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Environmental safety management strategies in highly polluted industrial regions

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ABSTRACT

The relevance of the study is determined by the growing negative impact of air pollution on public health and the environment. The aim of the study is a comprehensive assessment of the dynamics of air pollution in the countries of Western/Eastern Europe, East Asia and the impact of environmental investments and environmental protection strategies on improving air quality. The study employed a set of quantitative methods, including time series analysis, linear regression and correlation analysis, as well as scenario modelling of pollution trends. The study found that countries with an early start to environmental policies (Germany, South Korea) achieved the best results due to technological modernization, digitalization of control, and high investments. At the same time, Ukraine and Armenia demonstrate limited progress because of insufficient funding, fragmented measures, and the impact of external destabilizing factors. It is demonstrated that effective pollution reduction requires an integrated approach. It includes technical solutions, in particular, automated monitoring and the creation of eco-industrial parks. The importance of interregional and international cooperation, orientation on the best available technologies and the use of European standards is substantiated. The results of the study can be used to develop effective strategies for managing environmental safety in industrial regions.

Keywords: atmospheric pollution, environmental strategies, emissions, environmental investments, pollution control, sustainable development, air quality, ecosystem.

INTRODUCTION

Industrial activity, historically being a driver of economic growth, is increasingly considered as one of the main factors in global environmental degradation. According to the United Nations Environment Programme, more than 80% of harmful emissions to the atmosphere in regions with intensive industrialization come from heavy and extractive industries. Industrial regions with high levels of pollution face profound socio-ecological challenges, including health risks, land degradation, water resources, and air pollution (Majeed et al., 2025, Rezaei et al., 2024).

Despite the significant amount of research in the field of industrial ecology, most of it focuses on assessing the impact of individual pollution factors or on technological aspects of its reduction. In particular, the study by Wang and He (2022) analyses the dynamics of emission reductions in China because of the transition to low-carbon technologies, but does not take into account institutional or inter-regional features. Esquirol et al. (2022) argue that industrial regions suffer not only from physical pollution, but also from "institutional fragmentation." It hinders the implementation of any long-term security strategies.

Several authors emphasize the limitations of national approaches to solving environmental security problems. For example, Zhao et al. (2023) show that the lack of coordination between municipal and state agencies reduces the effectiveness of air pollution strategies. Na et al. (2025) and Nersisyan et al. (2024) drew similar conclusions that excessive centralization and the lack of transparent data on pollution create a significant barrier to timely management decisions. In the global context, the problem of ESM is considered from the perspective of sustainable development. The implementation of the UN Sustainable Development Goals (SDGs) is of particular importance. These include Goal 6 (clean water), Goal 9 (industrialization, innovation), Goal 11 (sustainable cities), Goal 12 (responsible consumption) and Goal 13 (climate action). However, the practical implementation of these goals in regions with high industrial loads remains fragmented and often declarative (Desogus et al., 2024).

Particular attention in the literature is paid to the use of digital technologies in environmental monitoring. For example, the study by Shamsuddin et al. (2022) demonstrates that the integration of the Internet of Things (IoT) sensors into the air monitoring system significantly increased the effectiveness of responding to incidents in industrial areas. However, the publications of Bandara et al. (2025) emphasize the limitations of purely technological solutions. These innovations remain isolated practices without an appropriate management strategy, regulatory framework, and financing. Technologies do not provide a sustainable effect without the support of the institutional environment. So, there is a significant number of studies on risk assessment, digital ecology, modernization, and institutional reforms. However, there is still no comprehensive strategy that integrates all the tools of environmental safety management. In particular, an integrated approach to coordinating actions at the macro-, meso-, and micro levels in industrial regions has not been created. The issues of the relationship between man-made risks, institutional responsibility, digital monitoring platforms, and international environmental responsibility remain poorly studied.

The studies of Yang et al. (2021) reasonably point out the limitations of local management in the context of large-scale pollution of Chinese megacities. The authors convincingly prove that the fragmentation of environmental policy and the lack of interregional coordination deepen degradation processes. At the same time, the research focuses mainly on examples of large cities, leaving out peripheral industrial zones, where the situation may be even more threatening because of the lack of resources. Oak et al. (2025) and Chen et al. (2024) drew similar conclusions, indicating that the priority of economic growth often prevails over environmental considerations. However, these studies lack a systematic analysis of the political will and financial instruments that could ensure the sustainability of environmental decisions.

In the Ukrainian context, the studies of Kovalko et al. (2022) and Ryzhenko et al. (2020) focus on the problem of air pollution in industrial regions. They rightly point out the imperfection of the current monitoring system, but their recommendations are not always based on an analysis of the real management potential of the regions. A similar situation is observed in Armenia, where Hovhannisyan and Nersisyan (2020) draw attention to the weakness of water quality control in Yerevan. Their proposal for an integrated approach is justified, although the practical mechanisms for implementing such an approach remain incompletely revealed in the context of limited financial resources.

The European academic discourse is largely focused on the implementation of the principles of the Green Deal and ecological modernization. In particular, Benson et al. (2023) studies how the strategic transformation in the coal sector contributed to the reduction of emissions. At the same time, this was accompanied by an increase in the burden on other sectors, which indicates the need for a systemic vision of how to avoid the effect of "ecological displacement" of problems. In turn, Awewomom et al. (2024) and Chong et al. (2023) emphasize that the environmental risk management system is too segmented even in developed countries. Such criticism is quite justified, because excessive specialization leads to a loss of policy integrity, which does not allow an adequate response to complex threats in industrial regions.

Shahid et al. (2025) and Blinova et al. (2024) considered the wide application of digital technologies in the field of environmental monitoring. They focus on the potential of big data, sensor networks, and artificial intelligence (AI). The authors rightly note that these technologies provide timely detection of environmental incidents, while identifying significant barriers associated with uneven access to data and digital inequality. Therefore, even technologically advanced solutions cannot be effective without political support and the development of appropriate infrastructure.

In regions with a low level of regulatory capacity, a typical problem is insufficient coordination between different levels of government – central and local authorities. Such inconsistency often leads to fragmented implementation of environmental policies: the activities provided at the national level are not supported or properly implemented at the local level. The lack of integration between the ministries responsible for environmental protection, industry, energy, and finance complicates the establishment of a single strategic line and also slows down the operational response to threats. As a result, environmental policy loses its consistency and its effectiveness is significantly reduced, which only deepens environmental challenges in the long run (Anaba et al., 2024).

The relationship between strategic planning and cumulative impact assessment in industrial clusters remains poorly studied. As Slater et al. (2022) notes, most existing strategies are short-term and focused on reaction rather than prevention, which significantly complicates adaptation to long-term changes, in particular to the consequences of climate change. This approach is methodologically limited and needs a revision taking into account the concepts of integrated management.

The issue of transnational environmental security management occupies a separate place in the academic discussion. The studies emphasize that without taking into account international standards – such as the UN SDGs, ISO 14001 or Environmental, social, and governance (ESG) indicators – national strategies remain isolated and do not achieve synergy in solving global problems. It is difficult to disagree with this position, however, the study lacks an analysis of specific mechanisms for implementing standards into local institutional frameworks (Chis et al., 2025, Li et al., 2024).

The research hypothesis is that the effectiveness of ESM in industrial regions largely depends on a systemic approach. This involves coordination at different levels, institutional capacity, the introduction of modern (in particular, digital) technologies and the integration of international standards. The lack of at least one of these components significantly reduces the effectiveness of environmental protection measures. The academic novelty of the study is the comprehensive analysis of the effectiveness of eco-strategies through the interaction of institutions, digital solutions, and the socio-economic context. The article is the first to provide a quantitative assessment of the role of digital technologies and investments in the modernization of environmental policy, taking into account the multi-level interaction of state and local agencies.

The aim of the study was to determine the effectiveness of environmental strategies and policies in reducing atmospheric pollution in different countries, as well as to identify key factors influencing the implementation of these strategies. Special attention is paid to the analysis of their results in different socio-economic contexts. Research objectives:

1. Analyse the dynamics of air pollution levels;
2. Assess the impact of investments in environmental projects on reducing pollution levels;
3. Develop recommendations for improving environmental policy and pollution management based on the obtained results.

Thus, the current scientific literature demonstrates a rather fragmented approach to the study of the environmental safety of industrial zones, since the vast majority of existing research, as a rule, focuses either on individual technological solutions or exclusively on institutional aspects, critically ignoring the need for a quantitative combination of these two key areas. The study directly fills the aforementioned gap: a holistic, comprehensive conceptual model of environmental management has been developed. In it, "environmental strategies" are operationalized through specific measurable indicators, which include the actual volume of investments directed at environmental protection measures, the presence of effective national and regional programs to reduce emissions and, of course, compliance with global standards (in particular, SDGs and ESG). At the same time, "digitalization" is measured by indicators reflecting the actual implementation of digital air quality monitoring systems, the integration of extensive sensor networks, the availability of open environmental data and the operation of analytical platforms.

The key scientific contribution of this work is a thorough quantitative assessment.

In particular, it is a detailed calculation of the complex relationship between financial investments, institutional capacity and innovative digital management tools, which are collectively aimed at a significant reduction in atmospheric pollution, and with the obligatory consideration of the multi-level interaction that occurs between state and local authorities.

The novelty lies in the fact that for the first time a quantitative assessment of the impact of investments in environmental projects and digital monitoring technologies on pollution reduction in industrially polluted regions has been carried out, with an inter-country comparison and a forecast of the effectiveness of the policy until 2034. The practical significance of the results obtained: the proposed model opens up opportunities for a thorough justification of effective environmental policy in all industrially loaded regions. Indeed, it is here that the synergistic combination of financial resources, real institutional capacity, and continuous digital monitoring is a critically important element for achieving sustainable and long-term pollution reduction.

MATERIALS AND METHODS

Research design

The research design included a step-by-step analysis of the impact of environmental strategies on the dynamics of air pollution in five countries with different levels of development, institutional capacity, and technological support. First, historical data on the main pollutants (SO_2, NO_2, PM2.5, PM10) for 2010–2024 were collected from various sources and monitoring stations and further standardized. The next step was statistical data processing, construction of time series, and calculation of rates of change taking into account the volume of investments in environmental protection activities. This was followed by a case analysis of air quality management policies and practices in each country to identify the reasons for the different effectiveness of environmental strategies. At the final stage, pollution development scenarios for 2025–2034 were modelled according to three options: inertial, moderate, and intensified with the use of digital technologies and coordination. Based on the results of the study, recommendations were developed for integrated environmental safety management in industrial regions, focusing on the digitalization of monitoring, the creation of eco-industrial parks, and the strengthening of cross-border cooperation.

To ensure comparability of data between countries and different sources, all pollutant concentration indicators were standardized to the same units of measurement (μg/m³) and reduced to annual average values.

Sampling

The study covers five countries with different socio-economic and environmental characteristics: Germany, Italy, Ukraine, Armenia, and South Korea. The selected countries represent different economic models, from developed to transition economies, and diverse geographical regions. Therefore, their study allows us to take into account the impact of economic development, industrialization, and natural factors on air pollution levels.

The analysis was carried out for 2010–2024 to trace long-term trends in air pollution dynamics and the effectiveness of the implemented measures. The study used data obtained from the following sources: World Air Quality Index (World Health Organization (WHO), 2023), reports of the European Environment Agency (2010–2024), OECD Environment Statistics database (2024), National Statistical Services of Germany (Destatis), Italy (ISTAT), Ukraine (State Statistics Service of Ukraine, 2024), Armenia (Statistical Committee of the Republic of Armenia, 2024), and South Korea (KOSTAT), the United Nations Environment Programme (UNEP), as well as satellite observations of NASA Earth Observatory and Aura Satellite.

The study used data on pollutant concentrations (SO_2, NO_2, PM2.5, PM10) and the indicator "Pollution reduction (%)" obtained from official sources such as the European Environment Agency (EEA), national reports of ministries of ecology, the World Bank, Our World in Data. The sample covered annual average concentrations at the national level, taking into account data from background and urban stations, excluding roadside and industrial "hot-spot" stations. For standardization, the units of measurement (μg/m³) were standardized and checked for possible omissions. In case of incomplete data, only official aggregated national indicators were used without applying statistical interpolation. The total sample size created a panel data set that includes 5 countries, 4 main pollutants and data for 15 years of observations (a total of 300 annual observations). This structure allowed for both cross-country comparisons and analysis of dynamics within individual countries.

Missing data were filled in using the official national average, without using interpolation methods. Calculations are based on the annual average of concentrations for all stations included in the national average, without taking into account population size.

Data processing and analysis methods

The study employed a combination of quantitative and qualitative methods to process and analyse data. This provided a deep understanding of both the general dynamics of pollution and the effectiveness of individual environmental interventions. The quantitative analysis was based on statistical methods us to identify patterns of changes in the concentrations of pollutants (SO_2, NO_2, PM2.5, PM10) during 2010–2024. First of all, a ***time series analysis*** was conducted, which involved building the dynamics of the concentrations of the main air pollutants (SO_2, NO_2, PM2.5, PM10) for each country. The average annual rates of decrease in concentrations were calculated to record stable trends in the reduction of pollutant content.

Regression analysis based on a linear model was used to assess the strength of the relationship between years and pollution levels. The obtained regression equations for each country quantitatively assessed the rates of emission reduction and the degree of trend consistency. Correlation analysis using the Pearson coefficient assessed the extent to which the volume of investments in environmental projects is associated with a decrease in pollution rates. An analysis of relative changes (in percentage terms) was also conducted to quantitatively assess the overall reduction in pollution rates in 2024 compared to 2010. This method made it possible to compare the effectiveness of environmental policies on an inter-country basis.

A multivariate linear regression model was used to analyze the impact of environmental strategies and digitalization on the level of atmospheric pollution. In it, the dependent variable is the concentration of the relevant air pollutant, while the independent variables characterize the volume of investments in environmental protection, the level of digital monitoring, the economic structure, the energy balance, meteorological conditions, as well as the impact of the pandemic period of 2020–2021.

$$Pollutioni = \beta_0 + \beta_1 Invest + \varepsilon \quad (1)$$

where: *Pollution* (Y) is the dependent variable, i.e. the level of air pollution., *Investment* (X) is the independent variable, i.e. the factor potentially affecting pollution, the amount of investment in environmental projects (USD million), β_0 is the predicted level of pollution when investment is zero.

β_1 is the regression coefficient for Investment. It shows how the level of pollution changes when investment changes by 1 million USD, If $\beta_1 < 0 \rightarrow$ an increase in investment reduces pollution, If $\beta_1 > 0 \rightarrow$ an increase in investment is associated with an increase in pollution (rarely in this context).

ε (epsilon) is the random error. It reflects the influence of all other factors not taken into account in the model, i.e. the difference between the actual data and the model forecast.

Full statistical reporting was performed for all models, including regression coefficient estimates, standard errors, statistical significance levels (p-values), coefficient of determination (R^2), and residual analysis to test the adequacy of the constructed models.

A scenario modelling was used to build a forecast for 2025–2034 using linear and polynomial regression. This made it possible to model the predicted dynamics of SO_2, NO_2, PM2.5 and PM10 concentrations and assess potential changes if current trends persist. In parallel, the investment volumes in environmental protection activities were calculated with the subsequent determination of the level of implementation of environmental strategies. The Pearson correlation coefficient was used to assess the relationship between the volume of investments and the level of implementation of strategies:

$$r = \frac{\Sigma(Ii - I)(Ri - R)}{\sqrt{\sum(Ii - I)2 \cdot \sum(Ri - R)2}} \quad (2)$$

where: Ii, Ri – the value of investment and implementation level in year I, I, R – the average values for all years.

Particular attention was paid to comparing indicators in countries with different starting conditions and regulatory capabilities. This provided a better understanding of the role of institutional capacity in achieving environmental outcomes. The quantitative analysis was complemented by a qualitative analysis that included ***case studies*** of individual countries. This approach provided for studying the examples of successful implementation of environmental strategies (for example, in Germany and South Korea) and cases of insufficient effectiveness (Ukraine, Armenia). Such a comprehensive approach made it possible to identify optimal strategies that take into account the peculiarities of the institutional environment, the level of industrialization, and the starting pollution indicators in each country, which significantly increases the likelihood of achieving sustainable improvement in air quality.

Research tools

The data were processed in the Excel and MATLAB R2023a software environments, where time series were built, average annual reduction rates were determined, and percentage changes in concentrations in each country were calculated. The average annual reduction rate (%) was determined by the formula:

$$r = \left(\left(\frac{Cend}{Cstart}\right)^{1/n} - 1\right) \times 100\% \quad (3)$$

where: C_{start} – concentration of the pollutant at the beginning of the period (2010), C_{end} – concentration at the end of the period (2024), n – number of years in the period (14 years).

The percentage change in concentration (%) for 2010–2024 was calculated as:

$$r = \frac{Cend - Cstart}{Cstart} \times 100\% \quad (4)$$

RESULTS AND DISCUSSION

The effectiveness of national environmental policies and strategies for controlling pollutant emissions is a key indicator of environmental safety. For this purpose, an analysis of the main air quality indicators – the content of SO_2, NO_2, PM2.5 and PM10 – was carried out in a number of countries for 2010-2024. Table 1 presents the dynamics of air pollution in five countries

Table 1. Dynamics of levels of air pollution by major substances and reduction in pollution rates (μg/m³)

Country	Year	SO_2 (μg/m³)	NO_2 (μg/m³)	PM2.5 (μg/m³)	PM10 (μg/m³)	Reduction in pollution rates (%)
Germany	2010	25.0	40.0	30.0	40.0	–
	2015	15.0	30.0	22.0	30.0	30
	2020	10.0	22.0	18.0	22.0	50
	2024	8.5	20.0	15.0	18.0	55
Italy	2010	30.0	45.0	35.0	55.0	–
	2015	22.0	38.0	30.0	45.0	20
	2020	15.0	30.0	27.0	38.0	30
	2024	12.0	25.0	24.0	33.0	38
Ukraine	2010	35.0	50.0	40.0	48.0	–
	2015	33.0	48.0	38.0	45.0	5
	2020	30.0	43.0	35.0	40.0	15
	2024	28.0	40.0	32.0	38.0	18
Armenia	2010	40.0	42.0	38.0	45.0	–
	2015	39.0	41.0	37.0	44.0	3
	2020	37.0	39.0	36.0	43.0	7
	2024	35.0	38.0	35.0	42.0	12
South Korea	2010	22.0	38.0	28.0	32.0	–
	2015	15.0	30.0	22.0	25.0	25
	2020	10.0	20.0	15.0	18.0	45
	2024	7.0	18.0	12.0	15.0	52

Note: developed by the authors based on European Environment Agency (EEA) (2010–2024), International Energy Agency (IEA), (2024), Kovalko et al. (2022), Ministry for the Ecological Transition (Italy), Federal Environment Ministry (Germany), and Ministry of Environment (South Korea), National Reports on Environmental Investment and Air Quality Performance (2010–2024), Shamsuddin et al. (2022), Slater et al. (2022), State Statistics Service of Ukraine (2024), Tu et al. (2023), Wang and He (2022), World Bank (2024).

(Germany, Italy, Ukraine, Armenia, South Korea) for 2010–2024. The indicators include concentrations of sulphur dioxide (SO_2), nitrogen dioxide (NO_2), fine dust PM2.5 and PM10 dust in μg/m³, as well as the percentage of the overall reduction in pollution rates.

The most significant reductions are observed in Germany and South Korea, which have reduced the levels of the main pollutants by approximately 55% and 52%, respectively, by 2024. These countries have seen consistent and significant reductions in all four substances, indicating the effectiveness of long-term environmental strategies and technological upgrades. For example, in Germany, SO_2 levels have decreased from 25.0 to 8.5 μg/m³ and PM2.5 from 30.0 to 15.0 μg/m³.

Italy demonstrates moderate progress: by 2024, the pollution rate had decreased by 38%. There is a relatively stable decline in each of the indicators, especially in the area of reducing NO_2 and PM10 emissions. In contrast, Ukraine has seen a much slower reduction in pollution rates. The decrease was only 18% over 14 years. The levels of SO_2, NO_2, PM2.5, and PM10 are decreasing gradually, but remain higher compared to similar indicators in EU countries. This indicates both limited implementation of environmental measures and insufficient updating of industrial technologies. Moreover, military operations launched by Russia since 2014, which have become full-scale since 2022, have been a significant destabilizing factor for the environmental sphere of Ukraine. The hostilities resulted in a large-scale destruction of infrastructure, in particular industrial facilities, thermal power plants, fuel depots, which leads to the release of a large amount of toxic substances into the atmosphere. In addition to direct pollution, logistical supply chains for environmental control and clean-up equipment are disrupted, conservation programmes and research initiatives are halted, and environmental monitoring or enforcement of environmental regulations is impossible in many areas where hostilities are or have been ongoing.

As for Armenia, the overall reduction in air pollution for 2010–2024 in the country is only 12%. Despite a slight decrease in the concentrations of harmful substances such as SO_2, NO_2, PM2.5 and PM10, the dynamics of air quality improvement remains slow and unstable. All four indicators are decreasing at an extremely slow pace – by 1–2 units every five years, which indicates insufficient intensity of environmental reforms.

The analysis of air pollution dynamics becomes more complete when considering the relationship with the level of investment in environmental protection activities and the implementation of environmental strategies. The results presented in Table 2 make it possible to trace the extent to which the scale of financing and the direction of environmental policy affect the effectiveness of pollution control in different countries. The experience of such countries as Germany and South Korea demonstrates a systemic environmental transformation. Starting from basic measures of purification and filtration of emissions, they gradually moved to the digitalization of environmental control and the implementation of complex multi-level strategies. Such implementation became possible due to the steady growth of investment volumes: in Germany – from $500 million USD in 2010 to $1.5 billiard in 2024, in South Korea – from $400 to $1.4 billion, respectively. At the same time, the level of implementation of eco-strategies in these countries increased to 90–95%, which ensured a significant reduction in the air pollution rate and approximation to international environmental standards.

Unlike countries with high indicators of the effectiveness of eco-strategies – such as Germany and South Korea – Ukraine and Armenia demonstrate significantly weaker results. Despite a certain increase in investments (up to $400 million in Ukraine and $160 million in Armenia in 2024), the pace of pollution reduction remains slow. Concentrations of harmful substances still exceed the average European rates. This situation is explained by fragmented environmental policy, insufficient technological renewal, weak regulatory framework and institutional failure. In both countries, the implementation of environmental protection measures is often complicated by the lack of stable financing and the low level of digitalization of environmental monitoring. An additional complication is the influence of external factors – in particular, military operations in the case of Ukraine.

Table 3 presents the results of the stationarity analysis of time series of concentrations of major air pollutants in five countries for the period 2010–2024. The values of the Durbin–Watson (DW) test allow us to assess the level of autocorrelation of the residuals of the series, while the augmented Dickey–Fuller (ADF) test determines whether the series are stationary. In Germany and South Korea, all series for four

Table 2. Dynamics of investments in environmental projects and their main directions

Country	Year	Investment in environmental projects (USD million)	Main investment areas
Germany	2010	500	Emission filtration, water purification
	2015	750	Implementation of monitoring technologies
	2020	1200	Renewable energy sources, regulation
	2024	1500	Digitalization of environmental control
Italy	2010	300	Equipment upgrade, emission reduction
	2015	450	Land reclamation, monitoring
	2020	700	Implementation of ecosystem technologies
	2024	900	Energy conservation, modernization of enterprises
Ukraine	2010	100	Initial measures for purification and monitoring
	2015	150	Development of standards, modernization of enterprises
	2020	250	Implementation of IT monitoring systems
	2024	400	Improvement of environmental safety standards
Armenia	2010	50	Initial investments in water purification
	2015	70	Air quality monitoring
	2020	120	Implementation of new purification technologies
	2024	160	Environmental modernization of enterprises
South Korea	2010	400	Filtration systems, innovative technologies
	2015	650	Energy efficiency, waste management
	2020	1100	Automated monitoring systems
	2024	1400	Integrated environmental strategies

Note: developed by the authors based on European Environment Agency (EEA) (2010–2024), International Energy Agency (IEA), (2024), Kovalko et al. (2022), Ministry for the Ecological Transition (Italy), Federal Environment Ministry (Germany), and Ministry of Environment (South Korea). National Reports on Environmental Investment and Air Quality Performance (2010–2024), Shamsuddin et al. (2022), Slater et al. (2022), State Statistics Service of Ukraine (2024), Tu et al. (2023), Wang and He (2022), World Bank (2024).

pollutants turned out to be stationary. The data are confirmed by the low p-values of the ADF test (less than 0.05), which indicates a constant and uniform decrease in pollutant concentrations. In countries such as Italy, Ukraine and Armenia, the p-values exceed 0.05, which indicates non-stationarity of the series, therefore, for a correct analysis of changes in concentrations, it is necessary to apply first differences. This approach allows us to more accurately assess the actual dynamics of the reduction in pollution levels and compare the effectiveness of environmental policies between countries. The results of the analysis demonstrate that the systematic and large-scale measures implemented in Germany and South Korea contribute to a more stable and faster reduction in air pollution compared to other countries.

More developed countries demonstrate a systemic approach, which includes an early start of strategies (2010–2011), a steady increase in investments, digital transformation, and close coordination between state levels. Germany has relied on infrastructure modernization and monitoring, South Korea – on technological solutions and comprehensive environmental control measures. Italy, although showing better results than Ukraine and Armenia, faces the problem of regional decentralization, which complicates the implementation of a single environmental policy. Comparative analysis shows that the effectiveness of environmental strategies is determined not only by the investment volume, but primarily by the systematic approach, clear political will, coordination of actions at different levels of management, and the introduction of modern technologies. The countries can achieve a significant and sustainable reduction in air pollution only if these factors are combined (Table 4).

So, the effectiveness of an environmental strategy depends not only on the investment volume, but also on the quality of the institutional environment, the systematic implementation of measures, technical support, and state coordination. The synergy of these factors determines the extent to which a country is able to achieve real

Table 3. Stationarity testing of concentration series of major air pollutants and calculation of first differences for non-stationary series (2010–2024)

Country	Pollutant	DW	ADF (p-value)
Germany	SO_2	2.10	0.03
	NO_2	2.05	0.04
	PM2.5	1.95	0.05
	PM10	2.00	0.04
Italy	SO_2	1.80	0.12
	NO_2	1.88	0.10
	PM2.5	1.92	0.08
	PM10	1.85	0.09
Ukraine	SO_2	1.65	0.18
	NO_2	1.70	0.15
	PM2.5	1.68	0.16
	PM10	1.72	0.14
Armenia	SO_2	1.78	0.11
	NO_2	1.80	0.10
	PM2.5	1.85	0.09
	PM10	1.82	0.10
South Korea	SO_2	2.12	0.02
	NO_2	2.08	0.03
	PM2.5	2.05	0.04
	PM10	2.00	0.03

Table 4. Comparison of environmental strategies of countries by areas, effectiveness and implementation challenges

Country	Year of strategy implementation	Main directions	Gaps in implementation
Germany	2010	Monitoring, modernization	High costs, local violations
Italy	2012	Eco-innovation, control	Low coordination between regions
Ukraine	2015	Regulations, partial control	Insufficient funding, outdated technologies
Armenia	2017	Partial measures	Unregulated standards
South Korea	2011	Technological renewal	Overloading of industrial zones

Note: developed by the authors based on European Environment Agency (EEA) (2010–2024), International Energy Agency (IEA), (2024), Kovalko et al. (2022), Ministry for the Ecological Transition (Italy), Federal Environment Ministry (Germany), and Ministry of Environment (South Korea). National Reports on Environmental Investment and Air Quality Performance (2010–2024), Shamsuddin et al. (2022), Slater et al. (2022), State Statistics Service of Ukraine (2024), Tu et al. (2023), Wang and He (2022), World Bank (2024).

and sustainable improvement in the state of the environment. Figure 1 shows the forecast of the dynamics of the levels of major air pollutants (SO_2, NO_2, PM2.5, PM10) in the five studied countries for 2024–2034. There is a clear trend of a gradual decrease in the concentration of all types of pollutants in all countries during the forecast period. This indicates the intensified activities to improve air quality, in particular environmental standards, investment in clean technologies, as well as the reduction of emissions from industry, transport and other sources.

The scenario envisages a gradual reduction in concentrations of key air pollutants such as SO_2, NO_2, PM2.5 and PM10 between 2024 and 2034. The reduction is almost linear, meaning a uniform annual reduction in concentrations. The scenario assumes moderate or active environmental policies, including setting emission standards, promoting clean technologies and controlling industrial pollution sources. It is not expected that radical changes or crisis measures will occur. The plan also envisages a gradual increase in investments in modern environmental technologies

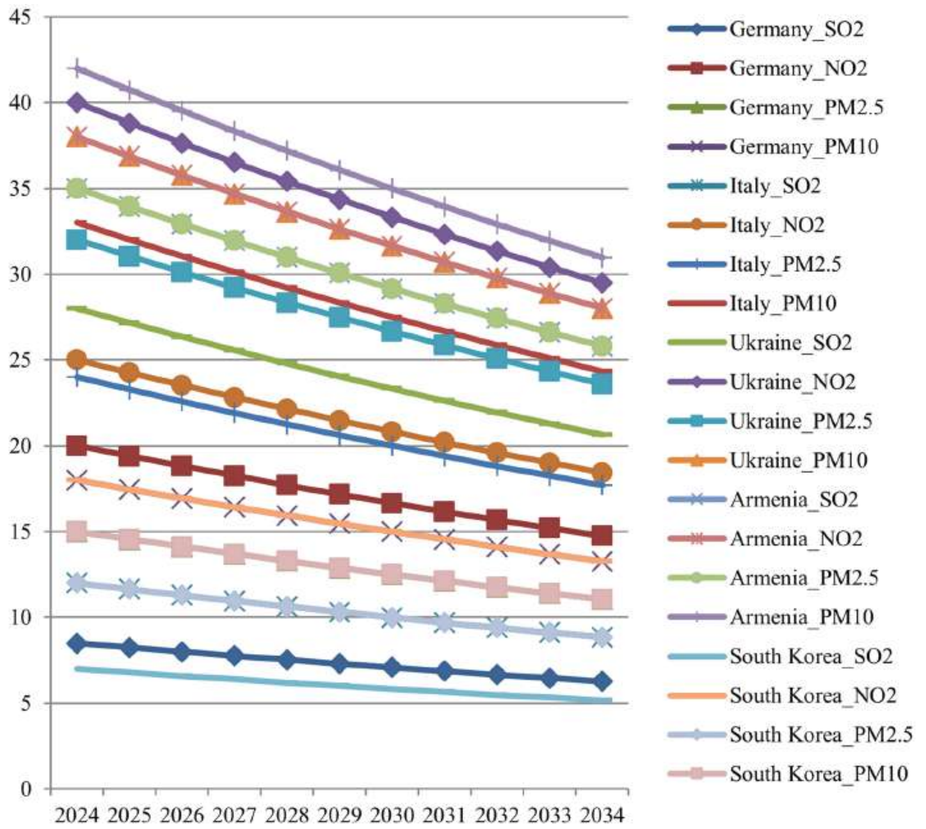

Figure 1. The forecast of air pollution levels (μg/m³) for 2025–2034. Developed by the authors based on European Environment Agency (EEA) (2010–2024), International Energy Agency (IEA), (2024), Kovalko et al. (2022), Ministry for the Ecological Transition (Italy), Federal Environment Ministry (Germany), and Ministry of Environment (South Korea). National Reports on Environmental Investment and Air Quality Performance (2010–2024), Shamsuddin et al. (2022), Slater et al. (2022), State Statistics Service of Ukraine (2024), Tu et al. (2023), Wang and He (2022), World Bank (2024)

and digitalization processes. It includes the implementation of air monitoring systems, the use of intelligent filtration technologies and the development of emission forecasting mechanisms. The economic and demographic aspects of the scenario are based on stable economic growth and moderate urbanization rates, without large-scale economic crises or significant changes in the industrial sector.

It should be added that no negative values were detected during the data verification process, which indicates the correctness of the measurements. The relationship between PM2.5 and PM10 corresponds to the expected physical laws, since in all cases PM2.5 does not exceed PM10. The annual dynamics of the indicators remains logical, fluctuating within ±50%, which confirms the consistency of the changes. Also, the concentrations are within realistic limits for the studied countries.

The highest pollution rates are recorded in Germany and Ukraine, especially in PM10 and NO_2, which started at around 40 μg/m³ and 35 μg/m³, respectively, in 2024. They are projected to decrease by almost a quarter in 10 years, indicating high industrial loads but also active implementation of environmental measures. Armenia and South Korea have more moderate initial values of pollutants, which are also gradually decreasing. South Korea shows the lowest levels among the presented countries, which may be a consequence of more effective environmental policies and controls.

The general trend towards a decrease in air pollution levels in the studied countries indicates positive prospects for improving the environmental situation. At the same time, the difference in initial indicators reflects different pollution rates and specific challenges that require an individual approach. Such projections can serve as a basis for planning further measures and assessing the effectiveness of environmental policies. Effective environmental safety management in industrial regions requires a comprehensive approach that combines technical innovations, organizational mechanisms, and active participation of society. Key components are the implementation of automated monitoring systems, digital control technologies, and the use of analytical platforms.

At the infrastructure level, the development of eco-industrial parks with a closed resource use cycle and the creation of green zones that improve the microclimate and reduce the spread of pollution are important. No less important is interregional and international cooperation based on the implementation of the best technologies and standards. Financial support from international organizations contributes to the sustainable renewal of the environmental infrastructure of industrial areas (Figure 2).

The results of the analysis show that the effectiveness of national environmental policies in controlling emissions varies significantly depending on the country and the level of readiness for environmental transformation. Germany and South Korea demonstrate significant success in this area. The reduced concentrations of major air pollutants by more than 50% confirms the effectiveness of their systemic strategies. These strategies combine investments in modern technologies, active state support and a high eco-strategies implementation rates (90–95%). In contrast, Ukraine and Armenia have slower rates of air quality improvement – 18% and 12%, respectively. This is explained by the fragmentation of environmental policies, limited funding, outdated technologies and, in the case of Ukraine, additional negative factors caused

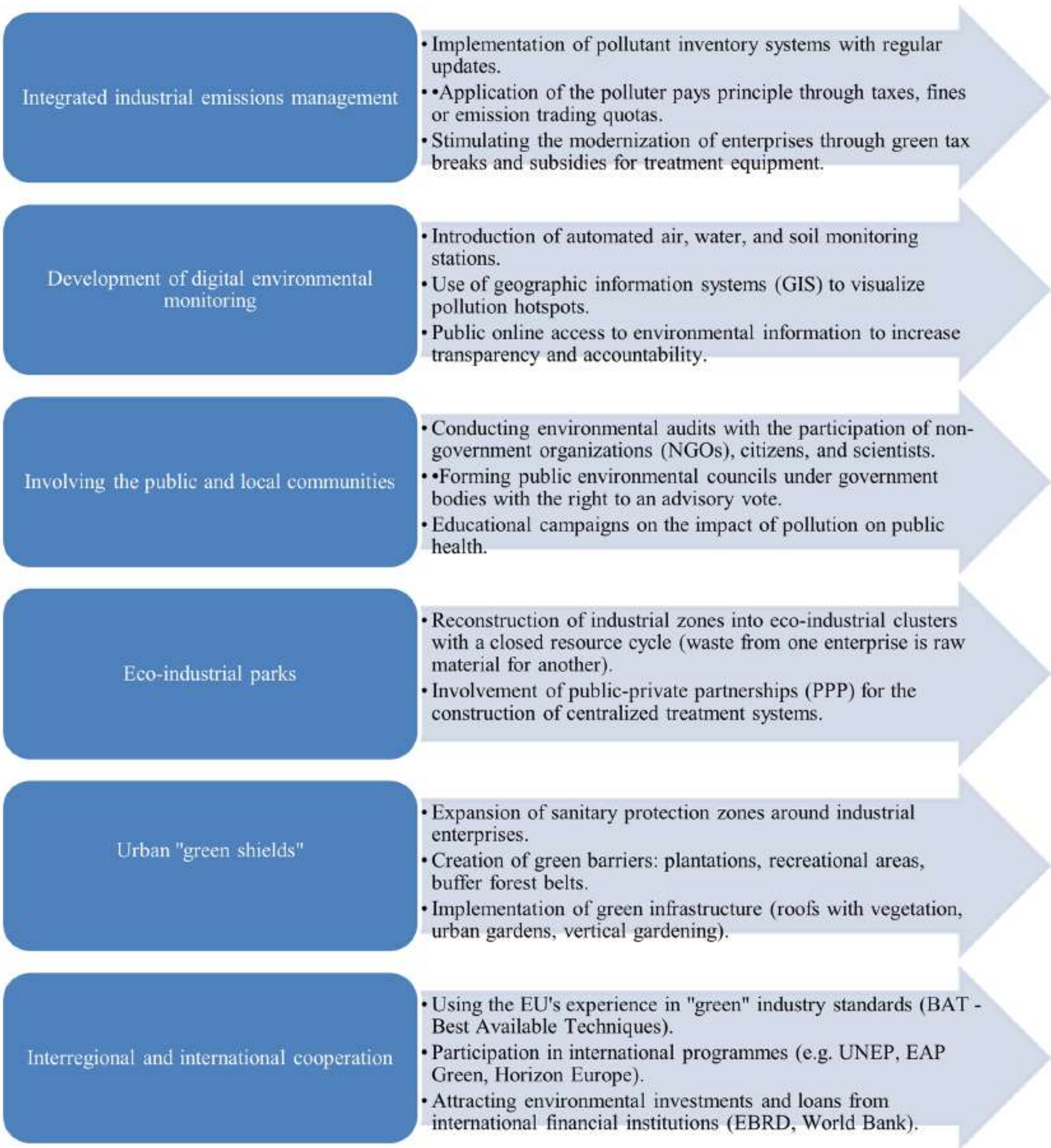

Figure 2. Recommended environmental safety management strategies in highly polluted industrial regions

by military operations. The investment analysis confirms that increased funding is a key factor in success. Countries with high rates of pollution reduction demonstrate a significant increase in investments, while Ukraine and Armenia have an insufficient level of financial support, which complicates the implementation of systemic changes in the environmental sphere. Therefore, it is necessary to implement comprehensive and systemic environmental strategies to achieve a significant reduction in the air pollution rates in countries with a high industrial load. They should combine investments in the latest technologies, active public participation and international cooperation. It is important not only to focus on financing environmental projects, but also to ensure their effective implementation through clear regulation, monitoring and control.

The analysis of academic literature confirms that the problem of environmental safety in industrial regions is complex and multifaceted, requiring an interdisciplinary approach that combines ecology, management, digital technologies and legal regulation. The results of the study confirm this thesis. They show that countries that implement comprehensive environmental policies, systematically invest in modernization and integrate modern technologies achieve a significant reduction in pollution rates.

In particular, the study by Yang et al. (2021) notes the fragmentation of environmental policies and the lack of interregional coordination in China, which contributes to the deepening of environmental degradation. Similar problems, in particular low coordination and weak institutional capacity, are also characteristic of Ukraine and Armenia. This is confirmed by the findings of Anaba et al. (2024) regarding the disconnection between central and local authorities, which leads to policy fragmentation and its decreasing effectiveness.

In contrast, countries with high investment rates and technological modernization, such as Germany and South Korea, show a significant decrease in the concentration of harmful substances in the air. These results are consistent with the findings of Chong et al. (2023) and Slater et al. (2022). The researchers emphasize the importance of early implementation of environmental policies, systematic financing and active involvement of the private sector. Their own results also confirm that digitalization of monitoring, active public participation and international cooperation are critical factors for successful environmental transformation. This is consistent with the findings of Shahid et al. (2025) and Blinova et al. (2024).

Particular attention should be paid to the low level of regulatory capacity and the lack of coordination between different levels of government, in particular in Armenia and Ukraine. This leads to significant delays in the implementation of environmental strategies and worsens the overall effectiveness of environmental protection measures. This conclusion is supported by Hovhannisyan and Nersisyan (2020), as well as Awewomom et al. (2024). They note the excessive segmentation of the management system in industrial regions, which limits the ability to adequately respond to complex environmental threats. Besides, Kim et al. (2022) and Ryzhenko et al. (2020) draw attention to the shortcomings of the short-term nature of most environmental strategies. Such an approach does not provide sufficient adaptability to long-term challenges, especially those related to climate change. The presented idea is consistent with our observations on the need for a systemic and integrated approach that combines preventive measures with technological renewal.

It is worth emphasizing that international standards, such as ISO 14001, ESG indicators and the UN SDGs, play a key role in current environmental management. They are considered fundamental tools for building effective environmental policy and sustainable development management. However, their implementation at the national level often faces a number of challenges related to the need to adapt to the specific socio-economic, political, and institutional conditions of each country. In particular, local features of legal systems, the level of infrastructure development, the capacity of government bodies, as well as cultural and economic factors can significantly affect the effectiveness of the implementation of these standards. This problem is noted by Chis et al. (2025), Li et al. (2024) in their studies. They emphasize the need to develop flexible mechanisms that allow for the integration of international norms, taking into account local conditions and the capabilities of the institutional system of a particular country. Our findings fully confirm this position, indicating that without such adaptation, standards risk remaining declarative and will not affect the real improvement of the environmental situation.

Comparison with the results of other researchers also indicates the positive impact of the systemic approach. Countries with active environmental policies, in particular Sweden and

Denmark, have reduced CO_2 emissions by 60% over the past 15 years. This was achieved thanks to investments in renewable energy sources and innovative technologies (Widerberg et al., 2024). Similarly, Slater et al. (2022) notes that Canada has reduced greenhouse gas emissions by 30% due to the introduction of environmental regulations and the active involvement of the private sector. In China, according to Z. Tu (2023), CO_2 emissions have decreased by 40% over the past 10 years, which is explained by the introduction of electric vehicles and modern eco-technologies.

The obtained results confirm the hypothesis that effective environmental safety management in industrial regions requires a systemic approach. This approach includes coordination at different levels of government, the introduction of modern technologies, adequate financing, and the adaptation of international standards. The absence of any of these components significantly reduces the effectiveness of environmental protection measures and hinders the improvement of the environmental situation. Practical application implies creating comprehensive strategies that combine technological innovations, in particular digital monitoring. Important components are also increased interaction between central and local authorities and active public participation through the transparency of environmental data. Adaptation of international standards taking into account national characteristics will contribute to increasing the effectiveness of measures. Such a comprehensive approach will contribute to reducing pollution, improving the quality of life, strengthening environmental safety and sustainable development of industrial regions. In addition, it can serve as the basis for the formation of state and regional environmental policies.

This study has two main limitations, namely the limited time period and the selection of countries. The study only covers the period 2010-2024, which may not reflect long-term trends in air quality and the effectiveness of environmental policies. The impact of environmental policies may manifest itself over longer time periods. The analysis was based on the example of only five countries, which may limit the generalizability of the results to other countries with different socio-economic conditions and environmental challenges. Another limitation is that linear and polynomial regression may not be effective enough to reflect complex seasonal and nonlinear fluctuations in pollutant time series, which may lead to biased assessment results. In addition, the study faced the limitation of not having full and detailed access to industrial data on emissions and pollution control measures in some regions.

It is recommended to implement comprehensive environmental strategies that include modern monitoring, emission reduction and development of renewable energy sources. It is also important to increase investment and support innovation. To achieve effectiveness, it is necessary to strengthen the institutional framework, ensure coordination, involve the public, strengthen international cooperation, and regularly evaluate the results for timely improvement of policies.

CONCLUSIONS

The study showed that reducing air pollution is a critically important task for ensuring environmental safety, public health, and sustainable development of countries. Analysis of the dynamics of air pollution in Germany, Italy, Ukraine, Armenia, and South Korea for 2010–2024 revealed significant differences in the effectiveness of environmental policies and strategies. Germany and South Korea demonstrated the most significant successes in reducing pollution. A systematic approach to environmental transformation in these two countries, investments in the latest technologies, and active participation of the state ensured a reduction in the levels of major pollutants by 55% and 52%, respectively. On the contrary, a slower reduction in pollution is observed in Ukraine and Armenia, which indicates the fragmented nature of environmental policy, insufficient funding and limited implementation of environmental measures.

Military operations in Ukraine have also significantly affected the environmental situation, complicating the implementation of environmental protection programmes. The results of the study emphasize the importance of an integrated approach to environmental safety management. It includes not only financing environmental projects, but also active public participation, international cooperation, and the introduction of modern monitoring technologies. To achieve sustainable improvement in air quality, it is necessary to ensure systematic, consistent implementation of environmental strategies and political will for environmental modernization. A significant reduction in pollution levels can be achieved only by integrating all these elements, which will contribute to the health of the population and the sustainable development of regions.

The results of the study have practical significance for shaping environmental policy. They can serve as a basis for the development and improvement of national strategies aimed at reducing air pollution and improving the quality of life of the population. The results can also be used to manage environmental safety, providing recommendations to state authorities, industrial enterprises, public organizations, academic institutions, and international partners. The recommendations relate to an integrated approach that includes monitoring, emission control, and active public participation. Prospects for further research are to expand the analysis of the impact of environmental policies on air quality in other countries. This will enable identifying general trends and specific factors that affect the effectiveness of pollution reduction measures. It is also important to investigate the impact of new technologies, such as digitalization of environmental control and automated monitoring systems, on the effectiveness of environmental strategies.

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