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ECONOMIC, ECOLOGICAL, AND SOCIAL DIMENSIONS OF INDUSTRIAL ENTERPRISES ENVIRONMENTAL SECURITY AND SUSTAINABILITY ENSURING

ABSTRACT

Industrial enterprise environmental security assessment refers to the assessment and analysis of industrial environmental security measures and vulnerabilities to protect against potential threats and risks to the environment. By conducting an environmental security assessment, industrial companies can proactively identify and eliminate security gaps, reduce the potential impact on the environment, and ensure compliance with regulatory acts. The article's purpose is to assess the industrial enterprises' environmental security level, transform strategies to reduce environmental risks, and formulate recommendations for simultaneously increasing economic and environmental security.

Our study presents an improved structured methodology for constructing an environmental security indicator system for industrial enterprises. Unlike conventional approaches, the proposed method follows a systematic sequence that includes defining the objectives and diagnostic tasks, collecting and processing relevant data, and ultimately forming a comprehensive indicator system. Central to this approach is the development of an integral indicator that reflects the overall level of environmental security. This indicator is derived from a balanced set of socio-economic, technical-technological, scientific-innovative, and managerial-organizational dimensions, incorporating both internal and external factors influencing enterprise operations. The uniqueness of the proposed model lies in its use of a geometric mean to synthesize integral indicators across the economic, ecological, and social domains, while accounting for the relative significance of each component. This weighting mechanism ensures a more accurate and nuanced assessment by recognizing the differential impact of individual indicators on overall environmental security. The level of environmental security was calculated for three companies in the railway transport industry.

Also, we form the strategies to mitigate environmental risks, which allow the industrial enterprises to enhance both economic resilience and ecological integrity, and to improve their overall security. In addition, we proposed recommendations for simultaneously improving the economic and environmental security of industrial enterprises.

Keywords: economic security, environmental security, environmental security management process, industrial enterprises, interaction, strategies

JEL Classification: D20, F64, P28, Q57

INTRODUCTION

Given today's global challenges, such as climate change, natural disasters, and loss of biodiversity, businesses, especially industrial ones, must be concerned not only with making a profit and achieving other economic indicators, but also with environmental security standards.

Simultaneous research into economic and environmental security offers a comprehensive framework for identifying synergies and trade-offs between profitability and ecological sustainability. It enables organizations to anticipate and mitigate risks arising from resource scarcity, regulatory pressure, climate change, and market volatility, while

also exploring opportunities for innovation and efficiency. Furthermore, integrated assessments provide more accurate and actionable insights for decision-makers, facilitating the alignment of operational practices with the principles of sustainable development.

The evaluation of the current state and future development prospects of industrial enterprises indicates that one of the most urgent challenges at present is the need to ensure socio-ecological and economic security. Today's realities require constant improvement of equipment and technologies due to scientific and technological progress, which leads to economic growth, which contributes to the increase of national production, and is one of the main goals of any state. As a result, all this leads to an increase in the natural resources usage, namely: mineral resources, agro-climatic, biotic, recreational, etc., as well as to the emergence of socio-economic and resource-environmental problems. The intensification of integration processes and the advancement of globalization necessitate an elevated level of security within industrial enterprises, rendering it a critical prerequisite for their stable operation. In contemporary conditions marked by the dynamic evolution of production systems and international economic relations, the challenges associated with socio-ecological and economic security have gained significant relevance. These issues warrant a comprehensive investigation not only at the national level but also across regional and enterprise-specific contexts. An industrial enterprise functions as a complex system encompassing social, economic, and ecological dimensions, which inherently introduces multifaceted and multilayered developmental objectives. The effective coordination of these objectives, along with the pursuit of balanced trade-offs, underscores the need for an integrated approach – one that synthesizes economic, environmental, and social considerations – in formulating a robust security framework for industrial enterprises.

Effective enterprise management necessitates the application of appropriate tools for the planning and implementation of measures that simultaneously address two critical objectives: minimizing the adverse anthropogenic impact on the environment and promoting the rational utilization of the natural resource potential of ecosystems, while also ensuring operational efficiency and profitability as foundational elements for achieving strategic goals. In this context, environmental security emerges as a significant criterion for evaluating the effectiveness of enterprise management and constitutes a core component of the enterprise's functional processes.

LITERATURE REVIEW

In the context of accelerating global environmental degradation and increasingly complex economic challenges, enterprises face the urgent need to ensure both economic viability and environmental responsibility. Traditionally, economic and environmental securities have been treated as distinct domains within corporate risk management and strategic planning. However, recent developments in sustainability science, corporate governance, and environmental policy underscore the critical interdependence of these two dimensions. The inability to recognize and manage the mutual impacts of economic and environmental risks can lead to systemic vulnerabilities, undermining the long-term stability and competitiveness of enterprises.

Simultaneous research into economic and environmental security offers a comprehensive framework for identifying synergies and trade-offs between profitability and ecological sustainability. It enables organizations to anticipate and mitigate risks arising from resource scarcity, regulatory pressure, climate change, and market volatility, while also exploring opportunities for innovation and efficiency. Furthermore, integrated assessments provide more accurate and actionable insights for decision-makers, facilitating the alignment of operational practices with the principles of sustainable development.

The essence and mechanism of enterprise economic security are investigated by Andriichuk (2020) and Batini (2019). The problem of ecological and economic security has been studied in scientific papers by economists Hryshenko (2012), Kharchenko (2015), Tiutchenko et al. (2024), Lyeonov et al. (2025) and Mentel et al. (2020). The environmental economics studies take place in the papers of such economists as Barkemeyer et al. (2017), Staniškis & Arbačiauskas (2009), Eletter (2024). Theoretical and methodological foundations of environmental security, development of new and adaptation of existing mechanisms and environmental and economic tools, a wide range of current issues of environmental security exist at all system levels (state – region – business – person).

The issue of environmental security has been the focus of numerous studies conducted at both regional and global levels. For instance, Wei et al. (2020) examined ecological security across African countries and concluded that, overall, the continent demonstrates relatively favorable ecological security conditions. Within the region, North Africa exhibited the highest levels of ecological security, whereas West Africa ranked lowest. At the national level, Guo et al. (2017) and Mohammad O. Al-Smadi (2025) analyzed the impact of industrial enterprise growth on environmental quality in China and Jordan, highlighting the complex interdependencies between economic development and ecological stability. While many contemporary evaluations of ecological security are concentrated on regional scales, there is also a growing body of

research addressing global dynamics. Notably, Huang et al. (2020) proposed a comprehensive ecological security index that integrates key biogeochemical cycles – including biological, oxygen, carbon, thermal, and hydrological components – alongside the effects of climate change and anthropogenic activities on ecosystem stability.

Research on the ecological and economic development state management mechanism was conducted by Shajdorov (2014). The formation of the ecological and economic mechanism of the national economy, an ecologically oriented development strategy, is studied in the paper of Varnaliy et al. (2016). The analysis of scientific literature on eco-innovation strategies for manufacturing practice is conducted by Janahi et al. (2021). The green transformation of industrial enterprises has increasingly attracted widespread attention of Li et al. (2019).

Mashchenko (2017) examined the relationship between economic security and the environmental economy, offering a theoretical foundation for the economic concept of “environmental security”. The study argues that environmental development should be regarded as a strategic priority for any society. Developed countries are identified as playing a crucial role in advancing sustainable development by aligning economic, social, and environmental objectives. Mashchenko (2017) emphasizes that ensuring environmental sustainability requires not only the protection of natural ecosystems and the exploration of resource potential but also a comprehensive understanding of regulatory mechanisms. This includes the optimization of resource use and the advancement of environmentally oriented innovations, which are integral to achieving long-term ecological and economic balance. The research suggests that improving the mechanism of environmental regulation requires modifying the tools and methods that incentivize rational resource management. While mechanisms supporting sustainable development are not entirely new, they are frequently refined or supplemented to reflect evolving business conditions. Furthermore, the study analyzes the components of the environmental security mechanism, identifying them as the objects and subjects of the environmental economy, environmental interests, regulatory instruments, methods, levers, and the informational and analytical infrastructure supporting environmental security. According to Mashchenko (2018), environmental security can be defined as the state of interaction between the economy and environmental protection that ensures resilience to both internal and external threats. This condition enables the resolution of challenges related to balanced economic growth, supports environmental improvement, and facilitates the formulation and implementation of national strategies and mechanisms for environmentally sustainable development.

Baik et al. (2021) present an analysis of the economic and legal dimensions of rational natural resource management as a critical element of environmental security. They propose the adoption of supplementary fiscal regulatory measures in Ukraine to enhance environmental governance. Specifically, the study recommends the provision of tax incentives for enterprises that implement environmentally protective initiatives, along with the development of mechanisms for environmental risk insurance.

Kolomoiets et al. (2024) link environmental security with the quality of atmospheric air. Their study highlights that the administrative and legal framework for the protection of atmospheric air encompasses a range of functional components. These include the regulation of air pollutant emissions within the limits of maximum permissible standards to safeguard individuals' rights to a safe and healthy environment; the environmental modernization of industrial processes; the implementation of ecological fuel quality standards; and the sustainable transformation of the energy sector, notably through the decentralization of the national energy system. Their paper concludes that maintaining the appropriate quality of atmospheric air constitutes a fundamental element of the broader environmental security mechanism.

Kupalova et al. (2025) formulate methodological recommendations aimed at enhancing the environmental management practices of industrial enterprises through the development of an optimization model. Their model is intended to evaluate the effectiveness of ecological modernization efforts and facilitate the adoption of innovative, environmentally sustainable technologies within production processes. The proposed framework is designed to serve as an analytical foundation for evidence-based managerial decision-making. The study introduces an optimization-based approach to investment planning in ecological modernization, with the goal of achieving the most efficient allocation of limited resources. The initial phase of the investment process encompasses a comprehensive assessment, including an inventory of the quantitative and qualitative state of production infrastructure, an environmental audit of anthropogenic impacts, an evaluation of the feasibility of implementing best available technologies and management practices, and the formulation of alternative modernization scenarios. An integral performance indicator for ecological modernization is developed, comprising two primary elements: an investment return index and an index reflecting the environmental impact categories. The optimization modeling framework enables the simulation and comparative analysis of various investment scenarios, thereby supporting the identification of the most effective modernization pathway. In practical application, the proposed optimization model for assessing the efficiency of ecological modernization has the potential to significantly enhance the effectiveness of environmental management in industrial enterprises. By providing a structured basis for scenario analysis and decision support, it contributes to more rational and sustainable resource use in the transition toward greener production systems.

Li & Hai (2023) investigate the interrelation between economic security and environmental protection within the framework of sustainable development and the evolving scientific-technological ecological landscape. The authors introduce a conceptual indicator system designed to assess the coordinated progress of eco-technological innovation alongside economic performance. Their study evaluates empirical data to determine the impacts on both economic stability and environmental outcomes. The findings demonstrate that the implementation of an integrated eco-technology innovation management system contributes to enhanced resource efficiency and cost performance. Specifically, post-implementation analysis indicates that the rate of material utilization has remained stable, while unit production costs have been consistently reduced in comparison to pre-implementation levels. These results highlight the potential of eco-technological innovation to support both environmental sustainability and economic resilience in industrial operations.

AIMS AND OBJECTIVES

The article's purpose is to assess the industrial enterprises' environmental security level, transform strategies to reduce environmental risks, and formulate recommendations for simultaneously increasing economic and environmental security. The formation of these strategies will make it possible to enhance both economic resilience and ecological integrity, and to improve the overall security of industrial enterprises.

To achieve the set goal, the following tasks were completed:

1. To characterize the process of enterprise environmental security management.
2. To build the conceptual scheme of management of social, ecological, and economic processes of industrial enterprises from a strategic perspective.
3. To improve the system of environmental security indicators of industrial enterprises, without taking into account external threats that cannot be eliminated at the moment.
4. To calculate the level of environmental security using the integrated indicator for three companies in the railway transport industry.
5. To develop strategies to improve environmental security.

METHODS

The generalization of scientific approaches made it possible to determine that environmental development is one of the strategic priorities for any society. This vector, which has a special power, is carried out in the most developed societies, which announce harmonious life development. Developed countries play a crucial role in ensuring sustainable development by coordinating economic, social, and environmental goals. The investigation of the mechanisms underlying environmental security is particularly relevant in the current context. This research is essential not only for the protection of the environment and the identification of the potential of natural resources but also for elucidating the role of these mechanisms in optimizing resource utilization and advancing environmental innovations.

Our research is based on the confirmation of the following empirical hypotheses:

- *Hypothesis 1.* The integration of economic and environmental risk factors into a unified management model leads to a statistically significant improvement in the overall security performance of industrial enterprises.
- *Hypothesis 2.* Strategically aligned environmental risk mitigation strategies enhance not only ecological integrity but also contribute positively to the economic resilience of enterprises in the railway transport industry.

In this research, we develop a methodology for assessing enterprise environmental security, utilizing an integrated indicator to evaluate its overall level. The analysis indicates that environmental security is maintained through an integrated system of organizational, economic, and legal measures designed to reduce socio-ecological and economic risks. This system serves as a foundational framework for achieving the social, economic, and environmental goals integral to the paradigm of sustainable national development. Environmental security issues are examined at both global and individual levels. A practical approach to defining enterprise environmental security management emphasizes a process-based perspective. Under this approach, environmental security management within an enterprise consists of interconnected processes operating within its internal environment to achieve strategic objectives while accounting for environmental factors (Figure 1). Effective management of enterprise environmental security necessitates ongoing, efficient collaboration among

enterprises, local communities, and municipal and governmental authorities, all within the framework of sustainable development principles. In this regard, ISO 14001:2004 represents a key standard in industrial environmental protection. This standard regulates environmental management practices in the European Union, Japan, the United States, and other regions.

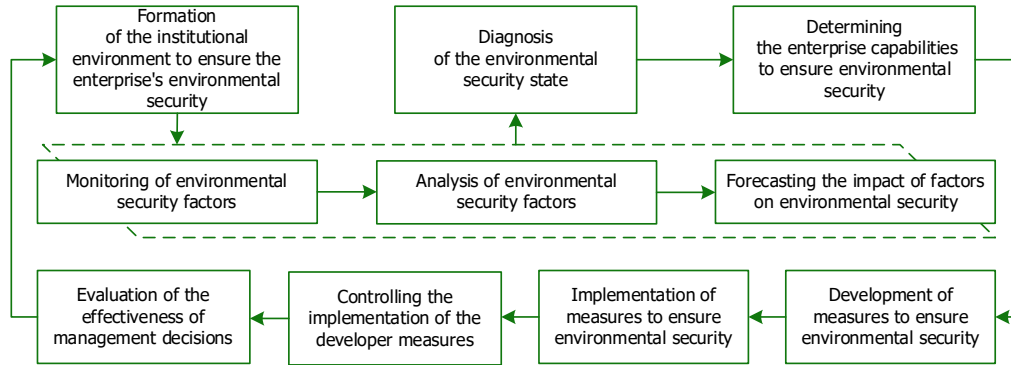


Figure 1. The process of enterprise environmental security management.

The ISO 14001 standard mandates the application of specific indicators to evaluate enterprise sustainable development. Incorporating these sustainability indicators into the routine operations of industrial enterprises is essential. Moreover, at the enterprise level, there is a need to develop and implement integrated indicators that capture the environmental impact of production activities. The absence of such comprehensive assessments complicates the construction of effective optimization models. By analyzing the characteristics of the key components involved in managing socio-ecological and economic processes within industrial enterprises, it becomes possible to propose a conceptual framework from a strategic perspective, as illustrated in Figure 2.

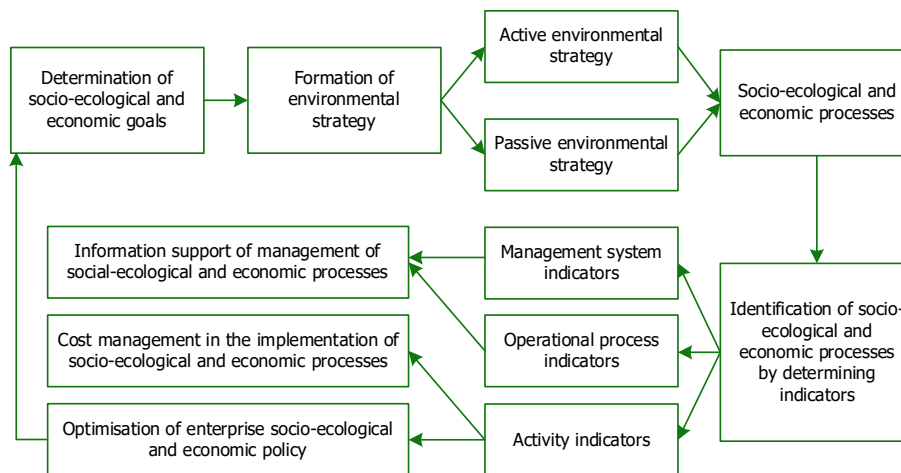


Figure 2. The conceptual scheme of management of social, ecological, and economic processes of industrial enterprises in the strategic perspective.

For industrial enterprises, a key component of environmental security management involves reducing technogenic pressure on local ecosystems resulting from production activities. The primary directions of ecological efforts include: implementing waste-free and low-waste technologies in both core and auxiliary production processes; adopting energy-efficient technologies; taking preventive and containment measures against the release of harmful substances; and installing systems for post-production emission treatment. In the context of globalization and the intensification of integration processes, enhancing enterprise-level environmental security has become a critical prerequisite for stable and sustainable operation. Given the accelerated pace of industrial and international economic development, environmental security issues at the enterprise level have gained renewed importance. These challenges demand continued investigation not only at the national level but also within specific regions and enterprises, particularly from a strategic planning perspective. It has been established that strategies for ensuring environmental security at the enterprise level must account for deteriorating socio-ecological and economic conditions. Accordingly, environmental security should be recognized as a national priority requiring greater attention from public authorities. The effectiveness of environmental policy depends on the robustness of its

strategic framework, which must define clear objectives and goals for the security system, identify key directions and implementation methods, and establish reserves for responding to and neutralizing potential threats.

A comprehensive strategy and appropriate tactical measures are essential to enable the full and effective functioning of the environmental security system. Integrating the management of socio-ecological and economic processes into the operational practice of industrial enterprises can lead to improved environmental quality, reduced risks of ecological disasters, greater engagement in solving environmental issues, more efficient use of energy and natural resources, and enhanced capacity to prevent emergencies. To ensure accurate assessment of environmental security levels, it is crucial to minimize subjective influence on the selection of evaluation indicators and avoid the arbitrary determination of threshold values. This can be achieved by assessing environmental security at both the national level and within individual economic sectors using integrated indicators derived through multivariate statistical techniques. Additionally, the use of a foundational indicator system allows for the objective establishment of threshold values for environmental security. The selection of indicators for assessing environmental security in Ukrainian industrial enterprises should be guided by a set of criteria, among which the most relevant can be identified as follows:

- real and potential threats to each industry's development;
- regulatory framework for regulating relations both within the industry and with the external environment;
- means of enterprises' environmental security ensuring in the industry;
- development strategy of each separate branch; the direction of action of challenges and threats to environmental security;
- the degree of significance of macroeconomic indicators' impact; the nature and duration of the risks' impact, etc.

The development of an environmental security indicator system for industrial enterprises is a structured process whose outcome is not only the creation of the indicator framework itself but also the assessment of the environmental security level of Ukraine's industrial sector based on these indicators. This process is carried out in several sequential stages. Initially, the objectives and specific tasks for diagnosing the environmental security status of industrial enterprises are defined. Subsequently, relevant data are selected and processed. The information gathered and refined during this stage serves as the foundational input for constructing the system of environmental security indicators for industrial enterprises. The development process for Ukraine's industrial environmental security indicator system should proceed as follows (Figure 3).

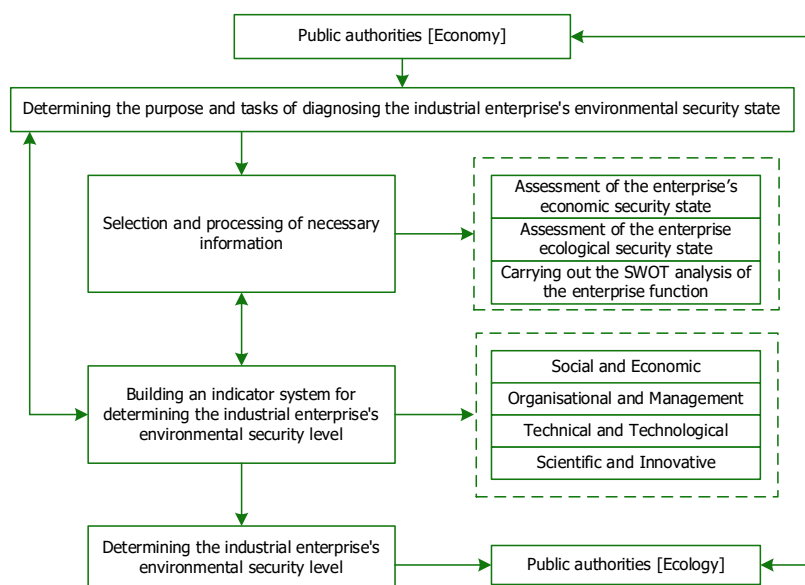


Figure 3. The process of developing the industrial enterprise environmental security indicators system.

It is demonstrated that constructing an environmental security indicator system for industrial enterprises is a multi-stage process. The stages include defining the objectives and tasks for diagnosing the environmental security status of the enterprise, selecting and processing the necessary data, and developing the system of environmental security indicators itself. The outcome of this process is the determination of the enterprise's environmental security level, expressed as an integrated indicator. This integrated indicator is constructed from a comprehensive array of metrics encompassing social and economic, technical and technological, scientific and innovative, as well as managerial and organizational dimensions,

with particular emphasis on criteria that capture both the external and internal environments of the enterprise. It is proposed to determine the industrial enterprise's environmental security level using an integrated indicator, which is calculated on the geometric mean of the integrated indicators of a complex assessment of its economic, ecological, and social components by the formula:

$$L_{ESIE} = \sqrt[3]{II_{Econ} \times II_{Ecol} \times II_{Soc}},$$

where, L_{ESIE} is the industrial enterprise environmental security level; II_{Econ} is a complex indicator of the economic component assessment; II_{Ecol} is a complex indicator of the ecological component assessment; II_{Soc} is a complex indicator of the social component assessment.

The analysis of the economic activities of enterprises within the railway industry was conducted using data extracted from the enterprises' financial statements. Key indicators considered included volumes of commodity production; quantities of products, works, and services sold; total cost of sold products, works, and services; profit generated from sales; and production profitability. Component coefficients according to local complex indicators of industrial enterprise environmental security level assessment are given in Table 1.

Table 1. Indicators and constituent factors of the complex assessment of the environmental security level.		
Indexes	Component factors (coefficients)	Requirements
Complex indicator of the economic component assessment		
Return on fixed assets	Calculated as the ratio of the volume of marketable products to the average annual value of the enterprise's fixed assets (UAH thousand).	Increase
Material efficiency	Determined by the ratio of material costs to the volume of marketable products (UAH thousand)	Decrease
Labor productivity ratio	Calculated as the ratio of the volume of marketable products to the average number of industrial and production personnel (UAH thousand/person)	Increase
Profitability ratio	Defined as the ratio of net profit to the cost of production and sales (UAH thousand)	Increase
Complex indicator of the ecological component assessment		
Coefficient of social utility of production	Calculated as the ratio of the useful effect of enterprise activity to the monetary assessment of its negative environmental impact (UAH thousand)	Increase
Coefficient of public utility of product use	Takes into account production volumes, costs for environmental protection, and the utility or harm caused by the enterprise's products (UAH thousand).	Increase
Coefficient of resource intensity of production	Calculated as the ratio of the monetary assessment of the resources used in production to the useful effect of enterprise activity (UAH thousand)	Decrease
Complex indicator of the social component assessment		
Staff turnover ratio	Defined as the number of employees dismissed voluntarily or for violations, divided by the average number of staff (persons)	Decrease
Coefficient of costs for the enterprise social infrastructure development	Ratio of the enterprise's expenditures on social infrastructure to the total cost of production and sales (UAH thousand)	> 0.1
Staff development cost ratio	Ratio of costs for staff training and development to the total production and sales cost of the enterprise (UAH thousand)	> 0

The proposed indicator systems contain both indicators-destimulators and indicators-stimulators. That is why, before bringing them into an integrated indicator, first normalize:

- for indicator-stimulator:

$$\delta_i = \frac{I_i}{I_{max}},$$

- for indicator-destimulator:

$$\delta_i = \frac{I_{min}}{I_i},$$

where I_i is the i -th indicator value; I_{max} is the largest indicator value for the analyzed period; I_{min} is the lowest indicator value for the analyzed period.

The generalizing (integral) indicator is determined as the arithmetic mean of the normalized indicators:

$$II = \frac{\sum_{i=1}^n \delta_{ii}}{I_{max}}$$

where *II* is an integrated indicator of a complex assessment of the industrial enterprise environmental security component in the analysis direction; δ_{ii} is the normalized value of the *i*-th indicator, which is a component of the integral.

At the same time, the considered technique does not give the chance to consider various degrees of significance of local indicators. Therefore, it is necessary to improve the existing methodology by determining the significance level of each system indicator. It is advisable to determine the significant share of local indicators using expert assessments. In this case, for determining the coefficients of importance of individual indicators in the integrated indicator, it is proposed to use the average ranks method:

$$\lambda_i = \frac{\sum_{j=1}^n R_{ij}}{\sum_{i=1}^n \sum_{j=1}^n R_{ij}}$$

where λ_i is a specific weight (coefficient of importance); R_{ij} is the transformed rank of parameter *i* in expert *j*; *n* is the number of parameters (indicators).

Experts are asked to rank indicators according to their importance, and it is possible to give the same rankings to indicators that they consider equally important. Then the obtained ranks are converted. When applying the procedure of collective expert evaluations, the final value of the coefficients of importance is determined as the arithmetic mean of the number of experts, of course, taking into account the values of concordance coefficients, which must be calculated for each of the studied indicators separately. The stages of environmental security assessment at the industrial enterprise are proposed in the form of an algorithm presented in Figure 4.

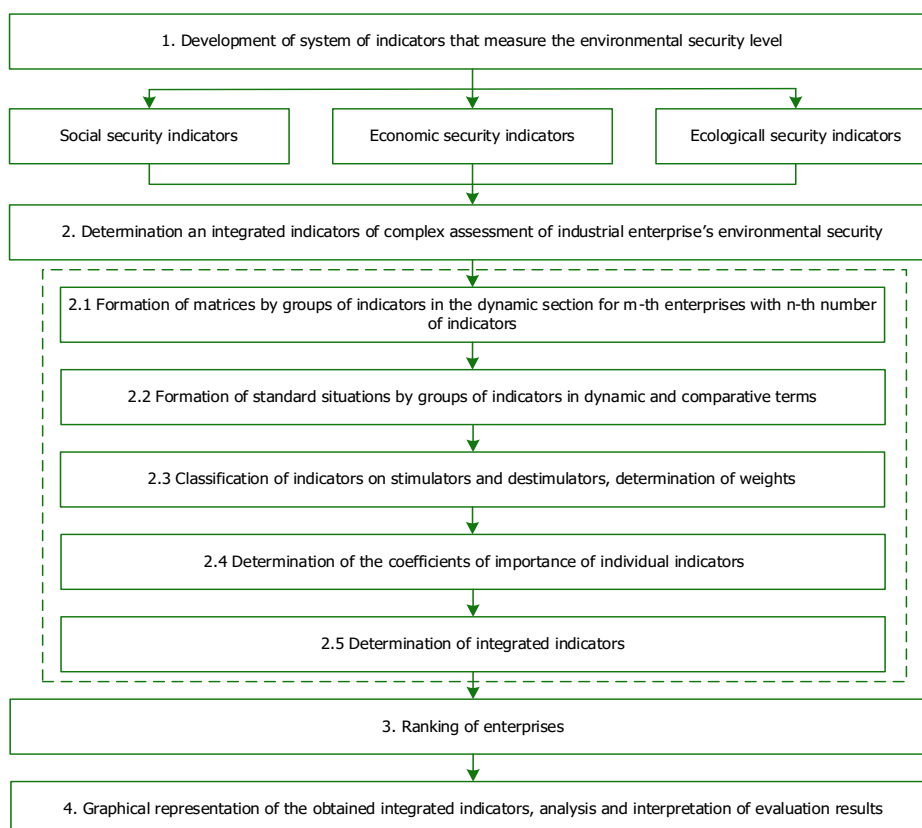


Figure 4. Stages of assessment of the environmental security level.

So, after the realization of a complex assessment method of industrial enterprise environmental security components in the direction of analysis, the level of significance of each system indicator, the integrated indicator of complex assessment of industrial enterprise environmental security will be determined as the arithmetic mean of normalized indicators:

$$II = \frac{\sum_{j=1}^n \delta_{Ii} \times \lambda_i}{n},$$

where *II* is the integrated indicator of a complex assessment of industrial enterprise environmental security; δ_{Ii} is the normalized value of the *i*-th indicator, which is part of the integral; λ_i is the coefficient of importance of each of the system of *n* indicators.

RESULTS

The environmental security level was calculated for 3 industrial enterprises of railway transport, namely car repair plants operating in the field of Ukrainian railway transport and similar in activity type. The results of the calculations are presented in Figures 5-7. In accordance with the developed threshold values scale for the integral indicator assessing the level of environmental security, the current level of environmental security provision at the branch "Panyutynsky Wagon Repair Plant" of PJSC "Ukrzaliznytsia" is at the lowest level. Approaches to environmental security management at the enterprise are of a formal nature, indicating that the management of the enterprise does not pay sufficient attention to the issues of ensuring environmental security (Figure 5).

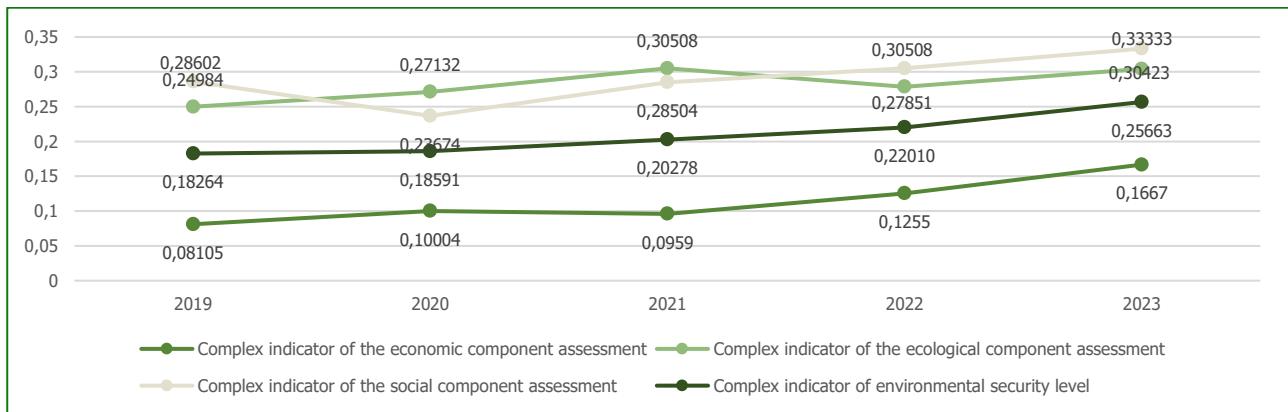


Figure 5. Graphic interpretation of environmental security level assessment of the branch "Panyutyn Car Repair Plant" of PJSC "Ukrzaliznytsia".

In accordance with the developed threshold values scale for the integral indicator assessing the level of environmental security, the current level of environmental security provision at the branch "Darnytskyi Wagon Repair Plant" of PJSC "Ukrzaliznytsia" is at the lowest level. Approaches to environmental security management at the enterprise are of a formal nature, indicating that the management of the enterprise does not pay sufficient attention to the issues of ensuring environmental security (Figure 6).

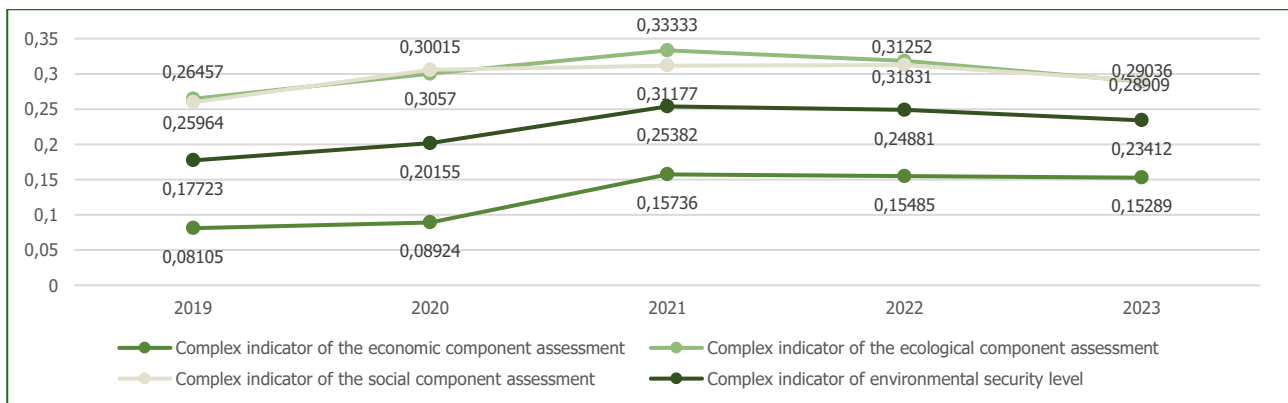


Figure 6. Graphic interpretation of environmental security level assessment of the branch "Darnytskyi Car Repair Plant" of PJSC "Ukrzaliznytsia".

In accordance with the developed threshold values scale for the integral indicator assessing the level of environmental security, the current level of environmental security provision at the branch "Stryi Wagon Repair Plant" of PJSC "Ukrzaliznytsia" is at the lowest level. Approaches to environmental security management at the enterprise are of a formal nature, indicating that the management of the enterprise does not pay sufficient attention to the issues of ensuring environmental security (Figure 7).

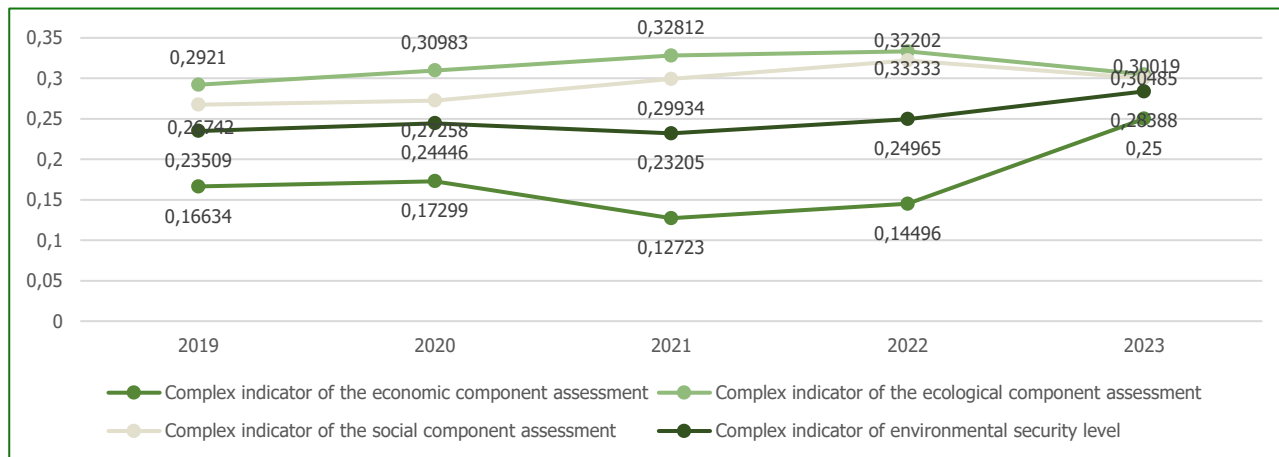


Figure 7. Graphic interpretation of environmental security level assessment of the branch "Stryi Car Repair Plant" of PJSC "Ukrzaliznytsia".

Thus, a comprehensive process for developing an environmental security indicator system for industrial enterprises has been proposed. Unlike existing approaches, this method is structured as an algorithm comprising sequential stages: defining the goals and objectives for diagnosing the environmental security status of the enterprise, selecting and processing the required data, and ultimately constructing the environmental security indicator system. The outcome of this process is the assessment of the enterprise's environmental security level through an integrated indicator. This indicator is formulated based on a comprehensive set of socio-economic, technical-technological, scientific-innovative, organizational, and managerial parameters, with explicit attention given to criteria pertaining to both the external and internal environments of the enterprise. A specific methodological toolkit is introduced to support this approach. The environmental security level of the enterprise is determined using an integrated indicator that, unlike existing methods, is calculated as the geometric mean of composite indicators reflecting economic, environmental, and social dimensions. This approach also incorporates the relative significance of each indicator within the overall assessment system, enabling a more precise and meaningful evaluation of environmental security.

The calculated indicator of environmental security level, based on its threshold values, demonstrates the following classifications:

1. An indicator value within the range of [0-0,25] corresponds to a formal approach to environmental security management at the enterprise, characterized by insufficient attention from management to environmental security issues.
2. Values between [0,26-0,5] indicate a limited approach to environmental security management, where only select aspects are addressed, preventing the achievement of high enterprise efficiency.
3. A range of [0,51-0,75] reflects that environmental security management practices are largely implemented; however, challenges persist in securing necessary resources, including financial support, for the adoption of environmental technologies and social program initiatives.
4. Values within [0,76–1] signify that environmental security management approaches generate tangible benefits for the enterprise.

Applying this threshold scale to assess the current environmental security levels at the analyzed enterprises reveals that they predominantly fall within the lowest category, indicative of formal and insufficient management attention to environmental security.

Based on the defined threshold criteria, it can be concluded that all evaluated enterprises exhibit inadequate emphasis on environmental security, which adversely impacts overall enterprise performance.

In order to increase the level of environmental security and simultaneously improve the economic performance of enterprises, we propose the appropriate strategies. The key transformed strategies to mitigate environmental risks effectively are presented in Table 2.

Table 2. The key transformed strategies to mitigate environmental risks.

Strategy	Activities within the framework of the strategy
1. Risk-driven environmental investment planning	1. Prioritize investment in technologies that offer high environmental impact reduction and economic return (e.g., energy efficiency, closed-loop systems). 2. Use integrated indicators to rank projects by environmental and financial performance.
2. Adaptive environmental management	1. Develop dynamic response plans for environmental emergencies and regulatory changes. 2. Implement real-time monitoring systems for key environmental parameters (emissions, water use, waste output).
3. Green innovation and technology transfer	1. Invest in R&D and partnerships to adopt best available technologies that reduce emissions and improve resource efficiency. 2. Establish innovation hubs within the enterprise to pilot eco-efficient solutions and eco-innovations.
4. Circular economy and resource optimization	1. Redesign production processes to reduce inputs, reuse materials, and recycle waste. 2. Apply life cycle assessment tools to identify environmental hotspots and guide process improvements.
5. Cross-functional governance structures	1. Establish interdisciplinary sustainability committees that oversee environmental strategy, risk alignment, and compliance. 2. Integrate environmental KPIs into executive performance metrics.
6. Stakeholder engagement and transparency	1. Develop communication strategies to involve local communities, regulators, and investors in environmental initiatives. 2. Publish sustainability performance reports based on the integrated model's indicators.

The proposed strategies offer a comprehensive and flexible approach to aligning environmental risk mitigation with the economic performance increasing of industrial enterprises. Within the framework of the developed strategies, specific measures are proposed to improve the environmental security and economic security of industrial enterprises (Table 3).

Table 3. Recommendations to improve the environmental security and economic security of industrial enterprises.

Recommendations to improve environmental security	Measures to improve environmental security	Recommendations to improve economic security	Measures to improve economic security
Adopt clean technologies and renewable energy	1. Investment in low-emission equipment and cleaner production processes. 2. Shifting to solar, wind, or other renewable energy sources to reduce dependence on fossil fuels	Diversify revenue streams	1. Expanding into new markets or products to reduce reliance on a single income source. 2. Exploring digital services, licensing, or vertical integration.
Implement environmental management systems	1. Establishment ISO 14001 or equivalent frameworks to monitor and improve environmental performance. 2. Conducting regular audits, risk assessments, and reporting.	Adopt energy and resource efficiency measures	1. Reducing operational costs through lean manufacturing, automation, and smart energy use. 2. Conducting cost-benefit analysis for sustainability investments.
Enhance waste management and resource efficiency	1. Introducing circular economy principles: reduce, reuse, recycle. 2. Implementation of zero-waste strategies and optimization of raw material usage.	Invest in risk management and business continuity planning	1. Development of contingency plans for supply chain disruptions, regulatory changes, and climate events. 2. Using insurance and hedging strategies to manage financial risks.
Upgrade pollution control measures	1. Installment of advanced filters, scrubbers, and emission reduction systems. 2. Monitoring air, water, and soil quality in and around facilities.	Enhance cybersecurity and data protection	1. Secure digital assets, intellectual property, and industrial control systems from cyber threats.
Strengthen compliance and transparency	1. Ensuring adherence to local, national, and international environmental laws. 2. Publishing sustainability and ESG (Environmental, Social, Governance) reports.	Modernize infrastructure and technology	1. Investment in automation and robotics to improve productivity and predictive maintenance. 2. Upgrading outdated machinery to reduce downtime and operational risks.
Invest in environmental training and culture	1. Training employees in sustainable practices and environmental security. 2. Encouraging reporting of environmental risks and near misses.	Optimize supply chain resilience	1. Building strong relationships with multiple suppliers. 2. Using local suppliers where possible to reduce exposure to global disruptions.
Biodiversity and land use management	1. Minimization of ecological disruption through sustainable land use planning. 2. Rehabilitation or restoring impacted ecosystems.	Seek public-private partnerships and incentives	1. Interaction with government authorities, leverage government grants, tax incentives, or green financing for sustainable initiatives. 2. Collaboration with universities and innovation hubs to co-develop technologies.

So, improving both environmental security and economic security in industrial enterprises is not only a regulatory or corporate responsibility, but a strategic necessity for long-term sustainability and competitiveness. By investing in clean technologies, responsible resource management, and robust environmental systems, enterprises can significantly reduce ecological risks and comply with evolving environmental standards. At the same time, enhancing economic resilience through innovation, diversification, and operational efficiency strengthens the enterprise's ability to withstand market volatility, supply chain disruptions, and financial pressures. These two dimensions – environmental and economic – are deeply interconnected: sustainable practices often lead to cost savings, better risk management, and new market opportunities. The industrial enterprises that proactively integrate environmental and economic security into their core strategy are more likely to achieve stable growth, maintain license to operate, and remain competitive in a rapidly changing global landscape.

DISCUSSION

While numerous studies have examined the environmental performance and sustainability of industrial enterprises, many existing methodologies lack a holistic and structured framework for assessing environmental security in direct connection with financial and economic dimensions. For instance, prior research typically relies on fragmented indicator systems or unweighted aggregations of environmental factors, which may result in either overgeneralized conclusions or an underestimation of specific risk dimensions (Staniškis & Arbačiauskas, 2009).

While studies such as Pavláková Dočekalová & Kocmanová (2016) and Mentel et al. (2021) have developed composite indicators combining environmental, economic, and energy domains, they rely on PCA-based or correlational aggregation techniques that do not leverage strategic weighting or a geometric mean approach. Those methods also often operate at macro or sectoral levels, limiting enterprise-level specificity. Similarly, models like the port-based environmental index by Kegalj et al. (2018) focus exclusively on environmental impacts and do not integrate broader socio-economic or managerial dimensions. Our structured methodology introduces a novel sequence of diagnostic objectives, data processing, and geometric synthesis of enterprise-level indicators – weighted across socio-economic, technical, scientific, innovative, and managerial domains. This enables a more nuanced, actionable, and financially grounded assessment of environmental security, validated in the railway transport industry and extended to risk-mitigating strategy recommendations. Mentel et al. (2020) offer a multidimensional assessment but emphasize macro-level interdependencies, especially in the energy-environment nexus. Our approach, in contrast, is enterprise-specific, combining socio-economic, technical, technological, scientific, innovative, and managerial domains through a geometrically aggregated index that recognizes relative importance at the firm level.

So, in contrast to these approaches, our study introduces a significantly improved, systematic methodology for constructing an environmental security indicator system tailored specifically to industrial enterprises. Unlike conventional models that often treat environmental indicators in isolation or prioritize only ecological parameters, our method integrates environmental, economic, and social dimensions into a cohesive assessment framework. This is achieved by defining clear diagnostic objectives, processing relevant data, and ultimately synthesizing results into an integral indicator using a geometric mean-based aggregation – a technique seldom employed in prior studies.

The novelty of our research lies in several key aspects, such as multidimensional integration, weighted synthesis of indicators, geometric mean methodology, and empirical validation, which are manifested in the following:

1. Our model balances socio-economic, technical-technological, scientific-innovative, and organizational-managerial factors, ensuring a more realistic representation of both internal and external risk vectors.
2. By applying differentiated weights based on the significance of each component, we overcome the limitations of equal-weight or purely additive models used in previous research.
3. The use of a geometric mean to synthesize composite indicators enhances the sensitivity of the model to inter-indicator variability, thus providing a more nuanced and rigorous assessment.
4. The methodology was applied to real-world data from three industrial enterprises in the railway transport sector, confirming its practical relevance and adaptability.

Moreover, where earlier studies often stopped at environmental diagnosis, our research advances further by formulating specific strategies to reduce environmental risks. These strategies are aimed not only at enhancing ecological integrity but also at boosting economic resilience – a dual goal rarely addressed simultaneously in the literature.

Finally, we offer practical recommendations for improving both environmental and economic security, contributing to the development of sustainable transformation strategies that are financially feasible and operationally effective. This positions

our work at the intersection of environmental science, enterprise strategy, and financial management – an interdisciplinary space that remains underexplored in much of the existing research.

Our results highlight the critical importance of an integrated approach to managing economic and environmental risks within industrial enterprises. The development of a comprehensive risk management model, as proposed in this research, demonstrates the potential for aligning economic resilience with environmental integrity, rather than treating them as competing priorities.

The characterization of the environmental security management process revealed significant fragmentation in current practices. In many studies conducted earlier, environmental risks are often addressed reactively and in isolation from broader economic objectives. This siloed approach limits the effectiveness of risk mitigation efforts and undermines the long-term sustainability of enterprises. By contrast, the integrated framework proposed by us in this study promotes a proactive and systemic view, where ecological and economic dimensions are jointly considered in strategic planning. The conceptual scheme developed to manage the interrelated social, ecological, and economic processes of industrial enterprises provides a valuable strategic perspective. It emphasizes that environmental security cannot be dissociated from socio-economic dynamics, particularly in sectors such as railway transport, where infrastructure, human capital, and environmental factors are deeply interconnected.

Despite the progress made in developing the conceptual scheme of management of social, ecological, and economic processes of industrial enterprises in the strategic perspective and integrated risk management model that simultaneously addresses economic and environmental security, several important questions remain insufficiently explored.

Firstly, while this study focused on internal factors of environmental security, a significant challenge remains in how to systematically account for external threats – such as geopolitical instability, environmental consequences of military actions in Ukraine, climate change, natural disasters, etc. – in enterprise-level models. These factors, although currently hard to control, have a growing influence on both environmental and economic outcomes.

Secondly, the enterprises in Ukraine often operate under conditions of uncertainty, particularly when implementing long-term sustainability strategies. The role of uncertainty in environmental-economic risk modeling – and how managers can make informed decisions with incomplete data – remains a vital yet under-researched topic.

These open questions highlight the need for continued interdisciplinary research, combining insights from environmental science, economics, systems engineering, and decision theory. Addressing these gaps will be essential to further refine integrated models and make them more effective in supporting industrial enterprises on the path to sustainable and resilient growth.

CONCLUSIONS

The article successfully provided a detailed characterization of the environmental security management process within industrial enterprises. It identified key internal and external factors influencing environmental security. This characterization laid the groundwork for understanding how environmental risks are currently managed and where improvements are needed.

A conceptual scheme was developed that integrates social, ecological, and economic dimensions into a unified management framework. This model supports long-term strategic planning by highlighting the interdependencies between sustainability goals and enterprise performance, facilitating more balanced and informed decision-making in industrial management.

An enhanced system of indicators was proposed to more accurately assess environmental security levels. These refined indicators focus solely on controllable, internal enterprise factors, thus providing a realistic and actionable assessment framework. The updated system enables enterprises to measure their environmental performance more precisely and identify priority areas for intervention. Unlike traditional approaches, this method consists of clearly defined, sequential stages: establishing the objectives and tasks for diagnosing the environmental security status of the enterprise, collecting and processing relevant data, and ultimately developing the environmental security indicator system itself. The result of this approach is the assessment of the enterprise's environmental security level using an integrated indicator. This composite measure is constructed from a range of socio-economic, technical-technological, scientific-innovative, and managerial-organizational indicators, with careful consideration given to criteria associated with both the external and internal operational environments of the enterprise. The proposed methodology defines the enterprise's environmental security level through an integrated indicator calculated, unlike existing methods, as the geometric mean of composite assessments

of its economic, environmental, and social components. This approach incorporates the relative importance of each indicator within the system, allowing for a more precise and meaningful evaluation of the enterprise's current environmental security status. Moreover, the developed framework emphasizes the necessity of accounting for the significance of each indicator in the overall assessment. Including these significance levels adds analytical depth, capturing the varying degrees of influence that different factors exert on the enterprise's overall environmental security.

Using the developed indicators, the study calculated and compared the integrated environmental security levels for three railway transport enterprises. The results revealed differences in environmental performance, highlighting both strengths and areas requiring improvement. This practical application validated the effectiveness of the proposed methodology and confirmed its relevance for real-world industrial scenarios. The evidence suggests that enterprises that adopt such models are better positioned to anticipate risks, capitalize on sustainability trends, and maintain operational resilience in an increasingly complex environment.

Based on the findings, a set of targeted strategies was formulated to reduce environmental risks and enhance the security of industrial enterprises. These strategies include technological modernization, improved waste management, and the integration of ecological considerations into strategic planning. The recommendations aim to align economic goals with environmental responsibilities, promoting sustainable enterprise development.

Our future research will focus on incorporating external environmental threats, such as climate change, into the assessment model to create a more comprehensive risk management framework. Also, we plan to study the role of stakeholder engagement, including employees, local communities, and state authorities, in improving environmental security practices, which will offer valuable insights into the social dimension of industrial sustainability.

ADDITIONAL INFORMATION

AUTHOR CONTRIBUTIONS

All authors have contributed equally.

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CONFLICT OF INTEREST

The Authors declare that there is no conflict of interest.

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ЕКОНОМІЧНІ, ЕКОЛОГІЧНІ ТА СОЦІАЛЬНІ ВИМІРИ ЗАБЕЗПЕЧЕННЯ ЕКОЛОГІЧНОЇ БЕЗПЕКИ ТА СТАЛОГО РОЗВИТКУ ПРОМИСЛОВИХ ПІДПРИЄМСТВ

Оцінка екологічної безпеки промислових підприємств стосується оцінки й аналізу заходів промислової екологічної безпеки та вразливостей для захисту від потенційних загроз і ризиків для навколишнього середовища. Проводячи оцінку екологічної безпеки, промислові підприємства можуть проактивно виявляти й усувати прогалини в безпеці,

зменшувати потенційний вплив на навколишнє середовище та забезпечувати дотримання нормативних актів. Метою дослідження є оцінка рівня екологічної безпеки промислових підприємств, трансформація стратегій для зменшення екологічних ризиків і формування рекомендацій для одночасного підвищення економічної та екологічної безпеки.

Наше дослідження пропонує вдосконалену структуровану методологію побудови системи показників екологічної безпеки для промислових підприємств. На відміну від традиційних підходів, запропонований метод дотримується систематичної послідовності, яка включає визначення цілей і діагностичних завдань, збирання та обробку відповідних даних і зрештою формування комплексної системи показників. Центральним у цьому підході є розробка інтегрального показника, що відображає загальний рівень екологічної безпеки, який виводиться зі збалансованого набору соціально-економічних, техніко-технологічних, науково-інноваційних та управлінсько-організаційних вимірів, що включає й внутрішні, і зовнішні фактори, які впливають на діяльність підприємства. Унікальність запропонованої моделі полягає у використанні геометричного середнього для синтезу інтегральних показників в економічній, екологічній та соціальній галузях, ураховуючи при цьому значущість кожного компонента. Цей механізм зважування забезпечує більш точну та нюансовану оцінку, враховуючи різний вплив окремих показників на загальну екологічну безпеку. Рівень екологічної безпеки було розраховано для трьох компаній залізничної транспортної галузі.

Також ми сформуваємо стратегії пом'якшення екологічних ризиків, які дозволяють промисловим підприємствам підвищити й економічну стійкість, і екологічну цілісність та покращити свою загальну безпеку. Крім того, ми запропонуємо рекомендації для одночасного покращення економічної та екологічної безпеки промислових підприємств.

Ключові слова: економічна безпека, екологічна безпека, процес управління екологічною безпекою, промислові підприємства, взаємодія, стратегії

JEL Класифікація: D20, F64, P28, Q57