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ARTICLE

Spatiotemporal Analysis of NO_2 Dynamics and Anthropogenic Activity in the Navoi Region of Uzbekistan: A Comparative Study Across the COVID-19 Period (2019–2023)

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ABSTRACT

Air pollution has emerged as one of the most pressing public health challenges of the twenty-first century. According to the World Health Organization (WHO), more than 7 million premature deaths occur annually as a direct consequence of exposure to polluted air, which is estimated to affect over 90% of the global population. Air pollution manifests in two principal forms: outdoor pollution, largely driven by industrial emissions, transportation, and energy production, and

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indoor pollution, often linked to inadequate ventilation, heating systems, and household fuel use. Both forms contribute significantly to a wide range of health outcomes, including chronic respiratory illnesses, cardiovascular complications, strokes, and various types of cancer. Vulnerable groups—such as children, the elderly, and individuals with pre-existing medical conditions—are disproportionately at risk. Efforts to mitigate the harmful effects of air pollution include stricter emission regulations, adoption of clean and renewable technologies, expansion of sustainable public transportation networks, and public education campaigns aimed at raising awareness of health risks and preventive strategies. Uzbekistan is not exempt from these challenges. In particular, the Navoi region, recognized as one of the country's most industrialized areas, faces heightened exposure to harmful substances released into the atmosphere. A comparative analysis of air quality indicators in Navoi's urban centers before and after the COVID-19 pandemic revealed a significant post-pandemic rise in pollution levels, linked to economic recovery, industrial activity, and transport flows. These findings provide valuable insights for policymakers and local authorities in developing targeted environmental and public health interventions.

Keywords: WHO; Urban Air Pollution; Vulnerable Populations; Cities of Navoi Region; Asthma; Indoor and Outdoor Pollution

1. Introduction

1.1. Pollution Indicators in the Era of COVID-19

The first days of 2020 were assessed by the World Health Organization as an emergency and called on all countries to take enhanced quarantine measures. In Uzbekistan, these measures began on March 19, 2020, and as a result of these restrictions, restricting the activities of all sectors of the economy, the amount of various harmful emissions from industry and transport has relatively decreased. In recent years, factors such as the widespread development of urbanization processes worldwide, and the advancement of industrial and transportation infrastructure to a new level have not escaped the cities of Uzbekistan. As a result, we can see that the amount of various harmful substances released into the atmosphere has increased year by year (for example, in 2010, in the republic, a total of 729 thousand tons of harmful substances were released into the atmosphere, and in 2018, this figure was 883.7 thousand tons, the object of research in the Navoi region, these figures were 40.3 thousand tons and 49.9 thousand tons, respectively). The latest studies show that the risk of lung cancer is more than 10% for people living in settlements within 50 meters of a highway. In addition, unsatisfactory air quality can cause heart and various related diseases and attacks [1,2].

1.2. Anthropogenic Processes and Pollution Sources

It is known that nitrogen (78%) occupies the main place in most of the atmosphere. Our observations show that even in the industrialized Navoi region, nitrogen oxide and nitrogen dioxide pollution are very high. Nitrogen is emitted from transportation, thermal power plants, and industries, causing significant pollution. Thermal power plants in and around cities are hotspots of nitrogen pollution. This shows that the rates of respiratory and cardiovascular diseases and deaths from these diseases are increasing in the urban population. For example, every year in the world, 0.1 million people die due to nitrogen pollution [2], and 4 million people suffer from asthma [3].

1.3. Literature Review

Urban air pollution remains one of the most pressing environmental challenges globally, particularly in rapidly developing regions. Numerous studies have explored the dynamics of air pollution and its anthropogenic drivers, with specific attention to industrial activity, vehicular emissions, urban expansion, and land-use change [4,5]. In Central Asia, including Uzbekistan, the issue has gained increasing scholarly attention as urbanisation accelerates and environmental health concerns intensify [6,7]. Air pollutants such as nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and particulate matter

($PM_{2.5}$) are strongly linked to human health outcomes, especially respiratory and cardiovascular conditions [8]. These pollutants are predominantly emitted from fossil fuel combustion in transportation, industrial production, and domestic energy use [9]. In arid and semi-arid environments like the Navoi region, atmospheric dispersion is limited, making pollutant accumulation more severe [10].

The COVID-19 pandemic introduced an unplanned global experiment, allowing researchers to analyse air quality changes in response to abrupt reductions in human activity. Studies across the globe documented temporary declines in NO_2, SO_2, and $PM_{2.5}$ due to lockdowns and industrial slowdowns [11,12]. Central Asian cities, including those in Uzbekistan, followed a similar pattern, with emissions declining in early 2020 but rebounding rapidly post-lockdown [13,14].

While several studies have evaluated air quality across Uzbekistan's major urban centres, literature focusing specifically on the Navoi region remains limited. However, recent research by Komilova et al. [15] has addressed urban ecological dynamics and anthropogenic pressures in cities like Navoi, Zarafshan, and Uchkuduk. These studies have revealed a strong correlation between industrial land use, transportation density, and elevated pollution levels. They also emphasise the role of green infrastructure in mitigating air pollution, echoing global findings [16].

Despite a growing body of literature on urban air pollution, comparative analyses of pollution levels before and after the COVID-19 pandemic in Uzbekistan, particularly in secondary cities, are scarce [17]. This study addresses this gap by focusing on the Navoi region, examining shifts in pollutant concentrations in conjunction with land use, population density, industrial activity, and transport patterns. The research provides empirical evidence for policymakers aiming to develop sustainable and resilient urban strategies in the face of ongoing environmental and public health risks. Urban air pollution, driven by industrial activity, vehicular emissions, urban expansion, and land-use change, is a major environmental concern globally, especially in developing regions. This is increasingly relevant in Central Asia, including Uzbekistan, due to rapid urbanisation and growing environmental health concerns. Pollutants such as NO_2, SO_2, and $PM_{2.5}$, primarily from fossil fuel combustion, are linked to respiratory and cardiovascular problems [18–20]. Arid regions like Navoi are particularly vulnerable to pollutant accumulation due to limited atmospheric dispersion.

The COVID-19 pandemic provided an opportunity to observe air quality changes during activity reductions. Studies in Central Asian cities, including those in Uzbekistan, showed temporary declines in pollutants during lockdowns, followed by rapid rebounds.

While air quality in major Uzbek cities has been investigated, research on the Navoi region remains limited. Recent studies highlight the connection between industrial land use, transportation density, pollution, and the role of green infrastructure in cities like Navoi, Zarafshan, and Uchkuduk.

This study addresses the lack of comparative analyses of pre- and post-COVID-19 pollution levels in Uzbekistan, focusing on the Navoi region. It examines shifts in pollutant concentrations related to land use, population density, industrial activity, and transportation patterns, providing policymakers with data to develop sustainable urban strategies that address environmental and public health risks.

1.4. Objectives of the Study and Study Area

This study aims to compare air pollution in industrialized regions and cities before, during, and after the pandemic and to explain the importance of several factors affecting it. These factors include population density, the proportion of urban dwellings, the amount of green space available, land used by industry, and the total number of vehicles registered in the city. Seven existing cities in the Navoi region - Navoi, Zarafshan, Uchkuduk, Nurota, Yangirabot, Kyziltepa, and Gazgan cities were taken as the object of study (**Figure 1**). Analyzing the results from this study may allow for urban re-planning and "ecological gentrification".

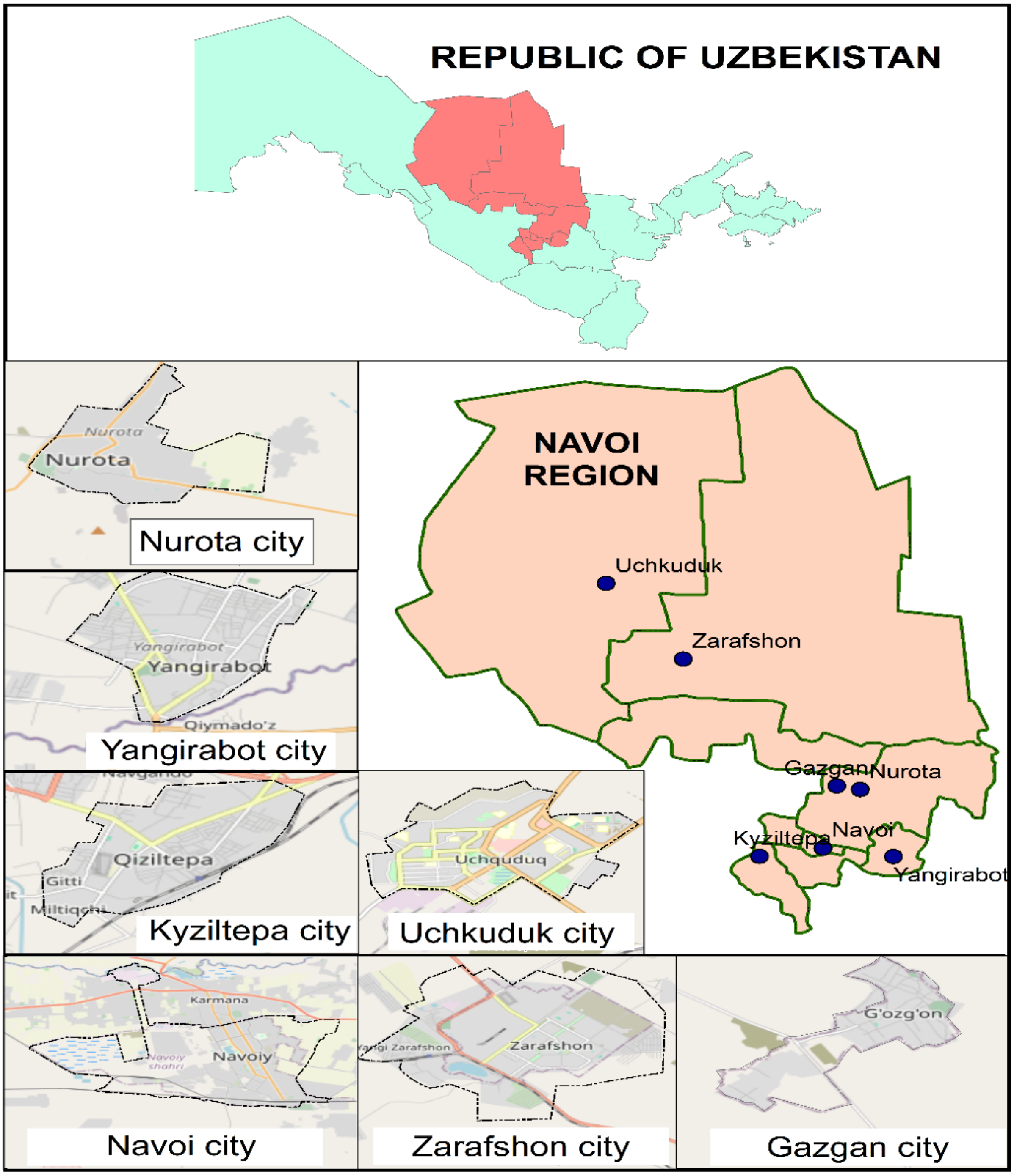


Figure 1. Study area.

2. Methodology and Data Collection

2.1. Methodology

Figure 2 illustrates the stages of the research methodology employed in this study. Initially, problems related to pollution in the cities of the Navoi region were studied. An analysis of new foreign research, technologies, and literature related to these problems was carried out. Factors affecting pollution were formed, and the interaction of the main substances polluting cities and their indicators with these factors was considered. These analysis processes were carried out using different types of graphs and histograms, the results were discussed, and conclusions and suggestions were given.

Figure 2. Methodology flow chart.

2.2. Data Collection

In collecting data, various statistical collections of the Republic of Uzbekistan and the Navoi region, and official websites of city administrations, observation data of researchers were used (**Table 1** and **Figure 3**).

Table 1. City wise anthropogenic factors responsible for pollution exposure.

City	Area (ha)	Population (Thousand People)	Population Density (in Persons per km^2)	Land Use (%)				Total Registered Transport Vehicles
				Transportation and Communication	Residential	Green Space	Industrial	
Navoi	2,213	156	7,050	28	41	0.25	22	69,045
Zarafshan	1,756	86.5	6,439	49.60	37	1.59	3	34,523
Uchkuduk	516	34.2	3,062	58.90	29	2.71	6,30	17,261
Nurota	1,767	50	2,829	28.20	34	0.12	17	13,809
Kyziltepa	502	49.8	2,437	7.51	11	1.53	20	24,166
Yangirabot	832	47.8	5,745	24.10	25	2.37	8.53	10,357
Gazgan	465	9.1	1,956	42.50	20	1	6.50	2,500

Figure 3. Scatter plot of cities data.

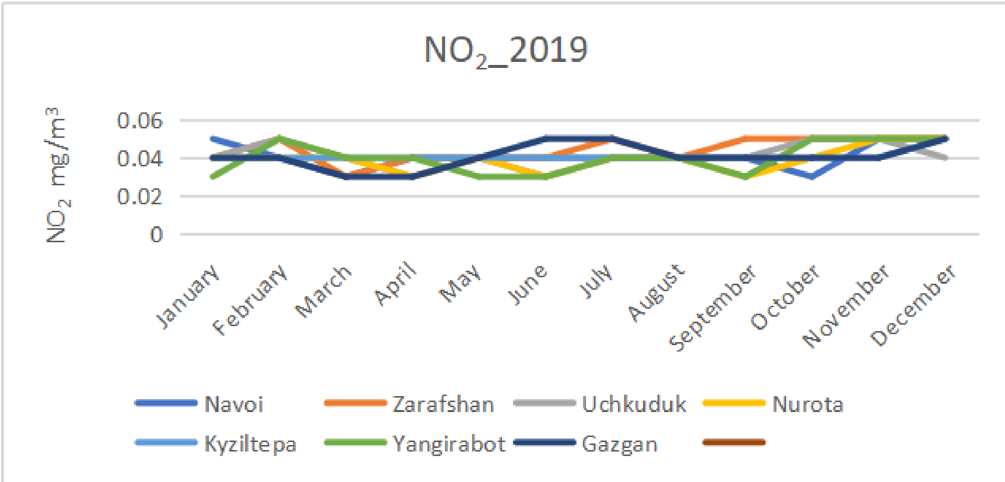
3. Data Analysis

Most of the studied cities are based on natural resources or specialize in various industries, where pollution levels with nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and small dispersed particles ($PM_{2.5}$) are quite high [21–24]. Data analysis was carried out for each month of 2019, 2021, and 2023 (**Figures 4–6**). The data for 2020 was ideal compared to the rest of the periods, because in the same year, restrictions against epidemics were established all over the world, and the relatively low concentration of harmful substances was seen as the reason why this period was not included in the research analysis.

Figure 4 shows the concentration of nitrogen dioxide pollution in the region's cities in 2019, 2021, and 2023. The average indicator of nitrogen dioxide pollution was 0.0408 mg/m^3 in 2019, 0.0408 mg/m^3 in 2021, and 0.0420 mg/m^3 in 2023. The highest concentration level is in the cities of Navoi (0.56 mg in 2023), Uchkuduk (0.53 mg); moderate pollution in Gazgan (0.51 mg), Nurota (0.51 mg), Zarafshan (0.51 mg); relatively low levels of pollution were in Yangirabot (0.47 mg), and in Kyziltepa (0.49 mg).

Figure 5 shows the trend of sulfur dioxide pollution in cities. According to it, in 2019 and 2021, the average level of SO_2 pollution in seven cities was 0.004 mg/m^3, and in 2023, we can see that it increased to 0.005 mg. There are several reasons for this: first, the increase in the volume of industrial production in cities; secondly, an increase in the number of vehicles in the city; thirdly, an increase in the number and density of the population from year to year. In 2023, the highest concentration of this substance was observed in the cities of Navoi (0.067 mg) and Zarafshan (0.068 mg), while it was average (0.062 mg) in Uchkuduq and Kyziltepa, and relatively low in the cities of Yangirabot, Gazgan, and Nurota—level of pollution.

The level of $PM_{2.5}$ fine particulate matter pollution is also increasing in cities (**Figure 6**). The concentration of $PM_{2.5}$ in the region is increasing due to the continuous use of resources in the context of global climate change. In 2019, the average level of pollution with dust particles in existing cities was 0.076 mg/m^3, and it increased to 0.085 mg in 2021 and 0.10 mg in 2023. also leads to an increase. During this period, a high level of pollution with dust particles was observed in the cities of Navoi and Uchkuduq, while it was average in Zarafshan and Kyziltepa, and slightly lower in the cities of Yangirabot, Nurota, and Gazgan. It should also be noted that the Navoi region and its cities are located in an arid climate; the climate here is hot in summer and bitterly cold in winter. This means that dust particles rise a lot, mainly in the summer months.



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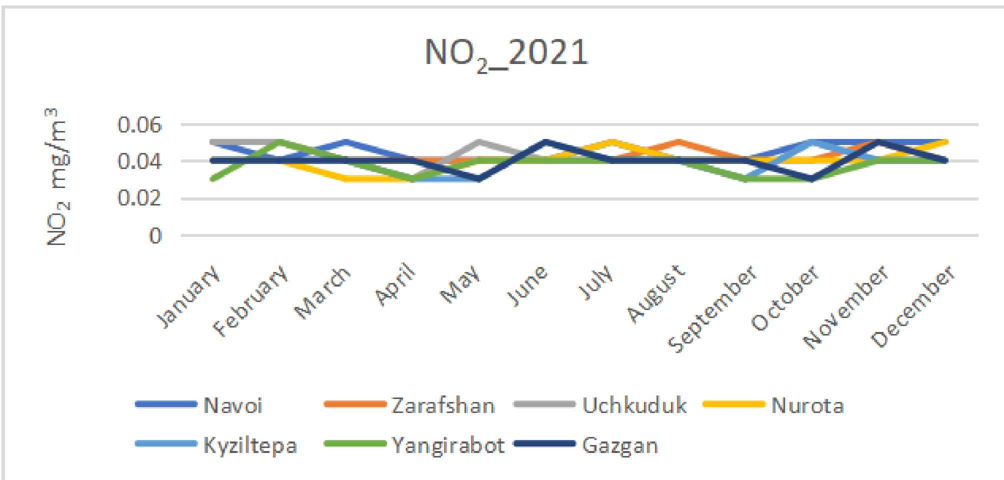

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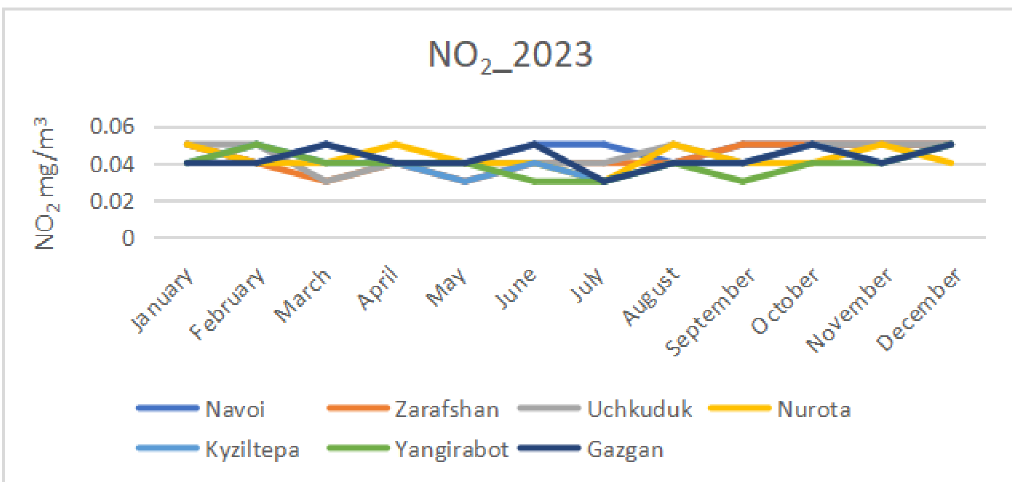

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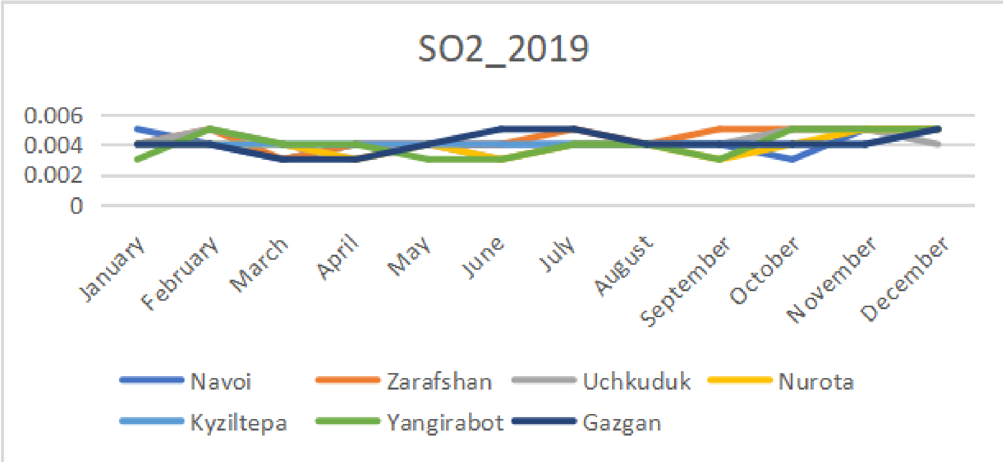
Figure 4. Concentration of NO_2 in area of cities.



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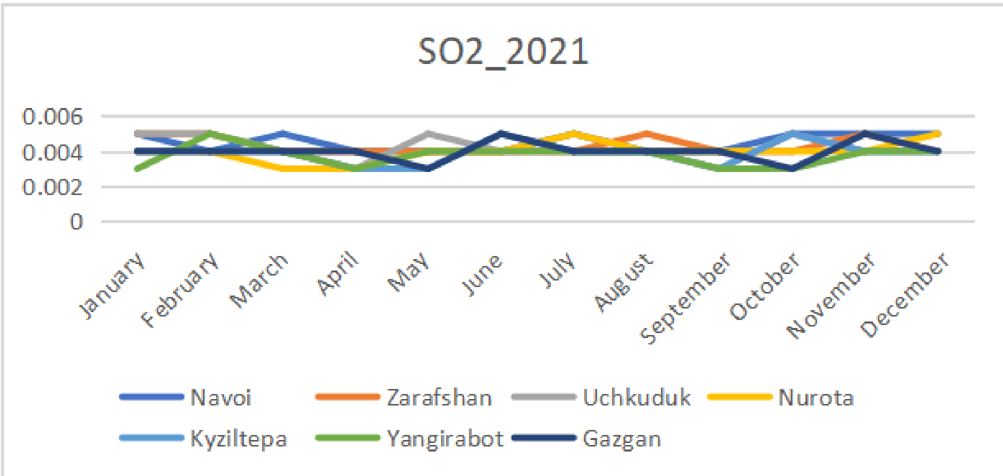

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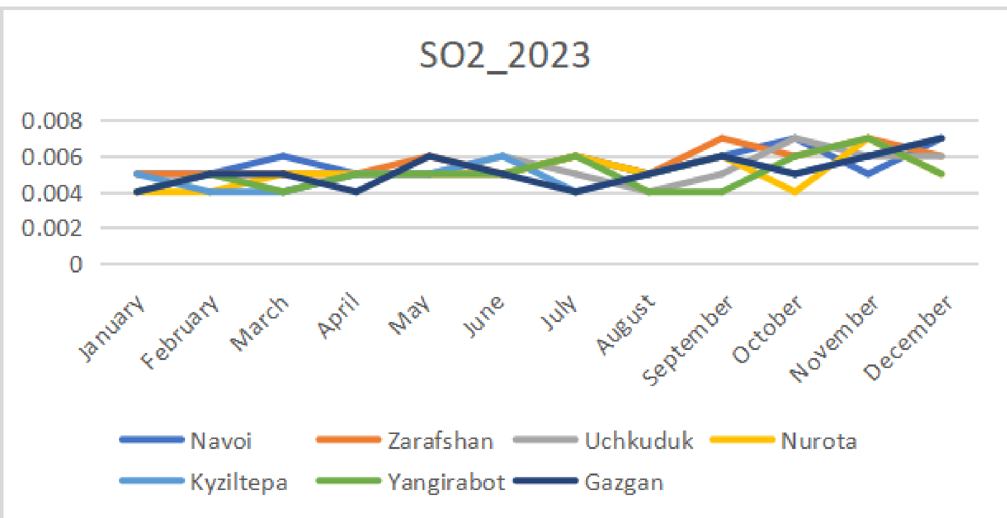

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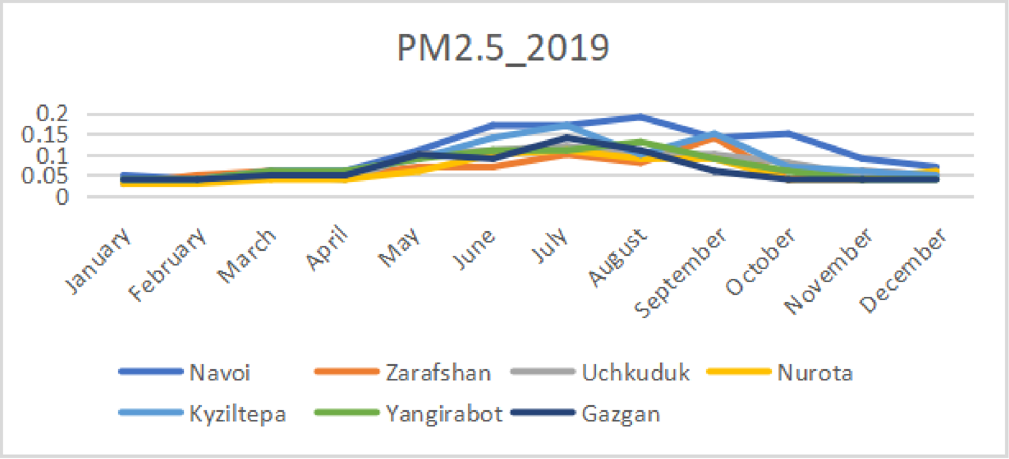
Figure 5. Concentration of SO_2 in area of cities.



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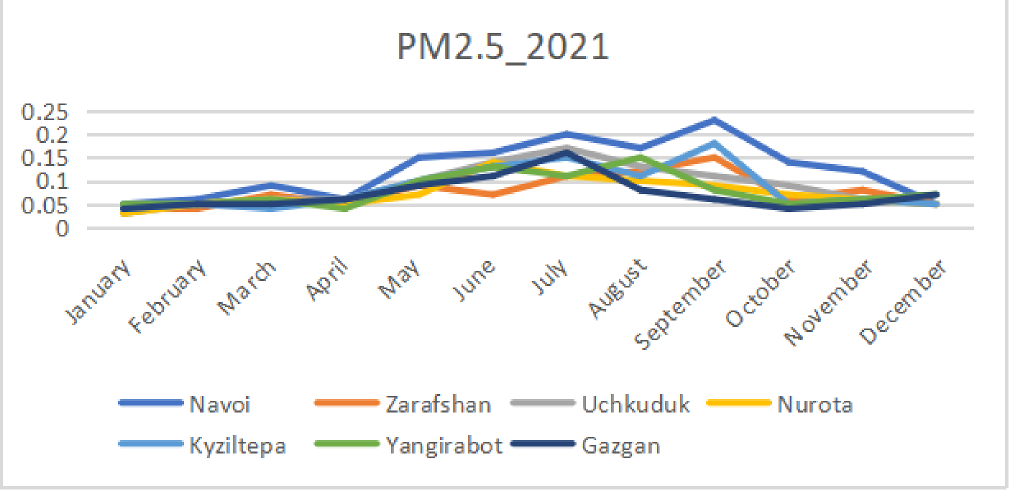

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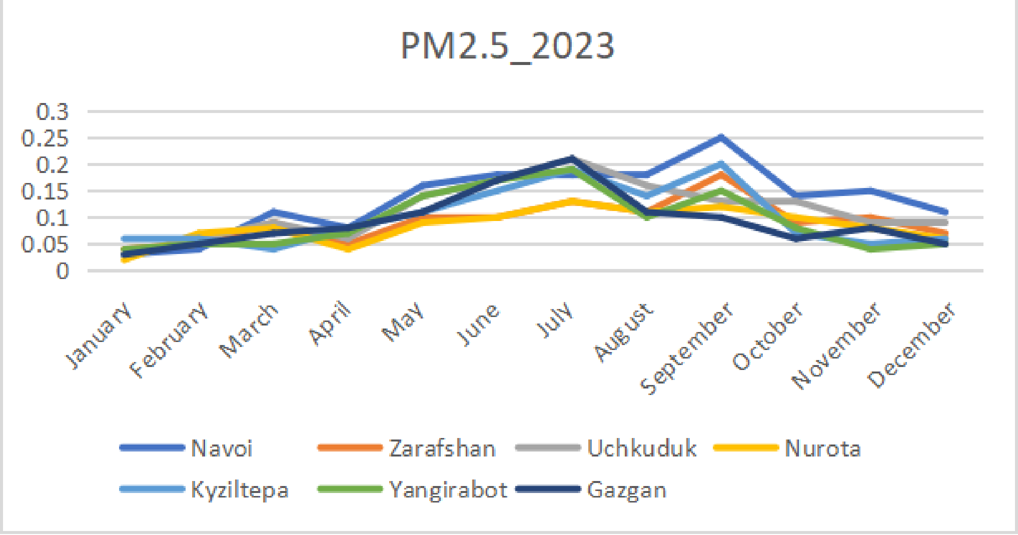

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Figure 6. Concentration of $PM_{2.5}$ in area of cities.

4. Effect of Anthropogenic Activities on Pollution Concentrations

The high level of anthropogenic influence causes an increase in pollution in urbanized areas, which was considered based on several selected factors. Factors affecting urban pollution include population density, the proportion of residential complexes in the urban area, the proportion of available green areas, the industrial area, the total number of registered vehicles, and their interaction with the most polluting sources—the relationship was analyzed.

4.1. Influence on Nitrogen Dioxide (NO_2) Concentration

4.1.1. Influence of Residential Land Use

Cities characterised by a higher proportion of residential land use—such as Navoi and Zarafshan—tend to show elevated concentrations of nitrogen dioxide (NO_2). This pattern is primarily due to increased energy consumption and transportation demands commonly linked to densely populated residential areas. In these zones, households rely heavily on energy for heating, cooking, and cooling, especially during seasonal extremes. Furthermore, the clustering of residential settlements often results in higher traffic volumes, including private vehicles and public transport, which significantly contribute to NO_2 emissions through fossil fuel combustion.

Figure 7 shows scatterplots illustrating the relationship between residential land use (%) and atmospheric NO_2 concentrations (ppm) across three different years: 2019, 2021, and 2023. Each subplot includes a fitted linear regression line with corresponding Pearson correlation coefficients (r) and p-values, providing insight into the strength and statistical significance of these associations. In 2019, the correlation between residential land use and NO_2 levels was weak and not statistically significant (r = 0.23, p = 0.618), suggesting a limited influence of residential land use on NO_2 concentrations during that year. By contrast, in 2021, the relationship became markedly stronger (r = 0.73, p = 0.061), approaching statistical significance. This suggests a possible increase in residential emissions or changes in atmospheric conditions that affect NO_2 build-up, possibly due to behavioural or environmental shifts following the COVID-19 lockdown. In 2023, the positive correlation remains (r = 0.63, p = 0.126), although it is slightly weaker than in 2021, and still not statistically significant.

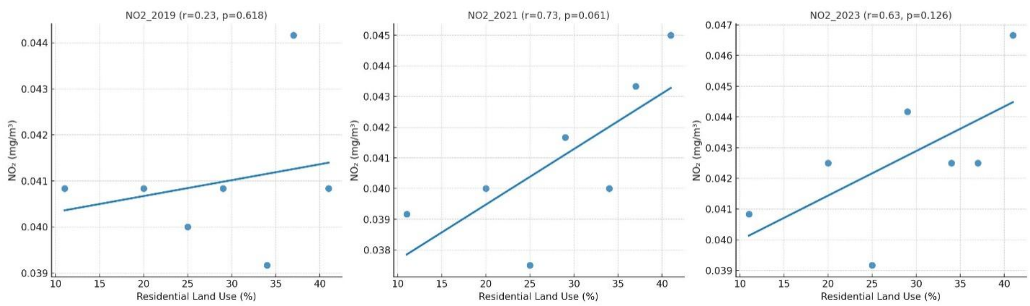

Figure 7. Influence of residential land use on NO_2.

Overall, the trend over the years suggests a growing association between residential land use and NO_2 concentrations, implying that residential areas may be increasingly contributing to urban NO_2 levels. However, the lack of statistical significance emphasises the need for larger sample sizes or the inclusion of confounding factors such as traffic density, meteorological variations, or land use policy changes to refine these interpretations.

4.1.2. Influence of Population Density

Figure 8 shows the correlation between population density (persons/km²) and nitrogen dioxide (NO_2) concentrations (ppm) for 2019, 2021, and 2023, with linear regression fits, Pearson's r, and p-values. A statistically non-significant, moderate positive correlation was seen in 2019 (r = 0.43, p = 0.338) between population density and NO_2. This relationship strengthened slightly in 2021 (r = 0.53, p = 0.219), potentially reflecting increased anthropogenic NO_2 from post-pandemic activities in denser areas. However, the correlation weakened in 2023 (r = 0.26, *p* = 0.578). This temporal trend suggests that the relationship varies over time, possibly influenced by urban planning, transportation policies, or emission control technologies. The consistently non-significant associations across all years indicate that population density alone is not a strong predictor of NO_2 levels without considering other factors like traffic, industry, and weather.

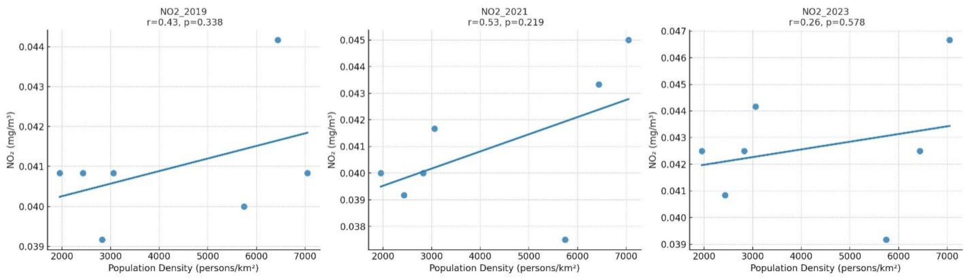

Figure 8. Influence of population density on NO_2.

4.1.3. Influence of Green Space

Figure 9 shows scatterplots analysing the relationship between green space percentage and NO_2 concentrations (ppm) in 2019, 2021, and 2023. Each plot includes a linear regression line, Pearson's r, and *p*-value. In 2019, a weak, statistically insignificant positive correlation was observed (r = 0.22, *p* = 0.642), suggesting a slight increase in NO_2 with more green space, possibly due to a small sample size or low green space coverage. Conversely, the correlation became negative in 2021 (r = −0.35, *p* = 0.447) and stronger in 2023 (r = −0.62, *p* = 0.337), though still statistically insignificant. This trend aligns with research indicating that green spaces reduce NO_2 via deposition, dispersion, and pollutant uptake.

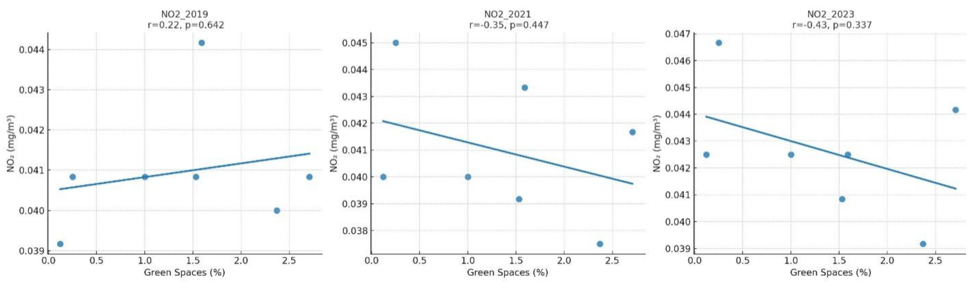

Figure 9. Influence of green space on NO_2.

Despite the lack of statistical significance, the consistent negative correlation in later years suggests a potential role for urban greenery in improving air quality, warranting further investigation with broader data and controls for confounding variables.

4.1.4. Influence of Industrial Land Use

Correlation analysis showed a statistically insignificant, weak to moderate relationship between industrial land use and nitrogen dioxide (NO_2) concentrations in the studied cities (**Figure 10**). In 2019, a negative correlation (r = −0.50, *p* = 0.253) was observed, indicating a non-significant inverse association. This relationship weakened further in 2021 (r = 0.11, *p* = 0.810). By 2023, the correlation had become slightly positive (r = 0.28, *p* = 0.540), but remained weak and statistically insignificant.

These findings suggest that industrial land use is not the primary determinant of NO_2 levels. Other factors, such as vehicular emissions, domestic heating, and meteorological conditions, likely have a greater influence. The small sample size and low variability in NO_2 levels may also limit the analysis's statistical power. Further research integrating land-use data with emission inventories, population density, and climatic factors is needed for a better understanding of urban air pollution.

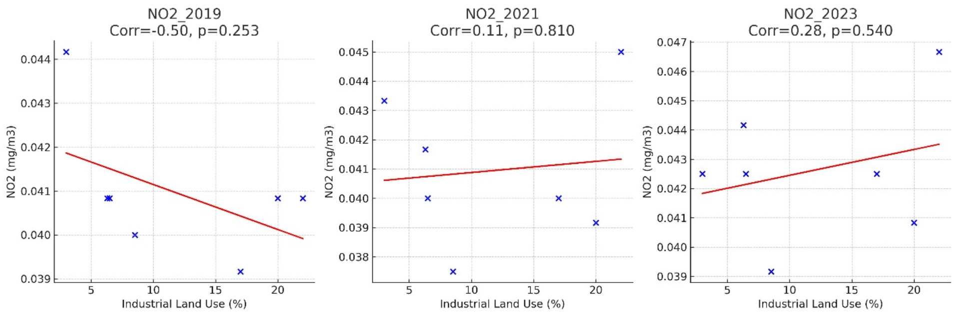

Figure 10. Influence of industrial landuse on NO_2.

4.1.5. Influence of Total Registered Transport Vehicles

Nitrogen dioxide (NO_2) levels in urban areas are directly linked to the number of registered vehicles. Navoi, a city with a high volume of motor vehicles, consistently shows high levels of NO_2 pollution. This relationship highlights the significant impact of vehicular emissions on urban air quality deterioration. Combustion engines, especially those powered by petrol and diesel, produce nitrogen oxides (NO_x) as a byproduct of fuel burning, with NO_2 being one of the main pollutants released into the atmosphere.

The data suggest that as vehicle density rises, so does the ambient concentration of NO_2, emphasising transportation's role as a key source of nitrogen-based air pollution. This trend is especially evident in urban centres where traffic congestion, frequent idling, and limited use of emission control technologies worsen pollutant levels. These findings underscore the urgent need for transportation-related policy measures aimed at reducing vehicular emissions. Encouraging public transportation, switching to electric or hybrid vehicles, and enforcing stricter vehicle emission standards are essential strategies for reducing NO_2 pollution. Tackling emissions from the transportation sector is crucial not only for environmental sustainability but also for protecting public health in rapidly urbanising regions.

4.2. Influence of Different Parameters on Sulfur Dioxide Pollutant Concentration

4.2.1. Influence of Population Density

Densely populated urban areas tend to show higher levels of sulfur dioxide (SO_2) emissions, mainly due to increased energy use from both residential and commercial activities. In cities like Navoi and Zarafshan, this pattern is especially noticeable, with significantly higher SO_2 concentrations compared to less populated regions. The high population density in these cities creates greater demand for electricity, heating, and other energy-intensive services, often powered by fossil fuels—particularly coal and oil—known for releasing substantial amounts of sulfur compounds into the atmosphere.

This positive link between population density and SO_2 levels underscores the cumulative environmental effect of urban expansion and greater energy consumption. In many post-Soviet urban areas, outdated infrastructure, inefficient heating systems, and limited access to clean energy sources further increase sulfur emissions. The concentration of emissions in densely populated zones raises serious public health issues, as prolonged exposure to SO_2 is linked to respiratory illnesses and other health problems. To tackle these issues, it is crucial to promote cleaner energy technologies, enhance building energy efficiency, and modernise urban infrastructure. Strategic planning and policy reforms targeting high-emission urban areas can play a vital role in reducing SO_2 pollution and improving overall urban air quality.

4.2.2. Influence of Residential Land Use

Higher residential density is generally linked to increased levels of sulfur dioxide (SO_2), mainly due to the higher demand for domestic heating and the prevalence of localised combustion activities in densely populated areas. In urban settings where residential buildings are clustered, energy consumption often rises significantly, especially during colder months when heating needs grow. This increased energy demand frequently leads to the combustion of sulfur-containing fuels, such as coal, diesel, or low-grade heating oils, which are known to release SO_2 into the atmosphere.

However, while a positive correlation exists between residential density and SO_2 levels, this relationship appears to be weaker than that observed for nitrogen dioxide (NO_2). This indicates that other factors—such as industrial emissions, energy infrastructure, and weather conditions—may also significantly influence urban SO_2 pollution patterns. For instance, the proximity of industrial zones or power stations, variations in fuel types, and ventilation effects can all affect local SO_2 levels independently of residential density. These findings highlight the complexity of urban air pollution dynamics and emphasise the importance of multifactorial evaluations in environmental planning. Policies aimed at reducing SO_2 emissions should therefore consider not only population density but also broader systemic factors, including energy sources, heating technologies, and regional atmospheric conditions.

4.2.3. Influence of Green Space

In Navoi cities, green space is also effective at reducing sulfur dioxide (SO_2) pollution, similar to its impact on nitrogen dioxide (NO_2). There is a consistent inverse relationship between green space coverage and SO_2 concentrations among urban centres such as Nurota, Yangirabot, and Navoi city. A more extensive green zone and natural vegetation characterise Nurota and Yangirabot, which tend to record significantly lower levels of SO_2. Compared to Navoi city, which has a relatively limited green space due to higher urban density and industrial infrastructure, SO_2 concentrations are markedly higher.

There are multiple mechanisms by which urban vegetation contributes to air purification, including stomatal absorption of sulfur compounds, dry deposition, and chemical transformation at the leaf surface. In addition to filtering atmospheric pollutants, greenery improves air quality by acting as a natural air cleaner. Urban planning should prioritise the development of green infrastructure in the Navoi region. Green belts, tree cover expansion, and preserving natural landscapes can reduce SO_2 pollution in an efficient, low-cost manner. Cities require such interventions to foster healthier living environments and become more resilient to environmental stressors.

4.2.4. Influence of Industrial Land Use

Sulfur dioxide (SO_2) emissions in urban areas are heavily affected by the scale and intensity of industrial activity, especially processes involving the combustion of fossil fuels. This trend is particularly notable in the Navoi region of Uzbekistan, where cities like Navoi and Uchkuduk—both marked by large industrial zones—record some of the highest SO_2 levels in the area. These urban centres host various energy-intensive industries, including mining, metallurgical plants, and chemical processing facilities, all of which contribute significant amounts of sulfur-based emissions to the atmosphere.

The burning of coal, petroleum products, and other fuels containing sulfur during industrial operations is a chief source of SO_2. In Navoi city, large enterprises such as the Navoi Mining and Metallurgical Combine (NMMC) heighten sulfur pollution, adding to environmental pressures. Likewise, Uchkuduk, connected to uranium extraction and processing, also faces elevated SO_2 levels due to its dependence on fossil fuels. These findings highlight the strong link between industrial land use and SO_2 pollution in the Navoi region. Measures to reduce emissions should include stricter controls, adoption of cleaner technologies, and switching to low-sulfur fuels to lessen environmental and public health impacts caused by industrial sulfur emissions.

4.2.5. Influence of Total Registered Transport Vehicles

In the Navoi region, a moderate positive correlation exists between vehicular density and ambient sulfur dioxide (SO_2) concentrations. Although transportation is not the main source of SO_2 emissions—unlike industrial activities—it still contributes, especially in urban areas with many diesel-powered vehicles. Cities such as Navoi, which act as administrative and industrial centres, show both high vehicle registration figures and moderately elevated SO_2 levels, indicating a link between transportation patterns and sulfur pollution.

Diesel engines, often used in freight trucks, buses, and older vehicles, emit sulfur compounds, particularly when powered by high-sulfur diesel. In urban settings with frequent traffic congestion and idling—such as central Navoi—the combined emissions from these engines become more significant. Conversely, smaller cities like Yangirabot and Karmana, with lower vehicle densities and less heavy-duty traffic, typically report lower SO_2 levels. Although vehicular emissions are less impactful than industrial or residential combustion on SO_2 pollution, they should not be ignored. Implementing stricter vehicle emission standards, encouraging cleaner fuel options, and promoting public transportation can collectively reduce transportation-related sulfur emissions in the growing urban centres of the Navoi region.

4.3. Influence of Different Parameters on $PM_{2.5}$ Pollutant Concentration

4.3.1. Influence of Population Density

Particulate matter with a diameter of less than 2.5 micrometres ($PM_{2.5}$) is a vital indicator of urban air quality, and its levels tend to rise with increasing population density. In the Navoi region, this pattern is especially noticeable in cities such as Navoi and Uchkuduk, where higher population densities are linked to more human activities. These include expanded residential and commercial building, increased vehicle traffic, and higher demand for domestic heating—each contributing to $PM_{2.5}$ emissions.

Construction work produces large amounts of fine particulate matter through the use of heavy machinery, excavation, and dust from building materials. At the same time, the increase in vehicle numbers, especially those run on diesel, releases significant $PM_{2.5}$ through exhaust emissions. Furthermore, during colder months, densely populated areas depend heavily on domestic heating systems, often involving the burning of solid fuels, which is another major source of fine particles. In both Navoi and Uchkuduk, these combined factors lead to consistently higher $PM_{2.5}$ levels compared to less populated cities in the region. These results highlight the importance of integrated strategies for air quality management, such as improving regulation of construction practices, encouraging clean heating technologies, and expanding public transport to reduce particulate pollution in high-density urban areas.

4.3.2. Influence of Residential Land Use

A clear positive relationship exists between residential land use and ambient $PM_{2.5}$ levels in the Navoi region, especially in urban areas like Navoi city and Zarafshan. As residential zones grow, so do various local sources of fine particulate matter, such as domestic cooking, heating, road dust resuspension, and small-scale combustion emissions. While each source may be minor individually, their combined effect leads to higher $PM_{2.5}$ concentrations in densely populated residential areas.

The influence of residential land use on $PM_{2.5}$ pollution is also intensified by the dry and windy climate common in Navoi. Limited rainfall and vegetation leave surfaces dry and dusty, especially along unpaved or poorly maintained roads. Wind frequently lifts this dust into the air, increasing particulate matter levels in neighbourhoods. Additionally, in colder months, reliance on solid fuels and gas for heating in suburban and peripheral areas further boosts $PM_{2.5}$ emissions. This complex link between land use, climate, and pollution highlights the importance of urban planning policies that incorporate dust control, upgraded infrastructure, and cleaner energy use in homes to reduce particulate pollution as urban areas expand in the Navoi region.

4.3.3. Influence of Green Space

A clear inverse relationship exists between green space availability and $PM_{2.5}$ concentrations in urban environments across the Navoi region, especially in cities such as Nurota, Khatirchi, and Yangirabot, where vegetation coverage is relatively higher. These cities consistently report lower levels of fine particulate matter, emphasising the vital role that green infrastructure plays in managing urban air quality.

Vegetation performs multiple ecological functions that help reduce $PM_{2.5}$ pollution. Trees, shrubs, and grasslands act as natural filters, capturing airborne particulates on leaf surfaces and facilitating their eventual deposition onto the ground. In regions like Navoi, where arid conditions and frequent wind events worsen the suspension of dust and other particulate matter, green spaces serve as a natural buffer that mitigates pollutant dispersion.

Furthermore, urban greenery contributes to microclimatic regulation by stabilising surface temperatures and humidity levels, which can indirectly lessen the resuspension of dust from roads and construction sites. Cities such as Navoi and Zarafshan, which have relatively limited vegetation cover, display higher $PM_{2.5}$ levels, highlighting the protective function of green spaces. These findings support the strategic expansion and upkeep of urban green belts and parks as a vital aspect of sustainable air quality planning within the Navoi region's urban centres.

4.3.4. Influence of Industrial Land Use

Cities such as Uchkuduk and Navoi city are prominent examples of cities in the Navoi region with elevated $PM_{2.5}$ concentrations due to industrial activity. In these urban centres, there are extensive mining, metallurgy, and mineral processing industries, which are recognised sources of fine particulate emissions from fossil fuel combustion, mechanical operations, and material handling.

A major industrial activity in Uchkuduk is the mining and enrichment of uranium ore, which generates airborne particulates from excavation and transportation. In Navoi city, one of the largest industrial complexes in Uzbekistan—the Navoi Mining and Metallurgical Combine—$PM_{2.5}$ levels are persistently high. Industrial emissions come from a variety of sources, including direct combustion of fuels, secondary sources such as heavy vehicle traffic, dust from construction zones, and waste storage facilities within industrial zones.

By locating such facilities near residential areas, harmful pollutants are further amplified. Considering this spatial overlap, industrial plants should implement modern emission control technologies and conduct stringent air quality monitoring. Strengthening environmental regulations and promoting cleaner industrial practices are essential for reducing $PM_{2.5}$ pollution and protecting public health in the Navoi region's industrial cities.

4.3.5. Influence of Total Registered Transport Vehicles

There is a high density of motor vehicles in urban centres such as Navoi city and Zarafshan, which contributes to $PM_{2.5}$ pollution in the Navoi region. Transport emissions are not limited to exhaust gases but also include non-exhaust sources such as tyre wear, brake dust, abrasion of road surfaces, and fine dust particles that are resuspended from paved and unpaved roads. In Navoi city, which functions as a major industrial and administrative hub, daily traffic volumes are significant, comprising both passenger and freight vehicles. This heavy vehicular flow results in continuous particulate emissions throughout the day. Additionally, the frequent use of older diesel-powered vehicles, common in regional transportation fleets, worsens $PM_{2.5}$ pollution due to incomplete combustion and higher particulate output. Similarly, Zarafshan, which supports mining and related logistical activities, experiences increased vehicular activity from heavy-duty trucks and service vehicles, further raising ambient $PM_{2.5}$ levels. The cumulative impact of mobile sources on air quality in these urban areas underscores the urgent need for sustainable transport policies, including promoting public transportation, low-emission vehicles, and regular street cleaning practices to minimise resuspended dust in these dry, wind-prone regions.

5. Conclusion

We assess the spatial variability and determinants of air pollution in the Navoi region of Uzbekistan, specifically nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and fine particulate matter ($PM_{2.5}$). Anthropogenic activities and environmental factors interact to influence pollutant concentrations in complex ways, according to the findings.

Key indicators, including population density, residential land use, industrial activity, and transportation density, are found to have a statistically significant and mostly positive correlation with elevated levels of NO_2, SO_2, and $PM_{2.5}$. Urban centres like Navoi, Zarafshan, and Uchkuduk consistently recorded higher pollution levels due to dense settlement patterns, extensive industrial operations, and high vehicular traffic. Yangirabot and Nurota, on the other hand, have a higher proportion of green space and less intensive urban development, which indicates that vegetation can mitigate urban air pollution.

In response to growing environmental and public health concerns in the region, integrated urban planning, stricter emission controls, and an expansion of urban green infrastructure are urgently needed. In the Navoi region, policymakers should prioritise the adoption of clean energy, the preservation of green spaces, and the implementation of sustainable transportation systems.

Author Contributions

Conceptualization, N.L. and N.K.; methodology, B.T.; software, S.A. and D.E.; validation, S.F. and D.R.; formal analysis, M.N. and Z.M.; investigation, M.H.; resources, M.H. and N.K.; data curation, B.T.; writing—original draft preparation, N.L., N.K., and S.A.; writing—review and editing, N.L.; visualization, D.E. and M.N.; supervision,N.K., B.T., and M.H.; project administration, N.M.; funding acquisition, N.L. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare that there is no conflict of interest.

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