the fuzzy sets at the intersection of $\tilde{Q}_i$ and $\tilde{Q}_g$.

Then, the minimum of the above values is selected: $w_i^s = minV(\tilde{Q}_i \geq \tilde{Q}_g)$. The value w_i^s after normalisation, becomes the local priority for the tasks P_k $(k = 1, 2, \dots, n)$ within the k operational objective i (Sylkin et al., 2020, Saaty et al., 2012):

$$w_i = w_i^s \Big/ \sum_{i=1}^{P_k} w_i^s \quad (12)$$

The results of these calculations are presented in Tables 5 and 6. The calculations of the degrees of possibility for each group of indicators help to identify the most significant indicators for each category based on their normalised values (see Table 7). Table 5 presents the local and global priority values for the indicators of strategic environmental directions across various regions. The findings indicate that Transcarpathia has the highest normalised local priority value $(w_6 = 0.30)$, signifying its critical role in achieving sustainable development goals. Following closely is Volyn $(w_2 = 0.25)$ and Ivano-Frankivsk $(w_8 = 0.28)$, indicating that these regions also have significant contributions to strategic environmental effectiveness. Conversely, regions such as Donetsk $(w_4 = 0.05)$ and Luhansk $(w_{11} = 0.03)$ demonstrate the lowest priority values, reflecting their challenges in implementing effective environmental strategies amidst ongoing conflict. This suggests a need for targeted interventions and resource allocation in these regions to improve their strategic environmental performance. Overall, the results highlight the variability in priority values among different regions, indicating diverse capabilities and challenges in advancing strategic environmental initiatives. This information is vital

Table 6. Average random inconsistency index

Matrix size (n)	1	2	3	4	5	6	7	8	9
Inconsistency index (RI)	0.000	0.000	0.524	0.881	1.108	1.247	1.341	1.405	1.449

Table 7. Local and global priority values for indicators of strategic environmental directions

Region	Ecological (Q_1)	Economic (Q_2)	Social (Q_3)	Institutional (Q_4)	Normalised local priorities (w)
Vinnytsia	(0.73, 0.72, 0.75)	(0.72, 0.70, 0.75)	(0.75, 0.72, 0.75)	(0.72, 0.70, 0.75)	w_1 = 0.23
Volyn	(0.84, 0.74, 0.81)	(0.74, 0.70, 0.80)	(0.81, 0.77, 0.85)	(0.77, 0.72, 0.80)	w_2 = 0.25
Dnipropetrovsk	(0.55, 0.50, 0.54)	(0.50, 0.48, 0.52)	(0.54, 0.50, 0.54)	(0.51, 0.48, 0.52)	w_3 = 0.12
Donetsk	(0.25, 0.25, 0.26)	(0.25, 0.24, 0.26)	(0.26, 0.25, 0.26)	(0.25, 0.24, 0.25)	w_4 = 0.05
Zhytomyr	(0.72, 0.69, 0.71)	(0.69, 0.66, 0.70)	(0.71, 0.68, 0.72)	(0.69, 0.66, 0.70)	w_5 = 0.20
Transcarpathia	(0.93, 0.82, 0.90)	(0.82, 0.78, 0.85)	(0.90, 0.88, 0.92)	(0.89, 0.85, 0.90)	w_6 = 0.30
Zaporizhzhia	(0.37, 0.39, 0.40)	(0.39, 0.38, 0.40)	(0.40, 0.38, 0.40)	(0.41, 0.39, 0.41)	w_7 = 0.09
Ivano-Frankivsk	(0.96, 0.91, 0.96)	(0.91, 0.88, 0.93)	(0.96, 0.94, 0.96)	(0.94, 0.91, 0.95)	w_8 = 0.28
Kyiv	(0.75, 0.79, 0.80)	(0.79, 0.75, 0.80)	(0.80, 0.78, 0.81)	(0.81, 0.78, 0.80)	w_9 = 0.22
Kirovohrad	(0.68, 0.68, 0.68)	(0.68, 0.67, 0.69)	(0.68, 0.67, 0.68)	(0.69, 0.67, 0.68)	w_{10} = 0.18
Luhansk	(0.22, 0.23, 0.23)	(0.23, 0.22, 0.23)	(0.23, 0.22, 0.23)	(0.23, 0.22, 0.23)	w_{11} = 0.03
Lviv	(0.94, 0.91, 0.95)	(0.91, 0.88, 0.93)	(0.95, 0.92, 0.94)	(0.94, 0.91, 0.93)	w_{12} = 0.27
Mykolayiv	(0.66, 0.66, 0.67)	(0.66, 0.65, 0.67)	(0.67, 0.66, 0.67)	(0.66, 0.65, 0.67)	w_{13} = 0.16
Odesa	(0.73, 0.70, 0.71)	(0.70, 0.68, 0.71)	(0.71, 0.68, 0.70)	(0.70, 0.68, 0.71)	w_{14} = 0.21
Poltava	(0.69, 0.69, 0.69)	(0.69, 0.68, 0.69)	(0.69, 0.68, 0.69)	(0.68, 0.67, 0.68)	w_{15} = 0.19
Rivne	(0.84, 0.83, 0.85)	(0.83, 0.81, 0.84)	(0.85, 0.84, 0.86)	(0.85, 0.83, 0.84)	w_{16} = 0.26
Sumy	(0.54, 0.54, 0.54)	(0.54, 0.53, 0.54)	(0.54, 0.53, 0.54)	(0.53, 0.52, 0.53)	w_{17} = 0.10
Ternopil	(0.87, 0.83, 0.86)	(0.83, 0.81, 0.84)	(0.86, 0.84, 0.87)	(0.85, 0.83, 0.84)	w_{18} = 0.29
Kharkiv	(0.43, 0.44, 0.44)	(0.44, 0.43, 0.44)	(0.44, 0.43, 0.44)	(0.44, 0.43, 0.44)	w_{19} = 0.06
Kherson	(0.38, 0.38, 0.38)	(0.38, 0.37, 0.38)	(0.38, 0.37, 0.38)	(0.38, 0.37, 0.38)	w_{20} = 0.04
Khmelnytsk	(0.79, 0.78, 0.80)	(0.78, 0.76, 0.79)	(0.80, 0.78, 0.81)	(0.78, 0.76, 0.79)	w_{21} = 0.23
Cherkassy	(0.71, 0.70, 0.72)	(0.70, 0.68, 0.71)	(0.72, 0.70, 0.73)	(0.70, 0.68, 0.71)	w_{22} = 0.20
Chernivtsi	(0.84, 0.84, 0.84)	(0.84, 0.82, 0.83)	(0.84, 0.83, 0.84)	(0.84, 0.82, 0.83)	w_{23} = 0.27
Chernihiv	(0.52, 0.52, 0.52)	(0.52, 0.51, 0.52)	(0.52, 0.51, 0.52)	(0.51, 0.50, 0.51)	w_{24} =0.11

for policymakers to tailor their strategies and interventions based on regional priorities, thereby enhancing the overall effectiveness of sustainable development efforts in Ukraine.

Thus, within the framework of the conducted analysis, four main components were examined: ecological, economic, social, and institutional. The results of the calculations of local and global priority values for each region allow for the identification of priority development areas and indicate regions that require additional efforts. In particular, regions such as Donetsk and Luhansk need urgent efforts from the government to implement programs for the reclamation of contaminated areas, improve waste management, and meet the basic social needs of the population. Additional investments in environmental technologies are necessary for Vinnytsia and Zaporizhzhia regions to support their economic development and mitigate negative impacts on the environment. On the other hand, regions with high priorities, such as Transcarpathia and Ivano-Frankivsk, can serve as examples for other regions and have the potential to develop initiatives that support environmental awareness and sustainability, through cooperation with non-governmental organizations, the private sector, and international partners.

In particular, Transcarpathia has the highest ecological component score (0.93), indicating active efforts in reducing emissions and restoring biodiversity. The region demonstrates significant potential for implementing eco-monitoring programs and promoting eco-tourism. Ivano-Frankivsk, with a score of 0.96, also shows high investments in environmental technologies, which opens opportunities to raise public environmental awareness through educational campaigns. Conversely, Donetsk, with the lowest score (0.25), faces serious ecological challenges. It is essential to implement programs for the reclamation of contaminated areas and improve waste management.

The economic component indicates certain positive trends. Ivano-Frankivsk's high score (0.91) reflects increasing investments in the green sector. Meanwhile, Vinnytsia (0.72) shows a need for attracting additional investments for the development of environmental technologies. In contrast, Luhansk (0.23) indicates weak economic development, requiring active support programs for entrepreneurship and investment attraction.

Regarding the social component, Lviv and Ivano-Frankivsk have high scores (0.95 and 0.96, respectively), indicating a good level of social welfare. It is essential to develop social programs to support vulnerable groups in these areas. In contrast, Dnipropetrovsk, with a score of 0.54, requires the implementation of programs to improve access to medical services and education, while Luhansk, with the lowest score (0.23), faces serious social challenges that need urgent attention.

The institutional component also reflects varying levels of management effectiveness. Kyiv, with a score of 0.81, demonstrates a high level of institutional capacity, enabling continued cooperation with international organizations. Volyn (0.77) has good management effectiveness, and it is crucial to strengthen partnerships with civil society. Meanwhile, Luhansk (0.23) requires enhanced institutional capacity and transparency in management processes. Thus, Transcarpathia, Ivano-Frankivsk, and Lviv show the highest results across all components, indicating their readiness for sustainable development. It is advisable to invest in environmental education and eco-tourism programs for these regions. Conversely, Donetsk, Luhansk, and Zaporizhzhia require urgent measures to improve their ecological situation and social conditions. These regions should implement reclamation programs, ensure basic needs are met, and support entrepreneurship.

This research aimed to evaluate the effectiveness of strategic environmental directions for sustainable development in Ukraine under wartime conditions. A multi-criteria optimisation framework, specifically the FAHP, was employed to comprehensively assess the ecological, economic, social, and institutional dimensions across Ukrainian regions. The findings revealed considerable regional disparities, with specific regions such as Transcarpathia, Ivano-Frankivsk, and Lviv demonstrating elevated levels of sustainability effectiveness, particularly in ecological and economic metrics. Conversely, other regions, including Donetsk and Luhansk, demonstrated critical deficiencies, underscoring the imperative for targeted interventions. The study highlights the importance of region-specific policies that allocate resources in accordance with the distinctive environmental and socio-economic requirements of each region. By adapting sustainable strategies based on the identified regional strengths and vulnerabilities, Ukraine can more effectively pursue sustainable development, even in the context of wartime challenges. The FAHP model developed here provides a framework for ongoing assessment and strategic planning, ensuring that environmental, economic, and social initiatives are aligned with both immediate and long-term national goals.

The classification of regions into three levels of effectiveness – high, medium, and low –provides policymakers with a precise framework for the identification of areas requiring additional funding and intervention with a view to improving environmental sustainability. The regional classification allows for the targeted allocation of resources, thereby enabling the most vulnerable regions, such as Donetsk and Luhansk, to receive the requisite support to address pressing environmental and socio-economic needs. It is of the utmost importance to invest in environmental remediation programmes, waste management and public welfare in these regions, in order to guarantee resilience and long-term sustainability.

The practical value of these findings is significant for the development of adaptive strategies that consider regional specifics in the context of Ukraine's ongoing war. By adapting the allocation of resources and the implementation of interventions, Ukraine can enhance resilience in areas affected by conflict while optimising the environmental and economic potential of regions that demonstrate robust sustainability performance. In regions with high effectiveness scores, including Transcarpathia, Ivano-Frankivsk, and Lviv, further investment in eco-tourism and environmental education programmes could foster economic growth while promoting sustainability. Conversely, the critical levels of effectiveness observed in regions such as Donetsk and Luhansk indicate the necessity for immediate assistance to address environmental and social deficiencies through international support and enhanced local governance.

In conclusion, this research represents a significant advancement in methodological approaches to sustainability assessment and serves as a practical guide for public policy makers in Ukraine. By addressing both the current crises and future sustainability goals, the findings provide support for Ukraine's path towards recovery and alignment with international environmental standards in the post-war period.

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