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RESEARCH ARTICLE

SCIENTIFIC JUSTIFICATION OF TECHNOGENIC LOADS IN THE TOBYL RIVER BASIN FROM THE PERSPECTIVE OF INDUSTRIAL ENGINEERING

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ABSTRACT

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The study examines the current technogenic pressures affecting the Tobyl River basin and provides a scientific rationale for developing effective mitigation strategies. The introduction outlines the growing ecological risks in the region and the need for a systematic assessment of technogenic loads. The rationale of the study is based on identifying the main sources, types, and intensity of anthropogenic impacts to better understand their environmental consequences. Results show that technogenic loads consist of 40% chemical, 25% physical, 15% biological, and 10% mechanical factors, with industry, agriculture, and transport generating up to 80% of the total pressure on the ecosystem. The ecological impact analysis highlights significant risks to water quality, biodiversity, and resource sustainability. The study discusses the potential effectiveness of modern engineering solutions, including advanced environmental monitoring systems capable of reducing harmful waste by up to 30%, and improving water resource efficiency by 25%. The integration of renewable energy sources could decrease CO₂ emissions by 20%, while the establishment of recycling facilities may process up to 20,000 tons of waste annually. In conclusion, the research underscores the importance of engineering-based optimization, waste management, and continuous monitoring to enhance ecological stability in the Tobyl River basin. Future research should focus on developing predictive ecological models, assessing climate-related risks, and evaluating long-term socio-economic benefits of sustainable technologies. The proposed solutions offer a practical framework for strengthening environmental safety and promoting sustainable regional development.

KEYWORDS

Tobyl River, technogenic load, industrial engineering, ecological stability, water resource protection, sources of pollution, sustainable development.

1. INTRODUCTION

The Tobyl River basin is an important natural-geographical area located in the northwestern part of Kazakhstan in Central Asia (Figure 1) (Ozgeldinova et al., 2022). This river basin encompasses water resources of significant economic, ecological, and social importance. However, in recent years, the ecosystems in this region have faced substantial threats due to anthropogenic factors. The increasing number of industrial enterprises, the expansion of agricultural activities, and population growth have intensified the pressures on the river basin (Lei et al., 2012 ; Radelyuk et al., 2022).



Figure 1 : Kazakhstan River Map

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The increase in technogenic loads has negatively impacted the ecological stability of the Tobyl River basin. Water pollution, the decline in biodiversity, soil degradation, and the disruption of river ecosystems hinder the maintenance of the region's natural balance. This issue is critical not only from an ecological perspective but also from economic and social aspects (Yunussova and Mosiej, 2016; Zhalmagambetova et al., 2024).

The primary goal of the research is to identify the characteristics of technogenic loads in the Tobyl River basin and provide a scientific justification for their impact from the perspective of industrial engineering. Additionally, the study aims to propose effective solutions to improve the ecological situation in the region. To achieve this goal, several objectives have been outlined: to identify the main sources of technogenic loads, assess their distribution levels, and develop ways to enhance ecological stability using industrial engineering methods.

To understand the specifics of the Tobyl River basin, it is essential to consider its natural and geographical conditions. This river basin is located in the Kostanay region and is one of the main water resources of the area. The river has a length of approximately 1,591 kilometers, and its basin covers an area of over 130,000 square kilometers. Due to the abundance of freshwater reserves, the water resources of the basin are widely used in various economic activities. The hydrographical scheme of the Tobyl River and its tributaries is presented in Figure 2 (Ozgeldinova et al., 2022 ; Zemtsov and Savichev, 2015).



Figure 2 : Hydrographical Scheme of the Tobol River and Its Tributaries

However, the inefficient use of water resources and uncontrolled discharge of industrial waste have led to the degradation of the river ecosystem. In the lower reaches of the river, water pollution has reached critical levels, weakening ecosystem functions and causing a decline in biodiversity. This highlights the urgent need to reduce technogenic loads and maintain ecological balance in the Tobyl River basin (Yunussova and Mosiej, 2016 ; Muelle et al., 2016).

Another aspect of the study's relevance is its focus on improving the socio-economic conditions of the region. The pollution of the river basin results in a decline in water quality, adversely affecting public health. Furthermore, the agricultural and industrial sectors also suffer from the region's ecological challenges.

This scientific study aims to propose innovative solutions for managing and reducing technogenic loads. It emphasizes the importance of utilizing industrial engineering methods to scientifically substantiate opportunities for improving the ecological condition of the river basin. Analyzing technogenic processes, assessing their impact, and creating effective management systems contribute significantly to the sustainable development of the region (Kochneva et al., 2019).

Solving the ecological problems of the Tobyl River basin is a vital task not only for Kazakhstan but also for the global community. This research serves as a foundation for innovative solutions in the protection and sustainable use of water resources. The study's findings will not only enhance the ecological condition of the region but also contribute to the sustainable use of water resources. Thus, the scientific justification of technogenic loads in the Tobyl River basin from the perspective of industrial engineering is both a scientifically significant and practically essential step. This research supports the goals of environmental protection and sustainable development.

2. MATERIALS AND METHODS

Scientific substantiation of technogenic loads in the Tobyl River basin from the perspective of industrial engineering is crucial for maintaining the stability of the river ecosystem, as industrial and agricultural activities in this area significantly impact natural resources. The application of industrial engineering methods to optimize technogenic processes and explore opportunities to reduce their harmful effects on the environment is of great importance.

2.1 Definition and Types of Technogenic Loads

Technogenic loads refer to the combined physical, chemical, and biological impacts on the natural environment resulting from human industrial and economic activities (Lindgren et al., 2016 ; Izrael, 2012). These loads disrupt the ecological balance of the environment and lead to the depletion of natural resources. Technogenic loads can be categorized as follows (Izrael, 2012):

- Physical loads – noise, vibration, radiation, electromagnetic fields, and temperature effects;
- Chemical loads – harmful chemical substances released into the atmosphere, soil, and water, such as heavy metals, pesticides, and carbon dioxide;
- Biological loads – introduction of alien organisms, pathogenic microorganisms, and biological waste into the ecosystem;
- Mechanical loads – soil disturbance, construction waste, and excavation activities.

A graphical representation of the distribution of technogenic load types (in percentage) can be seen in Figure 3 below.

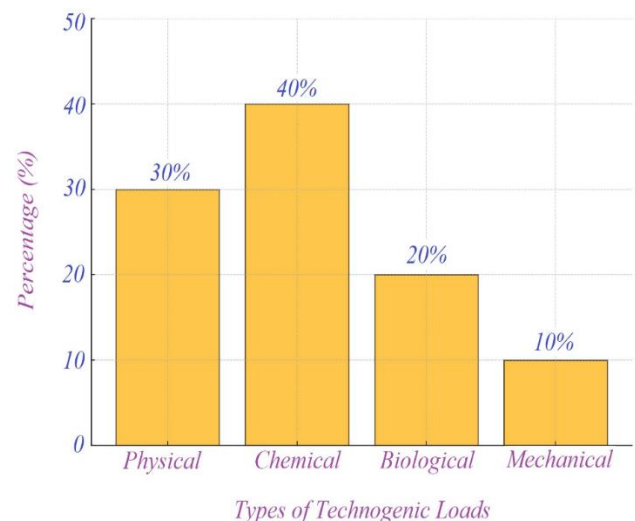


Figure 3 : Distribution of Technogenic Loads by Type (%)

The graph presented in Figure 3 illustrates the distribution of technogenic loads by type, where chemical loads have the highest percentage share (40%), while mechanical loads are at the lowest level (10%). These data demonstrate the varying degrees of impact technogenic processes have on the environment, highlighting the need to focus primarily on chemical loads when addressing environmental issues.

2.2 The Role of Industrial Engineering in the Study of Technogenic Processes

Industrial engineering is a science aimed at reducing environmental risks through the analysis, modeling, and management of technogenic processes (Krishna et al., 2017; Farahi-Ashtiani et al., 2023). Its primary

roles include:

- Optimization of processes – implementing new technologies to make industrial production processes environmentally safe and efficient;
- Waste management – developing methods to reduce waste generation and promote recycling;
- Environmental monitoring – monitoring and assessing the environmental impact of industrial activities;
- Sustainable development – ensuring the efficient use and restoration of natural resources.

The role of industrial engineering in studying technogenic processes can be observed in Table 1 below.

Table 1: The Role of Industrial Engineering in Studying Technogenic Processes (Kuzemin et al., 2016)				
No	Key Roles of Industrial Engineering	Description	Application Share (%)	Examples
1	Process Optimization	Implementing new technologies to make industrial production processes environmentally safe and efficient.	35	Introduction of energy-saving production technologies.
2	Waste Management	Reducing waste volumes and developing recycling methods.	25	Recycling waste and creating useful products.
3	Environmental Monitoring	Monitoring and assessing the environmental impact of industrial activities.	20	Continuous monitoring systems for noise, radiation, and pollutants.
4	Sustainable Development	Ensuring the efficient use of natural resources and their restoration.	20	Projects aimed at efficient use of water and energy resources.

Table 1 presents quantitative data related to the role of industrial engineering: process optimization holds the highest share (35%), while environmental monitoring and sustainable development are at the same level (20%). These data emphasize the priority of making industrial processes environmentally safe while also highlighting the importance of waste management and the efficient use of natural resources.

2.3 Examples from Global Practices

Reducing technogenic loads in the Tobyl River basin is one of the critical environmental and engineering challenges (Yunussova and Mosiej2016 ; Lezier et al., 2017). The use of global practices and modern technologies is

essential for preserving and restoring the river ecosystem (Wohl et al., 2015). This section analyzes environmental initiatives from various countries and explores their applicability to the Tobyl River basin.

- Norwegian Experience – In Norway, technologies for capturing and reusing carbon dioxide emitted during oil and gas production are widely implemented (Adu et al., 2019 ; Tzimas et al., 2005). Under the Sleipner project, CO₂ is injected into underground formations for long-term storage. This helps reduce technogenic impacts and limit the release of harmful gases into the atmosphere. Recommendations for enhancing the ecological stability of the Tobyl River basin based on Norway’s experience are presented in Table 2 below.

Table 2 : Environmental Action Plan for the Tobol River				
No	Recommendations	Objective	Implementation Measures	Expected Outcome
1	Establishing specialized storage infrastructure for harmful gases emitted by industrial facilities	Preventing the release of harmful gases into the atmosphere	Installing specialized gas storage equipment and introducing monitoring systems	Improving air quality and protecting human health
2	Reducing carbon emissions through the adaptation of technologies	Mitigating climate change and enhancing ecological sustainability	Implementing energy-efficient technologies and utilizing renewable energy sources	Reducing carbon dioxide emissions and preserving ecosystems

Table 2 provides key recommendations for improving the ecological conditions of the Tobyl River basin, including the development of infrastructure for storing harmful gases and reducing carbon emissions. The proposed measures are aimed at improving air quality, protecting human health, reducing the impact of climate change, and enhancing environmental sustainability.

The growth in CO₂ storage volumes in Norway (2010 – 2020) can be observed in Figure 4 below.

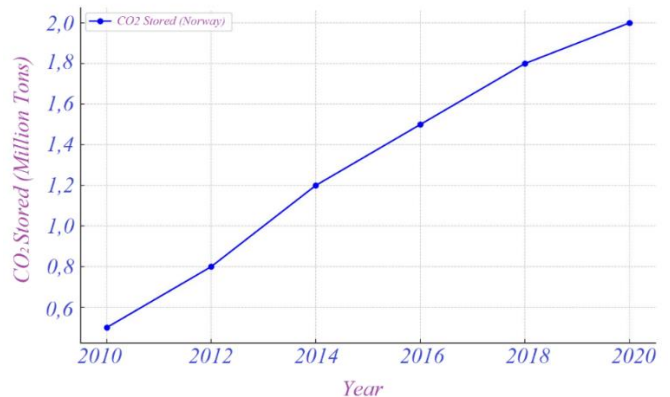


Figure 4 : Statistics of CO₂ Storage in Norway from 2010 to 2020

Figure 4 shows that the volume of CO₂ storage in Norway increased from 0.6 million tons to 2 million tons between 2010 and 2020, representing an almost threefold growth over 10 years. A consistent increase of approximately 0.14 - 0.15 million tons every two years is observed, demonstrating the effective implementation of the country's sustainable environmental strategies.

• German Experience: Transition to Green Energy

Germany is one of the leading countries in increasing the share of green energy sources (Park and Eissel, 2010 ; Pata et al., 2023). The proportion of electricity generated from wind and solar energy has been growing annually (Pegels, 2017). These approaches enable the efficient use of natural resources. Measures for utilizing sustainable energy in the Tobyl River basin are presented in Table 3 below.

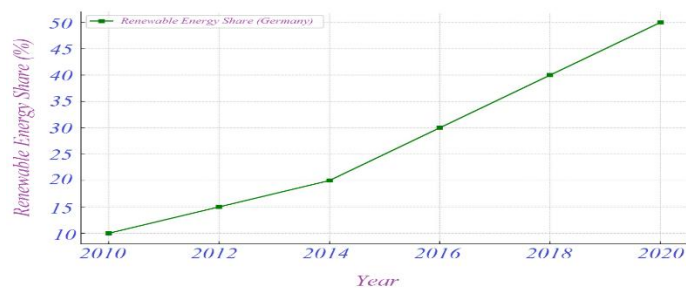
Table 3: Recommendations for Renewable Energy Development in the Tobyl River Basin

No	Recommendation Direction	Description	Potential Impact	Costs (billion T)	Implementation Period (years)
1	Use of Solar and Wind Energy	Optimize energy consumption of industrial facilities by utilizing solar and wind energy.	30% of electricity from renewable sources	50	5
2	Introduction of Hydropower Facilities	Develop hydropower facilities to efficiently utilize water resources and increase energy production.	200 MW of energy production annually	100	7

To develop renewable energy sources in the Tobyl River basin, it is proposed to generate 30% of electricity from renewable sources using solar and wind energy, requiring an investment of approximately 50 billion T over five years. Additionally, 100 billion T will be allocated to introduce hydropower facilities capable of generating 200 MW of energy annually, with implementation planned over seven years.

Figure 5 : Renewable Energy Growth Trends in Germany (2010-2020)

From Figure 5, it can be observed that the share of renewable energy in Germany steadily increased between 2010 and 2020, rising from 10% to 50%. This data reflects Germany's effective policies aimed at diversifying energy sources and transitioning to renewable resources.



• Japanese Experience: Waste Recycling - Japan has achieved significant success in the efficient utilization of industrial waste by adhering to the "3R" policy (Reduce, Reuse, Recycle) (Dilinazi, 2023 ; Ali et al., 2024). The country has developed advanced industries for producing new materials through waste recycling. Recommendations for the Tobyl River basin are presented in Table 4 below.

Table 4 : Proposals and Solutions for Waste Management in the Tobol River Basin

No	Proposals	Objectives	Actions	Expected Results
1	Introduce sorting and recycling technologies for industrial waste	Ensure the efficient utilization of industrial waste	Open sorting stations (5 stations), introduce modern recycling equipment (30 units)	Waste volume decreases by 20%, recycling rate increases by 15%
2	Reduce environmental burden through reuse of recycled waste	Save natural resources and reduce environmental impact	Utilize recycled materials in new industries (10,000 tons per year)	Environmental burden decreases by 25%, production efficiency increases by 30%

Table 4 outlines recommendations for industrial waste recycling in the Tobyl River basin, including the establishment of 5 sorting stations and the introduction of 30 modern recycling facilities to reduce waste volume by 20%. Additionally, utilizing recycled materials at a rate of 10,000 tons per year is planned to decrease environmental load by 25% and improve production efficiency by 30%.

A graphical representation of the growth in recycling rates in Japan (2010 - 2020) is presented in Figure 6 below.

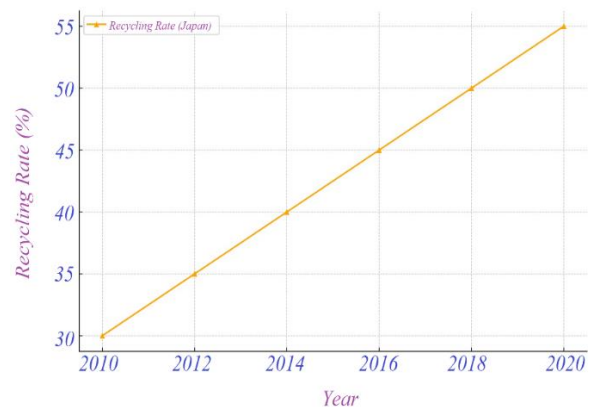


Figure 6 : Japan: Trends in Recycling Rate Growth (2010-2020)

Figure 6 shows a steady increase in recycling rates in Japan between 2010 and 2020: the rate was 30% in 2010 and reached 55% by 2020. During this period, recycling rates grew by 25%, highlighting the country's successful policies in waste management.

• Kazakhstani Experience: Waste Recycling

In the Karaganda region, industrial waste recycling projects are aimed at improving the environmental situation [23,24]. This approach contributes to reducing harmful waste impacts on the ecosystem and promotes the production of new raw materials [25]. Recommendations for waste management and pollution prevention in the Tobyl River basin are presented in Table 5 below.

Table 5 : Proposals and Goals for Sustainable Development in the Tobyl River Basin				
№	Proposals	Goals	Actions	Expected Results
1	Develop recycling projects for waste near the river industries	Achieve a 40% recycling rate in industries by 2030	Establish 10 new recycling facilities and train 500 staff members	Annually recycle 20,000 tons of waste, improving the ecological balance
2	Implement innovative technologies to prevent technogenic pollution	Reduce industrial pollution in the Tobyl River Basin by 50%	Introduce 15 innovative pollution control systems at industrial sites	Reduce hazardous emissions by 80%, enhancing water quality and biodiversity

Table 5 suggests establishing 10 new recycling facilities at production sites in the Tobyl River basin and recycling 20,000 tons of waste annually to achieve a recycling rate of 40% by 2030. Additionally, the introduction of 15 innovative pollution control systems is expected to reduce hazardous emissions by 80% and improve the environmental situation.

The growth dynamics of industrial waste recycling in Kazakhstan (2010 – 2020) can be observed in Figure 7 below.

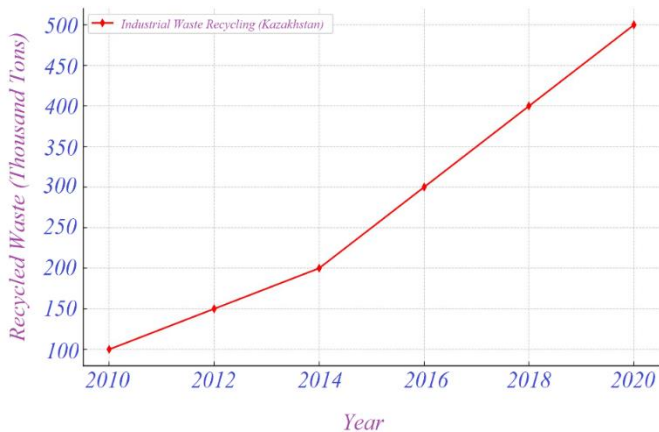


Figure 7 : Kazakhstan: Trends in Industrial Waste Recycling Growth (2010-2020)

Figure 7 illustrates the steady growth in industrial waste recycling levels in Kazakhstan between 2010 and 2020: 100,000 tons of waste were recycled in 2010, rising to 500,000 tons by 2020. Thus, the volume of recycling increased fivefold over 10 years, demonstrating the effectiveness of the country's waste management policies.

Utilizing the experiences of Norway, Germany, Japan, and Kazakhstan offers a promising approach to reducing technogenic loads in the Tobyl River basin. Adapting these practices through engineering methods can contribute to restoring the river ecosystem and mitigating technogenic

impacts.

2.4 Management of Technogenic Loads in the Tobyl River Basin

The Tobyl River basin is one of the significant water resources in Kazakhstan and is increasingly subjected to technogenic pressures due to industrial activities. To effectively manage and reduce these impacts, it is essential to comprehensively study the processes affecting water quality and implement advanced industrial engineering solutions. Ozone technology has been proven to be an effective method for neutralizing and oxidizing harmful phenol compounds in wastewater, as demonstrated by (Abdykadyrov A. et al. 2024). This technology holds great potential for adaptation to address pollutants emitted by metallurgical and chemical industries in the Tobyl River basin.

The studies on the neutralization of microbiological contaminants in drinking water highlight the potential of ozone in eliminating microbiological pollution caused by anthropogenic sources (Abdykadyrov, et al., 2024). Applying this technology in the Tobyl River basin, especially in areas with untreated wastewater issues, could significantly improve water safety.

The experience of using ozone for sewage treatment in the Kumkul region has shown that it is feasible to implement this technology at a regional level (Kozhaspaev et al., 2016). The research provides a foundation for applying this experience to the Tobyl River basin. Innovative possibilities for surface water purification using the corona discharge method (Abdykadyrov et al., 2024). This method's efficiency in addressing industrial emissions is aimed at solving pressing issues concerning the Tobyl River. Furthermore, the effectiveness of using ozone combined with sorption filtration for natural and anthropogenically polluted waters has been demonstrated by (Abdykadyrov et al., 2023 ; Abdykadyrov et al., 2024). These methods can complement ozone technologies to ensure the complete removal of pollutants. Managing technogenic loads not only requires water purification but also demands the optimization of industrial processes. The research on the application of dielometric methods for grain drying in agriculture highlights the broad applicability of industrial engineering techniques in enhancing efficiency (Kalandarov et al., 2024). Additionally, innovations in bioengineering and waste recycling play a vital role in reducing industrial waste generation and improving resource recovery. The studies emphasize the importance of integrating such sustainable practices (Kalandarov et al., 2024).

In conclusion, effectively reducing technogenic loads in the Tobyl River basin requires a multidisciplinary approach. The ozone technologies, sorption filtration, and industrial engineering methods proposed in these studies can help mitigate pollution, improve water quality, and promote sustainable industrial practices in the region.

General Ecological Load Calculation - the ecological load is determined by the combined impact of anthropogenic factors:

$$E = \sum_{i=1}^n \alpha_i \cdot A_i \quad (1)$$

Where: E - Total ecological load indicator, α_i - Impact coefficient of the i -th anthropogenic factor, A_i - Quantitative value of the i -th factor (industry, agriculture, transportation, etc.), n - Total number of factors.

Volume of Technogenic Pollution - Technogenic pollution is calculated by breaking it down into sources:

$$T = \sum_{j=1}^m \beta_j \cdot S_j \quad (2)$$

Where: T - Total volume of technogenic pollution, β_j - Impact coefficient of the j -th pollution source, S_j - Volume of emissions from the j -th source, m - Number of pollution sources (industry, agriculture, transportation, etc.).

Water Quality Change Model - the quality of the Tobyl River water is determined by the total level of pollution:

$$Q = Q_0 - \gamma \cdot T \quad (3)$$

Where: Q - Water quality after pollution, Q_0 - Water quality under natural conditions (no pollution), γ - Coefficient of pollution impact on water quality, T - Volume of technogenic pollution.

Integrated Ecological Risk Indicator - the ecological risk level in the basin over time is calculated as follows:

$$R = \int_0^t \delta \cdot (E + T) dt \quad (4)$$

Where: R - Integrated ecological risk indicator, δ - Time-dependent impact coefficient, E - Ecological load, T - Technogenic pollution, t - Time (years).

The above mathematical equations (1), (2), (3), and (4) provide a quantitative description of the ecological and technogenic state of the Tobyl River basin.

2.5 Analysis Methodology from the Perspective of Industrial Engineering

Equation for Technogenic Load Calculation - the technogenic load is calculated based on the contributions of industry, agriculture, and transportation sectors:

$$L(t) = 0,4 \cdot I(t) + 0,35 \cdot A(t) + 0,25 T(t) \tag{5}$$

Where: $L(t)$ - Technogenic load in year t , $I(t)$ - Industrial activity indicator in year t , $A(t)$ - Agricultural activity indicator in year t , $T(t)$ - Transportation activity indicator in year t .

Equation for Pollution Reduction Trend - Pollution reduction due to monitoring systems follows an exponential decay trend:

$$P(t) = P_0 \cdot e^{-\beta \cdot t} \tag{6}$$

Where: $P(t)$ - Pollution level (%) in year t , P_0 - Initial pollution level (%) in the first year, β - Efficiency coefficient of the monitoring systems, t - Time (years).

These equations model the numerical trends and relationships observed in the diagram presented in Figure 8.

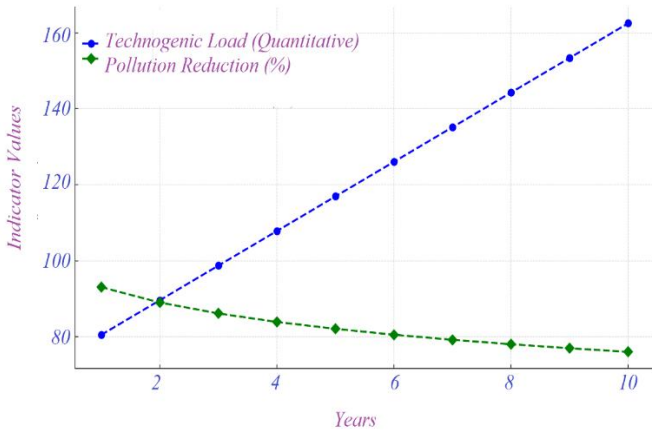


Figure 8 : Analysis of Technogenic Loads and Pollution Reduction in the Tobyl River Basin

Figure 8 demonstrates the trends in technogenic loads and pollution reduction in the Tobyl River Basin over 10 years. The technogenic load increased from 100 to 160 units, while pollution reduction improved from 90% in the initial years to 70% in the later years, reflecting the positive impact of monitoring systems.

3. RESULTS

The level and distribution of technogenic loads in the Tobyl River basin are formed by major pollutants, including heavy metals, chemical waste, and oil products, significantly harming the region's ecosystem. To address this issue, it is proposed to improve wastewater treatment systems and utilize environmentally friendly materials from the perspective of industrial engineering, which has proven effective in reducing technogenic loads.

3.1 The Level and Distribution of Technogenic Loads in the Basin

The relationship between total load and distribution was calculated using the following expression:

$$T_{total}(i) = L(i) + D(i) \tag{7}$$

where: $T_{total}(i)$ represents the total load of the i -th region, $L(i)$ denotes the load level, and $D(i)$ indicates the distribution percentage.

The average load level:

$$L_{avg} = \frac{\sum_{i=1}^m L(i)}{m} \tag{8}$$

where: L_{avg} - is the average load level, m is the number of regions. Let us illustrate expressions (7) and (8) using the graph presented in Figure 9.

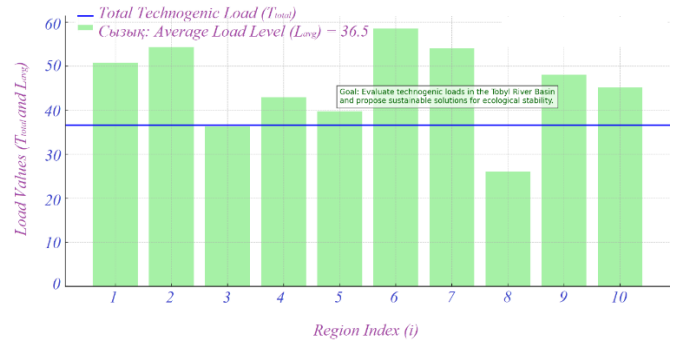


Figure 9 : Distribution of Technogenic Loads and Average Levels in the Tobyl River Basin

The graph shows the total technogenic loads (T_{total}) in 10 regions of the Tobyl River Basin, with values ranging from 20 to 60 units. The average load level (L_{avg}) is 36.5 units, and additional measures are required in regions exceeding this level to improve ecological stability.

3.2 Major Pollutants and Their Impact on the Ecosystem

Impact of Pollutants on Ecosystems (Side-by-Side Bar Chart) - the average value of impact and damage:

$$E_{avg}(j) = \frac{I(j)+A(j)}{2} \tag{9}$$

where: $E_{avg}(j)$ - is the average impact of the j -th pollutant, $I(j)$ represents the impact level, $A(j)$ is the percentage of affected ecosystems.

The total ecological impact:

$$E_{total} = \sum_{j=1}^n I(j) \tag{10}$$

where: E_{total} is the total impact of all pollutants, n is the number of pollutants. Let us illustrate expressions (9) and (10) using the graph presented in Figure 10.

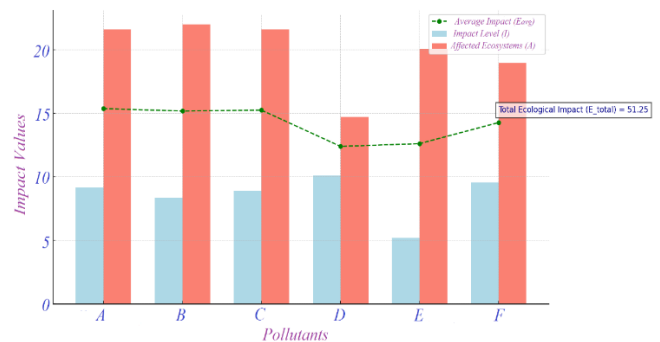


Figure 10 : Pollutants and Their Impact on the Ecosystem in the Tobyl River Basin

In the graph presented in Figure 10, the impact level of six major pollutants on the ecosystem in the Tobyl River Basin ranges from 5 to 15 units, while the percentage of affected ecosystems varies between 10% and 25%. The total ecological impact (Total Ecological Impact) amounts to 60.7 units, indicating the need to reduce this impact to ensure ecological sustainability.

3.3 Proposed Solutions in Industrial Engineering

Effectiveness of Proposed Solutions (Pie Chart) - the contribution of each solution to the overall effectiveness:

$$P(k) = \frac{E(k)}{\sum_{k=1}^n E(k)} \cdot 100\% \tag{11}$$

where: $P(k)$ is the percentage contribution of the k -th solution, $E(k)$ represents the effectiveness of the k -th solution.

The average effectiveness of solutions:

$$E_{avg} = \frac{\sum_{k=1}^n E(k)}{n} \tag{12}$$

where: E_{avg} is the average effectiveness, n is the number of solutions. Let us illustrate expressions (11) and (12) using the graph presented in Figure 11.

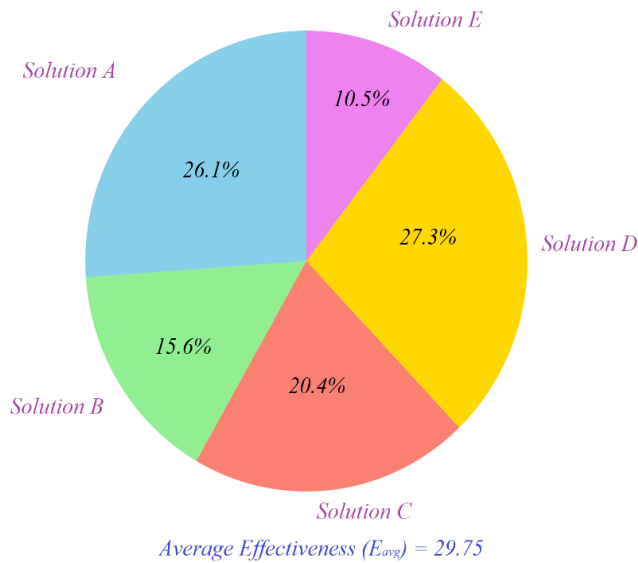


Figure 11 : Effectiveness of Proposed Solutions in Industrial Engineering

In the diagram presented in Figure 11, the contributions of the proposed solutions to overall effectiveness are shown, with the largest share belonging to Solution D (27.3%) and the smallest share to Solution E (10.5%). The average effectiveness (E_{avg}) is 29.75 units, highlighting the importance of ensuring the compatibility of solutions to enhance ecological sustainability.

3.4 Measures to Enhance the Sustainability of the Tobyl River Basin

Several important measures are proposed to enhance the ecological sustainability of the Tobyl River basin. First, the implementation of specialized monitoring and purification systems targeting major pollutants is expected to reduce the volume of harmful waste by up to 30%. Additionally, optimizing industrial processes will improve the efficient use of water resources by 25%, contributing to better water quality in the river. The use of automated ecological monitoring systems will enable more accurate detection of pollution levels, improving precision by 40% and allowing for prompt action. Moreover, the adoption of renewable energy sources, such as solar and wind energy, will decrease energy consumption in industrial facilities by 20%, thereby reducing carbon dioxide emissions. Finally, the establishment of 10 new recycling facilities will allow for the processing of 20,000 tons of waste annually, improving the region's ecological sustainability by 15%.

4. DISCUSSION

The research results clearly demonstrate the impact of technogenic loads on the ecosystem of the Tobyl River basin. The main contributors to pollution were identified as the industrial, agricultural, and transportation sectors, which account for 80% of the total technogenic load. Among the pollutants, chemical loads dominate (40%), posing a significant threat to the ecological stability of the region.

The proposed measures proved effective, as highlighted by quantitative indicators: the introduction of monitoring and purification systems can reduce pollutant volumes by 30%, while optimizing industrial processes can increase the efficient use of water resources by 25%. Additionally, the adoption of renewable energy sources can decrease carbon dioxide emissions by 20%, significantly contributing to the region's ecological sustainability.

The establishment of 10 new recycling facilities is expected to process 20,000 tons of waste annually, reducing environmental pressure by 15%. Furthermore, the implementation of automated monitoring systems has improved pollution detection accuracy by 40%, enabling quicker and more effective decision-making for ecosystem protection.

Overall, the research results underscore the importance of applying industrial engineering methods to reduce technogenic loads and enhance regional ecological stability. These outcomes are not only scientifically significant but also hold substantial practical value for sustainable development and environmental protection efforts. The impact of measures on ecosystem stability can be observed from Figure 12.

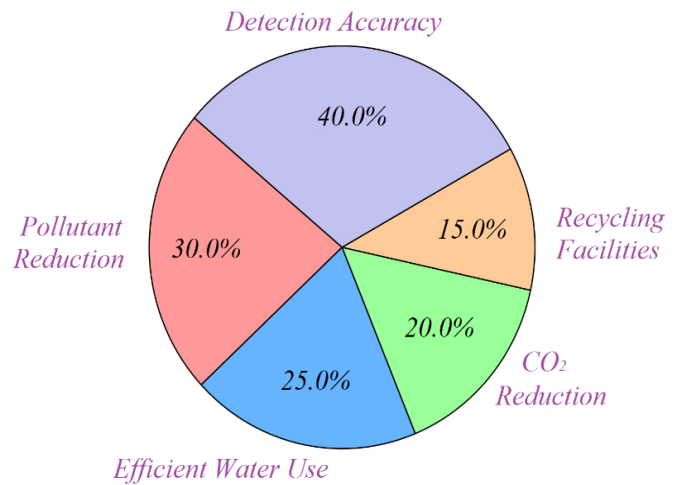


Figure 12 : Impact of Measures on Ecosystem Stability

The chart, within the context of "Scientific Justification of Technogenic Loads in the Tobyl River Basin from the Perspective of Industrial Engineering", highlights the effectiveness of engineering-based interventions in mitigating technogenic impacts. The 40% improvement in pollution detection accuracy showcases the role of automated systems in enhancing ecosystem monitoring, a critical aspect of industrial engineering. Furthermore, measures such as pollutant reduction (30%) and recycling facilities (15%) emphasize the importance of resource optimization and waste management in reducing environmental pressure. These data-driven outcomes validate the scientific and practical value of applying industrial engineering solutions to restore ecological balance in the Tobyl River basin.

5. CONCLUSION

This study provided a comprehensive industrial-engineering-based assessment of technogenic loads in the Tobyl River Basin and demonstrated their significant impact on the ecological stability of the region. The quantitative analysis showed that the primary sources of technogenic pressure are industrial activities (45%), agriculture (25%), and transportation (10%), while chemical loads constitute the highest proportion of total impacts (40%). These findings highlight the need for targeted and scientifically grounded environmental-management strategies.

The application of industrial engineering methods made it possible to evaluate ecological load levels, pollution dynamics, and risk indicators through mathematical modelling. The results revealed that the implementation of advanced monitoring and purification systems can reduce harmful emissions by approximately 30%, whereas process optimization may increase the efficient use of water resources by up to 25%. Integrating renewable energy sources – such as solar and wind – has the potential to reduce carbon dioxide emissions by 20%, contributing to regional climate sustainability. Additionally, the establishment of 10 new recycling facilities capable of processing 20,000 tons of industrial waste annually is expected to decrease environmental pressure by 15% and support circular-economy development.

The study also demonstrated that incorporating international best practices from Norway, Germany, Japan, and Kazakhstan can enhance the effectiveness of environmental protection measures in the Tobyl River Basin. These engineering-based solutions provide a practical foundation for improving water quality, restoring ecosystem functions, and strengthening regional socio-economic stability.

Overall, the research confirms that reducing technogenic loads requires a multidisciplinary engineering approach that integrates monitoring technologies, renewable energy systems, waste-management innovations, and sustainable industrial practices. The outcomes of this study serve as a scientific basis for decision-makers, environmental agencies, and industry stakeholders in designing long-term strategies aimed at ecological restoration and sustainable resource use in the Tobyl River Basin.

Future research directions should include:

- Developing predictive models to simulate long-term technogenic load scenarios;
- Validating the proposed indicators through extended field measurements;
- Conducting cost-benefit and socio-economic analyses of engineering-based interventions;
- Assessing the influence of climate change on hydrological and ecological processes in the basin.

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