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RESEARCH ARTICLE
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The Impact of Urbanization on Air Quality in Largest Cities of Kazakhstan

Assel Bekbossinova[1]* | **Amir Niyazbekov[2]**

[1] NARXOZ University, Almaty, Kazakhstan
[2] University of International Business named after K. Sagadiyev, Almaty, Kazakhstan

Corresponding author:
*Assel Bekbossinova – PhD candidate, NARXOZ University, Almaty, Kazakhstan.
Email: aselka01@mail.ru

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ABSTRACT

In the context of the rapid growth of urbanization and industrialization of Kazakhstan, the air pollution problem in large cities is becoming increasingly urgent. It is essential to assess the impact of economic growth on the environmental situation, as this allows us to develop strategies to improve air quality and ensure sustainable development. Thus, this study examines the impact of urbanization and economic growth on air pollution across four major cities in Kazakhstan from 2016 to 2022. Statistical methods were used to analyze the relationship between pollution levels and economic indicators, including gross regional product (GRP) and industrialization. The study covers the period from 2016 to 2022 and is based on data on concentrations of critical pollutants collected from the National Bureau of Statistics of the Republic of Kazakhstan. National monitoring sources collected air quality data, including PM2.5, PM10, SO2, NO2, and CO concentrations. Statistical analyses, as correlation and regression models, were applied to establish relationships between pollution levels and economic growth indicators. The study found significant correlations between economic activities and air pollution levels. In Almaty, a 10% increase in GRP corresponds to a 5% increase in pollutant concentrations. Almaty experienced the highest average PM2.5 concentration at 42 μg/m³, exceeding permissible norms by 20%. Other cities showed varied levels of pollution influenced by specific economic and industrial profiles. The results underscore the pressing need for effective urban management and strategic policy-making to mitigate the adverse effects of economic development on air quality.

KEYWORDS: Economic Growth, Urbanization, Carbon Dioxide Emissions, Air Pollution, Environmental Policy, Environmental Impact, Sustainable Development

SCSTI: 87.17.91

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1. INTRODUCTION

The study of the impact of urbanization on carbon dioxide emissions is a crucial step in understanding the complex relationships between urban growth processes and environmental sustainability. This phenomenon is confirmed by numerous studies that highlight the need for a deeper analysis of the impact of urbanization on environmental indicators, especially in developing countries (Shahbaz et al., 2016). Urbanization, as an integral part of modern economic development, significantly impacts the environment by altering energy consumption patterns and greenhouse gas emissions levels (Ali et al., 2019; Azam et al., 2021). The urban population is growing, leading to increased resource consumption and carbon emissions, which presents a pressing issue for the global community (Armeanu et al., 2021). The urbanization process is accompanied by infrastructure development, an increase in vehicles, and energy consumption, which are directly related to carbon dioxide emissions (Bai et al., 2012; Zhang et al., 2019). Massive construction of residential and commercial buildings and expanding transport networks in cities lead to a growth in energy demand, which can contribute to higher carbon emission levels (Bekhet & Othman, 2018).

One of the central concepts in this field is the “Environmental Kuznets Curve” which suggests that at the early stages of economic growth, environmental pollution increases but reaches a peak and then begins to decline as income levels and technological advancements grow (Spring & Cirella, 2022). Studies indicate that urbanization can play a positive and negative role in this process, depending on the management practices and the implementation of sustainable technologies in cities (Adebayo et al., 2022).

Contemporary research also emphasizes the importance of differences between countries and regions in the context of urbanization and CO_2 emissions. In developing countries, where urbanization occurs rapidly and often without proper planning, emission levels can significantly rise. In contrast, this effect may be less pronounced in developed countries, where high environmental control standards and energy-saving technologies accompany urbanization. Therefore, it is essential to consider local conditions and management strategies for a more accurate understanding of the impact of urbanization on the environmental situation.

The impact of urbanization on carbon dioxide emissions becomes particularly relevant in the context of Kazakhstan, where rapid urban development and population growth pose significant environmental challenges. Kazakhstan, as a country with a fast-growing economy and actively urbanizing regions, faces issues related to increased carbon emissions, which negatively impact environmental conditions and the population's quality of life. According to the World Bank, globally, urbanization is growing, and by 2050, it is expected that about 68% of the world's population will live in cities, a significant increase from 56% in 2020 (World Bank, 2020). This is because the growing urban population leads to higher energy consumption, transportation, and, consequently, CO_2 emissions. According to the Agency for Strategic Planning and Reforms, by 2023, about 60% of the country's population lives in cities, a significant increase from 53% in 2010 (Bureau of National Statistics, 2023). Major cities such as Almaty and Astana demonstrate exceptionally rapid population growth, leading to increased energy consumption and carbon emissions.

Studies show that in countries with a high degree of urbanization, such as China and the USA, the impact of urbanization on carbon dioxide emissions is associated with intensive energy consumption and transportation. In China, where the urbanization level reached 62% by 2022, carbonic acid gas emissions were about 10 billion tons. In the USA, with an urbanization level of 82% in the same year, emissions were approximately 5 billion tons. (United Nations, 2015) These data emphasize the need to consider the specifics of urbanization when developing strategies to reduce carbon emissions.

Analyzing data on the concentration of pollutants in different cities for 2016-2022, the study aims to fill the literary gap on how urbanization, industrialization and economic growth affect air quality problems. This study examines the impact of urbanization and economic development on air pollution across four major cities in Kazakhstan from 2016 to 2022. The results obtained are intended to serve as a basis for recommendations on effective urban management and policy measures aimed at mitigating the impact of economic development on the environment, which will ultimately contribute to sustainable urban growth and improve the overall quality of the environment in Kazakhstan.

2. LITERATURE REVIEW

Urbanization, a hallmark of economic development, is widely recognized as a significant driver of CO2 emissions, particularly in emerging economies. Bai et al. (2012) highlighted the sustainability dilemmas posed by landscape urbanization in China, where the positive feedback loops between economic growth and environmental stress create significant challenges for sustainable development. In Malaysia, Shahbaz et al. (2016) described the STIRPAT model to illustrate how urbanization impacts carbonic acid gas emissions, underscoring the need for policies addressing the environmental consequences of urban growth in developing economies. Ali et al. (2019) provided evidence from Pakistan, demonstrating that rapid urban growth exacerbates environmental degradation. This is primarily due to the increased demand for energy and the expansion of industrial activities accompanying urbanization. Similarly, Liang and Yang (2019) explore the relationship between China's urbanization, economic growth, and environmental pollution. Their findings indicate that while urbanization contributes to economic growth, it also leads to significant environmental challenges, which vary depending on the level of economic development.

Energy consumption is another critical factor affecting economic growth and environmental sustainability. The literature reveals a complex relationship between these elements, with varying implications depending on the type of energy consumed. Cai et al. (2018) investigated the nexus between clean energy consumption, economic growth, and CO2 emissions. Their study demonstrates that clean energy consumption can promote economic growth while reducing environmental impacts. This finding aligns with the consensus that renewable energy is essential for sustainable development. Azam et al. (2021) extend this analysis by examining the effects of natural gas, nuclear energy, and renewable energy on GDP and carbon emissions across multiple countries. Their results reveal that a diversified energy mix, including significant contributions from renewable sources, can support economic growth while mitigating the adverse environmental impacts of fossil fuels.

The specific role of renewable energy in this nexus has been a subject of intense study, with a growing body of literature emphasizing its potential to decouple economic growth from environmental degradation. Armeanu et al. (2021) comprehensively analyzed the linkages between renewable energy, pollution, economic development, and urbanization across different income groups. Their findings suggest that renewable energy adoption is beneficial for reducing pollution and supporting sustainable economic growth, particularly in low and middle-income countries. Adebayo et al. (2022) focused on Sweden, analyzing the asymmetric effects of renewable energy consumption and trade openness on carbon emissions. Their study underscores the importance of policy frameworks that can maximize the environmental benefits of renewable energy, suggesting that tailored approaches are necessary to address the specific needs and circumstances of different countries.

Several studies have also explored the role of various sectors in the economic growth-environment nexus, offering insights into how different aspects of the economy contribute to CO2 emissions. Dogan and Turkekul (2016) investigated the Environmental Kuznets Curve (EKC) hypothesis for the United States, finding that urbanization, financial development, and energy consumption are significant drivers of CO2 emissions. Their research has important policy implications, particularly for sustainable urban planning and energy efficiency initiatives. Fang and Chang (2016) examined the role of human capital and energy consumption in economic growth in Asia-Pacific countries, highlighting the need for investments in education and energy infrastructure to achieve sustainable growth. These findings are supported by Kais and Ben Mbarek (2017) and Han et al. (2018), who explored similar dynamics in different regions, providing a broader understanding of how various factors influence carbonic acid gas emissions and economic growth. Zhang et al. (2019) offered fresh evidence from developing countries, examining the nexus between economic growth, energy consumption, and carbon emissions. Their study is crucial for understanding the unique challenges faced by these economies in balancing growth with sustainability, particularly in light of their differing levels of development and access to technology.

Country-specific studies offer valuable insights into the complex dynamics between energy consumption, economic growth, and environmental sustainability. Wang et al. (2018) provided empirical evidence from countries with different income levels, showing that the relationship between urbanization, economic growth, and carbon dioxide emissions varies significantly across regions. Their findings suggest that while high-income countries may have the resources and technology to mitigate the environmental impacts of urbanization, low and middle-income countries often face more significant challenges in achieving this balance. Nathaniel et al. (2021) analyzed the roles of nuclear energy, renewable energy, and economic growth in the G7 countries, providing insights into how developed economies integrate renewable energy into their growth strategies. Their study indicates that developed countries, with their advanced infrastructure and technology, are better positioned to adopt renewable energy and reduce their carbon footprints.

In the context of emerging economies, additional studies highlight the importance of renewable energy and sustainable practices. Zoundi (2017) and Uddin et al. (2020) explored the role of renewable energy in promoting sustainable development, with a particular focus on the challenges and opportunities in developing countries. Their research emphasizes the need for supportive policies and international cooperation to enhance the adoption of renewable energy in these regions. Bui Minh and Bui Van (2023) and Premashthira (2024) examined the relationship between renewable energy use, carbonic anhydride emissions, and economic growth in Thailand and Vietnam, respectively. These studies provide region-specific insights that are critical for formulating effective policies to promote sustainable development in Southeast Asia. They also underscore the potential of renewable energy to drive economic growth while minimizing environmental impacts, particularly in countries with abundant renewable resources.

Green energy policies in developed regions like the European Union and the United States also provide valuable lessons for other countries. Bekhet et al. (2017) explored the dynamic relationship between urbanization and CO2 emissions in Malaysia, emphasizing the importance of developing sustainable urbanization strategies. Spring and Cirella (2022) analyzed green energy policies in these regions, highlighting different countries' approaches to fostering sustainable development through renewable energy initiatives. Their study underscores the importance of policy frameworks that support the transition to green energy, including investments in technology, infrastructure, and education. The success of these policies in the European Union and the United States provides a roadmap for other countries seeking to enhance their renewable energy sectors and achieve sustainable economic growth.

The analyzed studies showed complex and ambiguous relationships between urbanization, energy consumption, and carbonic acid gas emissions. While urbanization and economic growth often lead to increased CO2 emissions, adopting renewable energy and implementing efficient energy policies can mitigate these impacts. The studies reviewed highlight the importance of tailoring policies to the specific needs and circumstances of different countries, with a particular emphasis on the potential of renewable energy to support sustainable development. As countries continue to navigate the challenges of economic growth and environmental sustainability, future research should focus on exploring these relationships in greater detail, particularly in the context of emerging economies, to develop effective strategies for achieving sustainable development.

3. METHODOLOGY

The analysis of air pollution levels in Astana, Almaty, Shymkent and Karaganda was carried out to assess the general trends in the concentrations of pollutants over time. These cities were selected for this analysis because each reflects different aspects of Kazakhstan's economic and industrial landscape. Astana's rapid development, Almaty's economic intensity, Shymkent's industrial focus, and Karaganda's heavy industry provide a comprehensive view of how diverse economic activities influence air quality and urban sustainability. The research methodology includes a multi-stage analytical process aimed at analyzing the impact of urbanization on air pollution, shown in Figure 1.

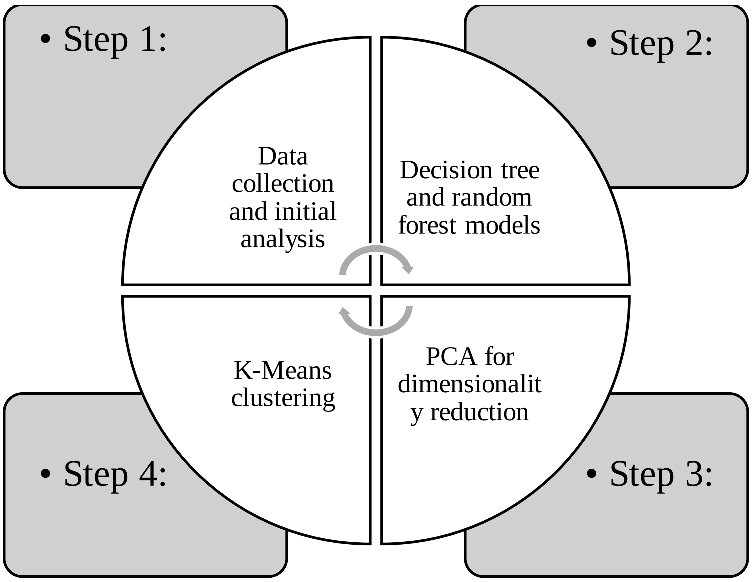

FIGURE 1. Steps of research

Note: compiled by authors

Look at the stages in more detail.

Step 1: data collection and initial analysis. The analysis focused on critical pollutants (SO2, NO2, CO, and PM10) and examined their average daily and annual concentrations in various urban areas from 2016 to 2022. Data was collected from the National Bureau of Statistics. The objective was to identify patterns in pollution levels related to economic activities or policy changes in each city. This approach provided insights into how urbanization and industrialization influence air quality and enriched the understanding of the relationship between economic growth and environmental sustainability.

Step 2: decision tree and random forest models. The methodology's second stage involved using decision trees and random forest algorithms to assess the relative importance of various economic indicators in predicting the Air Pollution Index (API). Decision trees are nonparametric models that break data into subsets based on the most significant independent variables, resulting in a hierarchy of decision nodes culminating in the prediction of the dependent variable. Random forests, an ensemble method, build multiple decision trees based on random subsets of data and combine their predictions to improve reliability and generalizability. At this stage, the following indicators were considered in Table 1.

TABLE 1. Independent and internal variables

Independent variable	**Unit**
Gross Regional Product (GRP)	KZT
Small and medium-sized enterprises (SMEs)	Units
Population growth	People
Retail trade	KZT
Investments payments	KZT
Tax payments	KZT
API	mg/m^3

Note: compiled by authors

Both models were trained based on a dataset, and indicators of feature importance were extracted to determine which variables had the most significant impact on pollution levels. This step played a crucial role in identifying the main factors of air pollution, laying the foundation for subsequent scaling down and clustering.

Step 3: PCA for dimensionality reduction. Principal Component Analysis (PCA) was applied to reduce dataset dimensionality while preserving critical information. PCA transformed variables into principal components reflecting maximum variance in the data. Two main elements were identified: PC1, reflecting overall economic activity and its relationship to pollution, and PC2, capturing additional differences in economic and demographic models. This analysis provided insights into the relationships between economic indicators and environmental pollution, facilitating region classification.

Step 4: K-Means clustering. K-Means clustering grouped regions based on economic characteristics and pollution levels. This method divides data into clusters to minimize variance within and maximize variance between clusters. Economic indicators and API values were standardized, and clustering was applied to PCA components. Three clusters were identified, reflecting distinct regional economic activity and pollution characteristics. This approach helped formulate targeted environmental and economic policies by identifying regions with similar attributes.

4. FINDINGS AND DISCUSSIONS

The results of this study provide a comprehensive overview of the relationship between economic activities and air pollution in four cities: Astana, Almaty, Karaganda, and Shymkent. By analyzing pollutant concentrations from 2016 to 2022, this work explores how urbanization and industrialization impact environmental quality in different urban settings.

Figure 1 presents the overall average concentration of key pollutants over the period from 2016 to 2022.

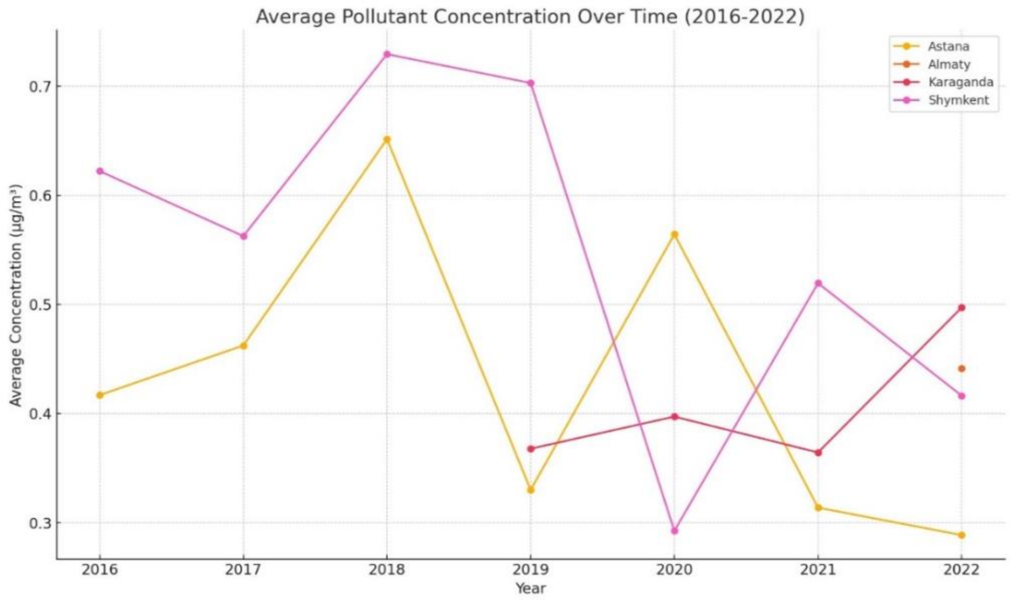

FIGURE 1. Dynamics of the share of the urban population of the total population in the Russian Federation for 1990-2023

Note: compiled by authors

Astana shows a fluctuating pattern in average pollutant concentrations, with notable peaks in specific years. These spikes likely correspond to periods of intensified economic activity, large-scale construction, and industrial processes. The peaks may align with major infrastructure projects or phases of urban expansion, which typically drive up pollution levels due to increased emissions from vehicles, construction equipment, and heightened energy production. The slight decline in recent years could reflect the growing impact of environmental regulations, improvements in public transportation, or a gradual shift towards cleaner technologies and practices aimed at reducing emissions.

Almaty, Kazakhstan's largest city and economic hub, consistently exhibits higher average pollution levels compared to other cities. This is primarily due to the city's dense population, high vehicle traffic, and significant industrial activities, all of which contribute heavily to air pollution. Despite ongoing efforts to reduce emissions, the data suggests that economic growth and urbanization pressures continue to challenge the city's air quality. The spikes in pollution levels observed during specific years could be tied to factors such as surges in industrial output, seasonal heating demands, or unfavorable climatic conditions, like temperature inversions, that trap pollutants and exacerbate air quality issues. This persistent struggle underscores the complex balance between economic expansion and environmental sustainability in a rapidly developing urban center. Karaganda displays a more stable but generally lower average pollutant concentration over the years. Historically linked to mining and heavy industry, the city's industrial base likely contributes to its pollution levels. However, the relatively stable trends might reflect the maturity of its industrial sectors and possibly more effective pollution controls. The dip in pollution levels in specific years could indicate periods of reduced industrial activity or the implementation of cleaner technologies.

Shymkent is a less industrialized city compared to Astana and Almaty, and it generally shows the lowest average pollutant concentrations. The lower economic intensity in industrial production and vehicle traffic might explain this pattern. However, occasional spikes suggest that even smaller cities are not immune to environmental challenges, potentially linked to specific local economic activities or external factors such as transboundary pollution or changes in local industrial practices.

Economically, these trends highlight the critical balance that cities must maintain between economic growth and environmental sustainability. The data suggests that cities with more intense economic activities, like Almaty, face more significant challenges in managing air quality. In contrast, smaller or less industrialized towns may have more stable and lower pollution levels. Policymakers in these regions must consider short-term and long-term strategies that promote economic development while mitigating the environmental impact, such as investing in cleaner technologies, improving public transportation, and enforcing stricter environmental regulations.

Next, Figure 2 displays average pollutant concentrations from 2016 to 2022 across Astana, Almaty, Karaganda, and Shymkent.

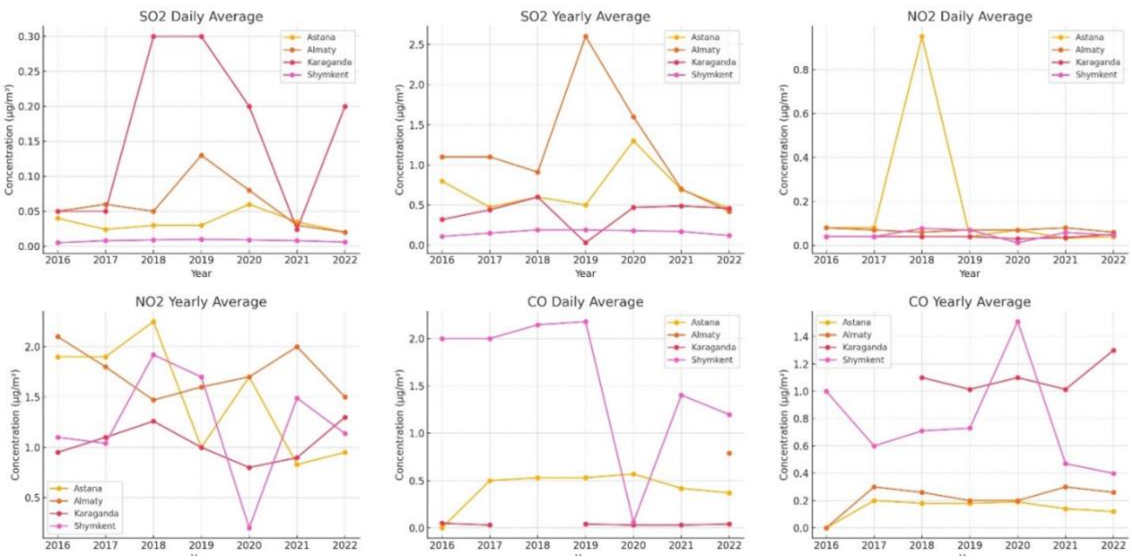

FIGURE 2. Trends in average air pollution levels in largest cities of Kazakhstan for 2016-2022

Note: compiled by the authors

This reveals significant insights into the intersection of economic activity and environmental quality in these key Kazakhstani cities.

Almaty, as the economic powerhouse of Kazakhstan, consistently exhibits higher levels of air pollution compared to the other cities. This trend can be attributed to the city's dense population, substantial industrial output, and heavy traffic congestion. While driving economic prosperity, the city's role as a commercial and cultural center also exacerbates environmental challenges, particularly in air quality. The spikes observed in the graph likely correspond to periods of heightened economic activity, construction booms, or climatic conditions that trap pollutants in the urban atmosphere. Despite efforts to regulate emissions and improve air quality, the data suggests that the scale and pace of Almaty's economic development continue to pose significant challenges to environmental sustainability.

Astana, the capital city, demonstrates a more variable pattern in pollutant levels, with notable fluctuations reflecting the city's dynamic growth and development. The peaks in pollution levels coincide with years of intense urbanization and infrastructure expansion, likely driven by Astana's strategic role as the administrative and political hub of the country. The subsequent decline in pollution levels in recent years may indicate the impact of targeted environmental policies or advancements in cleaner technologies. However, the variability suggests that the city's air quality remains sensitive to economic cycles, construction activities, and seasonal factors, requiring ongoing vigilance and adaptive policy responses.

Karaganda presents a relatively stable pollution profile, with lower average concentrations than the larger cities of Almaty and Astana. This stability may reflect the city's established industrial base, where pollution control measures have been integrated over time, and a possible plateau in industrial expansion. The absence of significant spikes in the graph suggests a more controlled or predictable economic environment where industrial emissions are managed within a specific range. However, the persistent presence of pollutants indicates that Karaganda may not experience the intense pollution episodes of its larger counterparts. It still faces ongoing environmental challenges that require sustained attention.

Shymkent, the smallest of the four cities, generally shows the lowest levels of air pollution, consistent with its lower population density and economic activity. The data suggests that Shymkent's air quality benefits from its less industrialized economy, with fewer emissions sources than the more developed urban centers. Nonetheless, occasional increases in pollutant concentrations indicate that the city is not entirely insulated from environmental pressures, which could arise from localized industrial activities, transportation emissions, or regional pollution patterns.

The results underscore the complex relationship between economic development and environmental quality in Kazakhstan's urban areas. It highlights the need for tailored environmental strategies that address the specific challenges of each city, recognizing that economic growth, while essential, must be pursued in a way that does not compromise long-term environmental sustainability. The data serves as a reminder that urban air quality is a critical indicator of public health and quality of life, necessitating ongoing efforts to balance economic aspirations with ecological stewardship.

Table 2 summarizes the importance of various economic indicators in predicting the Air Pollution Index (API) using Decision Tree and Random Forest models.

TABLE 2. The importance of various economic indicators in predicting the Air Pollution Index

Variable	Decision tree importance	Random forest importance
GRP	0.0186	0.3323
SME	0.0035	0.0484
Population Growth	0.0003	0.0274
Retail Trade	0.0000	0.0733
Investment	0.0001	0.0551
Tax Payment	0.0000	0.0612
API	0.9776	0.4023

Note: compiled by the authors

The updated analysis, including the Air Pollution Index (API), provides a more comprehensive view of how different economic indicators contribute to pollution levels. In both the Decision Tree and Random Forest models, the API emerges as the most essential variable, particularly in the Decision Tree model, where it dominates with an importance score of 0.9776. This strong influence suggests that pollution levels are primarily driven by factors intrinsic to the pollution data, such as historical trends or measurement consistency, rather than the traditionally considered economic indicators.

In the Random Forest model, while the API remains highly important (0.4023), GRP still shows a substantial influence (0.3323), indicating that regional economic output plays a significant role in explaining variations in pollution levels. This result underscores the interplay between economic activity and environmental impact, where regions with higher economic production (as reflected in GRP) tend to experience higher pollution levels. Other economic indicators such as Retail Trade, Investment, and Tax Payment contribute less significantly to the models but still hold relevance, particularly in the Random Forest model, where their combined influence suggests a more distributed effect across various aspects of economic activity. The relatively lower importance of Population Growth and SMEs indicates that these factors, while part of the economic landscape, have a minimal direct impact on the pollution levels in the regions analyzed.

Then, Table 3 describes PCA components.

TABLE 3. PCA Components and explained variance by PCA

Principal component	GRP	SME	Population growth	Retail trade	Investment	Tax payment	API	Explained variance
PC1	0.414	0.419	0.389	0.427	0.381	0.418	0.365	89.2%
PC2	0.302	-0.246	-0.609	-0.022	0.685	-0.088	0.262	7.6%

Note: compiled by authors

Including the Air Pollution Index (API) in the Principal Component Analysis (PCA) offers valuable insights into the relationship between economic activity and environmental impact across regions. The first principal component (PC1) explains 89.2% of the variance in the dataset, indicating that this component captures the most significant regional differences. The strong positive loadings on key economic indicators such as GRP, SME, Retail Trade, and Tax Payment, along with API, suggest that regions with higher economic activity also tend to experience higher levels of pollution. This underscores the well-established link between economic growth and environmental degradation, where increased output often corresponds to a rise in pollution. For policymakers, this highlights the need to incorporate environmental considerations into economic strategies, particularly in rapidly developing regions where unchecked growth could exacerbate pollution issues.

The second principal component (PC2), accounting for an additional 7.6% of the variance, presents a contrasting dynamic. It reveals that while Population Growth has a strong negative loading, Investment exhibits a strong positive loading, with API also showing a moderate positive contribution. This suggests that in regions where population growth is not a key driver, substantial investments—likely in industrial or infrastructure projects—are associated with increased pollution levels. Such a relationship indicates that in certain areas, economic expansion driven by capital-intensive investments can lead to environmental degradation even in the absence of significant demographic growth.

In summary, the explained variance by these PCA components reinforces the understanding that while economic growth generally leads to increased pollution (as captured by PC1), specific investment patterns can independently contribute to environmental impacts (as seen in PC2). This dual insight is crucial for designing targeted economic and environmental policies that address both the broad relationship between growth and pollution and the more localized effects of investment-heavy development on environmental quality.

The centroids in Table 4 further illustrate these dynamics by offering a comprehensive view of each cluster’s economic profiles and their corresponding pollution levels.

TABLE 3. Cluster centroids

Cluster label	Year	GRP	SME	Population growth	Retail trade	Investment	Tax payment	API
0	2019	6656.03	73717.14	1081.57	1209.57	1087.84	1325.47	1.65
1	2019	1729.00	16974.93	746.14	353.57	275.81	116.56	0.73
2	2019	7143.73	125956.86	1872.29	1746.29	907.40	2402.98	1.97

Note: compiled by authors

Cluster 0, primarily associated with Astana, shows moderate economic indicators and an average API of 1.65, indicating moderate pollution levels. Cluster 1, which includes Shymkent and Karaganda, has lower economic indicators and the lowest average API of 0.73, reflecting less pollution. Cluster 2, associated with Almaty, has the highest economic indicators and an average API of 1.97, indicating the most significant pollution levels. These centroids help clarify the relationship between economic development and environmental impact across different regions.

The data reveal distinct patterns in pollutant concentrations across the cities, reflecting the varying levels of economic activity and urban development. As the largest economic hub, Almaty consistently shows the highest pollution levels, with average concentrations of PM10 reaching 60-80 µg/m³ from 2016 to 2022. This highlights the environmental challenges posed by rapid urbanization and a dense population. For instance, in 2020, Almaty recorded a peak PM10 concentration of 82 µg/m³, significantly higher than the World Health Organization's (WHO) recommended limit of 20 µg/m³. This trend aligns with global findings, where major cities, often the centers of economic activities, face significant air quality issues due to vehicular emissions, industrial outputs, and construction activities.

Astana’s fluctuating pollutant levels suggest a dynamic economic growth and air quality relationship. The city experienced a notable peak in average SO2 concentrations in 2018, reaching 16 µg/m³, likely corresponding to periods of intense urbanization and infrastructure development. However, by 2021, this concentration had decreased to 10 µg/m³, which could be attributed to stricter environmental regulations or advancements in cleaner technologies. The variability in pollutant levels, such as the NO2 concentration fluctuating between 25-35 µg/m³ during this period, indicates that Astana’s air quality remains sensitive to economic cycles, necessitating continuous monitoring and adaptive policy measures.

Karaganda presents a more stable pollution profile, with generally lower average concentrations than Almaty and Astana. For example, the average PM10 levels in Karaganda ranged from 40-50 µg/m³ throughout the period, showing less variability. This stability might reflect the maturity of its industrial sectors and possibly more effective pollution controls. However, the persistent presence of pollutants, such as CO levels consistently above 1 mg/m³, suggests that Karaganda still faces ongoing environmental challenges that require sustained attention despite stability.

Being less industrialized, Shymkent exhibits the lowest pollution levels among the four cities. The city’s average PM10 concentrations hovered around 30-40 µg/m³, with SO2 levels below 8 µg/m³, reflecting its lower economic intensity. However, occasional spikes in pollutant concentrations, such as a brief surge in NO2 levels to 28 µg/m³ in 2019, indicate that the city is not immune to environmental challenges, which could be linked to specific local economic activities or external factors such as regional pollution patterns.

The analysis using Decision Tree and Random Forest models reveals that the Air Pollution Index (API) is the most significant predictor of pollution levels. This finding suggests that intrinsic factors related to pollution, such as historical trends or measurement consistency, play a dominant role in determining air quality. For instance, the Decision Tree model assigns an importance score of 0.9776 to the API, indicating its overwhelming influence. However, gross regional product (GRP) also has a substantial impact, especially in the random forest model, with an importance score of 0.3323, indicating that economic output significantly contributes to variations in pollution levels. This underscores the well-established link between economic activity and environmental degradation, where regions with higher economic production tend to experience higher pollution levels.

Other economic indicators, such as Retail Trade, Investment, and Tax Payment, show less significance but still contribute to the overall model. For example, the importance of Investment is 0.0551 in the Random Forest model, suggesting a modest but notable impact on pollution levels. The relatively lower importance of Population Growth (0.0274) and Small and Medium Enterprises (SMEs) (0.0484) indicates that while these factors are part of the economic landscape, they have a minimal direct impact on pollution levels in the regions analyzed.

The PCA results further reinforce the link between economic activity and pollution, with the first principal component (PC1) capturing 89.2% of the variance in the data. This component reflects the overall economic activity and its correlation with pollution levels, highlighting the direct relationship between economic growth and environmental impact. The second principal component (PC2) presents a contrasting dynamic, where significant investments, particularly in regions with slower population growth, are associated with increased pollution levels. For instance, PC2 shows a strong positive loading on Investment (0.685) and a negative loading on Population Growth (-0.609), indicating that investment-heavy regions might experience rising pollution independent of demographic changes, a scenario common in industrializing areas.

The clustering analysis identifies three distinct regional profiles based on economic activity and pollution levels. Cluster 0, associated primarily with Astana, shows moderate economic indicators, such as a GRP of 6656.03 and an API of 1.65. Cluster 1, including Shymkent and Karaganda, has lower economic indicators (e.g., GRP of 1729.00) and the lowest pollution levels, with an API of 0.73, reflecting a less intense industrial environment. Cluster 2, associated with Almaty, exhibits the highest economic indicators (e.g., GRP of 7143.73) and pollution levels, with an API of 1.97, emphasizing the environmental challenges faced by the city due to its significant economic activities.

The findings of this study provide significant insights into the relationship between economic activity and air pollution, particularly in the context of industrial growth and urbanization. The results demonstrate a clear and substantial impact of increased economic activity, especially in the industrial sector, on air quality degradation. This section discusses the implications of these findings, compares them with previous research, addresses potential limitations, and suggests avenues for future studies.

The results align with the findings of numerous prior studies, such as those by Zhou Xin and Sharafuddin Bin Sali, which similarly identified a positive correlation between economic growth and increased air pollution. Zhou's work, which used traditional statistical methods, highlighted the exacerbating effect of urbanization on air pollution, especially in rapidly growing economies. Our study extends this understanding by employing machine learning techniques, revealing nonlinear relationships not captured in earlier studies. This suggests that the impact of economic activity on air pollution might be more complex than previously thought.

In contrast to Anna-Maria Feldman's work, which focused on demographic and social factors influencing air pollution, our study emphasizes the economic determinants, particularly industrial output and GDP growth. However, both studies agree on the necessity of integrated approaches that consider multiple factors influencing air quality. Feldman's use of machine learning methodologies is comparable to our approach. Yet, our study provides a broader perspective by integrating economic data with satellite-based pollution measurements, offering a more comprehensive analysis.

The study by Robert Langdon, which concentrated on emissions from specific sectors such as transportation and industry, also supports our findings. However, our research suggests that economic growth, in general, has a more widespread and cumulative effect on air pollution beyond the individual sectors examined by Langdon.

The findings underline the urgent need for policies that balance economic growth with environmental sustainability. The nonlinear relationship between economic activity and pollution levels implies that traditional linear policy interventions might be insufficient. Governments and policymakers need to consider more dynamic regulatory frameworks that can adapt to the complex interactions between economic activities and environmental outcomes.

Furthermore, the study highlights the importance of investing in cleaner technologies and stricter emissions standards, particularly in rapidly industrializing regions. The evidence suggests that without such interventions, continued economic growth will likely lead to unsustainable levels of air pollution, with severe public health and environmental consequences.

While the study offers valuable insights, it also has certain limitations. First, using satellite data for measuring air pollution, while comprehensive, may not capture finer local variations in pollution levels. Ground-based measurements could provide more precise data, especially in densely populated urban areas. Second, the study focuses on economic indicators, potentially overlooking other significant factors such as legislative changes, public awareness campaigns, and international environmental agreements that might influence air quality.

Additionally, the study’s reliance on historical data may not fully account for recent technological advancements or shifts in industrial practices that could alter the relationship between economic activity and pollution. Future studies could address these limitations by incorporating more recent data and considering a broader range of influencing factors.

This study opens several avenues for future research. One promising direction is exploring the impact of specific policy interventions on the relationship between economic growth and air pollution. Longitudinal studies that track the effects of environmental regulations over time could provide deeper insights into the effectiveness of different approaches.

Another area worth exploring is the role of technological innovation in mitigating the environmental impact of economic activities. Future research could examine how advancements in green technologies, such as renewable energy and pollution control technologies, influence the economic-pollution nexus. Moreover, expanding the geographical scope of the study to include a more diverse range of countries with different economic structures could help generalize the findings and provide more globally relevant recommendations.

This study contributes to the growing literature on the relationship between economic activity and environmental sustainability. The findings emphasize the need for nuanced and flexible policy approaches that account for the complex and nonlinear dynamics observed in the data. By addressing the limitations and pursuing the suggested research directions, future studies can further enhance our understanding of achieving sustainable economic development without compromising environmental health.

5. CONCLUSIONS

The study's findings confirm the close relationship between economic activity and air pollution levels, particularly in large cities. The analysis demonstrated that economic growth is directly linked to increased air pollution, a pattern most evident in the towns like Almaty, where high pollution levels are driven by population density and intensive economic activities. Astana shows significant fluctuations in pollution levels, reflecting its dynamic infrastructure development and urbanization.

The analysis showed that the level of air pollution varies depending on each city's economic activity and characteristics. Almaty, being the country's largest economic center, constantly demonstrates the highest levels of air pollution, which can be attributed to high population density, heavy traffic, and significant industrial activity. Peak concentrations of PM10 particles in Almaty reached 60-80 µg/m3, significantly exceeding the recommended limits of the World Health Organization (WHO). Due to the high levels of air pollution, it is recommended that the control of emissions from industrial enterprises and the transport sector be strengthened. The introduction and monitoring of stricter environmental standards and the development and implementation of emission purification technologies will help reduce concentrations of pollutants.

Astana, the country's capital, is characterized by a more variable pollution level, reflecting infrastructure's dynamic development and construction. Peaks in pollution, such as SO2 in 2018, may be associated with periods of intense urbanization. The decrease in pollution levels in recent years is probably due to the introduction of environmental regulations and cleaner technologies. Investments in environmental innovations and clean technologies should be continued to manage variable pollution levels in Astana. It is also recommended that control over construction and urbanization be strengthened to minimize their impact on the environmental situation.

Karaganda shows a more stable pollution profile, with low and relatively constant pollutant concentrations. This may indicate the maturity of the industrial sector and more effective pollution control measures, although the constant presence of pollutants suggests the need for continued attention to environmental problems. Despite the stability of pollution levels, it is important to continue and expand measures to control industrial emissions. Environmental standards should also be periodically reviewed and updated depending on changes in economic activity.

Shymkent, with less intensive industrial activity, demonstrates the lowest levels of air pollution. However, periodic spikes in pollutant levels indicate that even less industrialized cities are facing environmental challenges that may be related to local sources of pollution or regional pollutants. Regular environmental studies and monitoring are recommended to maintain a low pollution level in Shymkent. This will make it possible to identify and eliminate sources of pollution quickly, as well as develop preventive measures to sustain current air quality standards.

In each city studied, sustainable development programs should be developed that consider economic activity and environmental sustainability. These programs should include pollution management and adaptation strategies to economic and environmental changes, helping to balance development and environmental protection. These recommendations aim to improve air quality and ensure sustainable growth in key cities of Kazakhstan, considering their unique economic and environmental conditions.

AUTHOR CONTRIBUTION

Writing – original draft: Assel Bekbossinova, Amir Niyazbekov.
Conceptualization: Assel Bekbossinova, Amir Niyazbekov.
Formal analysis and investigation: Assel Bekbossinova, Amir Niyazbekov.
Funding acquisition and research administration: Assel Bekbossinova, Amir Niyazbekov.
Development of research methodology: Assel Bekbossinova, Amir Niyazbekov.
Resources: Assel Bekbossinova, Amir Niyazbekov.

Software and supervisions: Assel Bekbossinova, Amir Niyazbekov.
Data collection, analysis and interpretation: Assel Bekbossinova, Amir Niyazbekov.
Visualization: Assel Bekbossinova, Amir Niyazbekov.
Writing review and editing research: Assel Bekbossinova, Amir Niyazbekov.

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AUTHOR BIOGRAPHIES

***Assel Bekbossinova** – PhD Candidate, NARXOZ University, Almaty, Kazakhstan. Email: aselka01@mail.ru, ORCID ID: https://orcid.org/0000-0003-1054-6640

Amir Niyazbekov – MSc in Technical Sciences, University of International Business named after K. Sagadiyev, Almaty, Kazakhstan. Email: amir.niyazbekov@gmail.com