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Integrated Hazard Analysis of Spatial Distribution of Air Pollution Indices in Tehran County

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Original Article

Abstract

INTRODUCTION: Urban air pollution, especially in densely populated metropolises such as Tehran, has become one of the most serious environmental and health challenges. Nitrogen dioxide (NO_2), as one of the most important pollutants resulting from human activities, accumulates persistently in the surface layers of the atmosphere, especially in the cold seasons and under temperature inversion conditions. This study conducts an integrated hazard analysis of the spatiotemporal distribution of NO_2 in Tehran County over a seven-year period (2018–2024), with a focus on the interplay between anthropogenic and natural factors in shaping this hazard.

METHODS: In this descriptive-analytical study with an integrated approach, daily NO2 concentration data were extracted from Sentinel-5P satellite images (TROPOMI sensor) during the winter seasons from 2018 to 2024 in Tehran. Using spatial extraction tools in the GIS environment, data were processed, seasonal averages were calculated, and raster-to-vector conversion was performed, and spatiotemporal distribution patterns of NO2 were plotted and analyzed.

FINDINGS: The findings showed that the distribution pattern of NO2 has undergone significant spatial and temporal changes over the seven years. In 2018 and 2019, the highest concentrations were observed in central Tehran and the northeastern districts. A marked decline occurred in 2020 and 2021, coinciding with mobility restrictions imposed during the COVID-19 pandemic. However, from 2022 onward, NO_2 levels began to rise again, with a notable increase in southern and eastern areas by 2024. These shifts reflect a transition in pollution hotspots—from the city center toward peripheral zones—followed by a partial return to a more centralized pattern, indicative of extensive urban expansion and intensified human activities in suburban areas.

CONCLUSION: According to the research results, NO_2 pollution in Tehran constitutes a “compound hazard,” resulting from the complex interaction of anthropogenic drivers (e.g., traffic, industry, and urban development) and natural conditions (e.g., temperature inversions and topography). The observed changes in NO_2 spatial patterns mirror transformations in urban morphology, land use, and environmental management policies.

Keywords: Nitrogen dioxide; Air pollution; Tehran; Sentinel 5P.

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Introduction

In the contemporary era, large cities—serving as primary hubs of population, industry, and transportation—have witnessed a dramatic increase in human activity. While these developments have driven progress, they have also intensified environmental hazards. Among these challenges, urban air pollution has emerged as one of the most critical environmental and public health crises, particularly in densely populated metropolises such as Tehran. With an urban agglomeration exceeding 15 million inhabitants, over 3.5 million registered vehicles, and a high concentration of industrial facilities, Tehran is widely recognized as one of the world’s most polluted cities (1). This situation has not only

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incurred significant economic and environmental costs, but has also severely affected public health, leading to increased rates of respiratory and cardiovascular diseases.

Nitrogen dioxide (NO_2) is one of the most important air pollutants, produced primarily through the combustion of fossil fuels in motor vehicles, industrial processes, and heating systems. Beyond acting as a key precursor in the formation of tropospheric ozone and particulate matter, it directly penetrates the respiratory system and exacerbates diseases such as asthma, bronchitis, and chronic cough (4). In addition, numerous studies have linked long-term exposure to high concentrations to histopathological changes in the kidneys, liver, and heart, decreased immune system resistance, and an increased risk of premature mortality (8).

During cold seasons, this hazard is further amplified by stable atmospheric conditions—particularly temperature inversions. Under such conditions, warmer air layers overlay cooler surface air, inhibiting the vertical dispersion of pollutants. Although this phenomenon has a natural origin, its interaction with anthropogenic factors—including increased heating fuel consumption, heavy traffic congestion, and unbalanced urban expansion—leads to persistent and widespread accumulation of NO_2 in the lower atmosphere. This interplay between natural elements (e.g., temperature inversions, topography, and a semi-arid climate) and urban drivers (e.g., population density, transportation networks, and industrial activity) renders Tehran a paradigmatic example of a "compound hazard"—a risk that, while anthropogenic in origin, is significantly modulated in intensity and duration by natural conditions (2).

Air pollution remains a major challenge in large industrial cities, profoundly impacting human life. Tehran, in particular, faces a severe air pollution crisis due to rapid population growth, a sharp increase in vehicle numbers, and the dense concentration of industrial facilities. Research indicates that approximately one in every three days in Tehran is affected by air pollution (2).

Daily air quality in cities is commonly reported using the Air Quality Index (AQI), which integrates measurements of five key pollutants: particulate matter (PM), carbon monoxide (CO), sulfur dioxide (SO_2), tropospheric ozone (O_3), and NO_2. The AQI is scaled from 0 to 500 (6). According to the World Health Organization (WHO), AQI levels in most major global cities consistently exceed recommended thresholds, prompting urban authorities to implement air pollution mitigation strategies. Unfortunately, many of these management plans have proven short-term and episodic, largely due to insufficient integration of spatiotemporal forecasting, thereby limiting their effectiveness in achieving sustained air quality improvements (7).

The excessive concentration of industries and factories within Tehran's geographical boundaries—combined with the region's unique topography, geography, and climate—has placed Tehran among the world's seven most polluted cities (2).

Numerous studies have demonstrated a strong association between air pollution and respiratory as well as cardiovascular diseases. Consequently, assessing air pollution levels and communicating their health implications can motivate both the public and policymakers to reduce pollution-generating activities. In recent years, growing public and policy interest has emerged regarding air quality assessment and its indexing. Clean air is a fundamental requirement for human health—a concern that has preoccupied the WHO for over five decades (8).

Fine particulate matter, which reduces visibility and damages the lungs and heart, is one of the pollutants that has a major impact on urban populations. The main sources of NO_2 emissions include vehicle exhaust, fossil fuel combustion, power plants, industrial boilers, waste incinerators, residential heating systems, as well as natural phenomena such as lightning and volcanic activity (3). Furthermore, NO_2 reacts with ammonia, moisture, and other compounds to form fine secondary particles that penetrate deep into the lungs, causing or worsening respiratory diseases such as asthma and bronchitis and increasing the frequency of coughing. Other health effects include tissue changes in the kidneys, liver, and heart; weight loss; and increased susceptibility to bacterial and viral infections (4).

Abdolazimi et al. (2023) conducted a study titled "Monitoring nitrogen dioxide concentrations during the COVID-19 pandemic using Sentinel-5 satellite data: a case study of Shiraz metropolitan area" which examined the spatiotemporal distribution of NO_2 using Sentinel-5P satellite data and analyzed its relationship with environmental variables over a 24-month period in Shiraz. Their findings indicated that the highest monthly average NO_2 concentrations occurred during autumn in 2019 and 2020, with district 2 of Shiraz identified as the most polluted area across both years. These results can inform urban livability strategies and crisis management planning(3).

In another study, Shami et al. (2020) assessed the spatiotemporal distribution of atmospheric pollutants (CO, NO_2, and O_3) across Iran using Sentinel-5P satellite data for Farvardin (March–April) 2020 and the corresponding period in 2019—coinciding with the onset of the coronavirus pandemic. Spatial analysis identified Tehran, Mashhad, Isfahan, and Tabriz as the most polluted cities. To validate satellite-derived results, ground-level measurements from Tehran's air quality monitoring stations—the most populous city in Iran—were utilized. Time-series analysis of station data revealed a consistent decline in CO, NO_2, and O_3 concentrations in Farvardin 2020 compared to the same period in 2019 (11).

Shahmohammadi et al. (2011), in a study titled "Synoptic analysis of Tehran's air pollution episodes" concluded that Tehran has become one of the world's most polluted cities, emitting over one million tons of air pollutants annually. Key contributing factors include geographical elements such as topography, wind patterns, and pressure systems—particularly during cold seasons. High-pressure systems (anticyclones) over Tehran's atmosphere suppress vertical air movement, trapping pollutants near the surface. Using daily pollution data from monitoring stations between 2003 and 2005, the study identified 31 days with unhealthy air quality. The period of 4–7 December 2005 marked by severe and persistent pollution, was selected for synoptic analysis, confirming atmospheric pressure as a critical driver of pollution intensity (14).

Lelieveld et al. (2018) investigated age-specific health risks from air pollution and modeled data on child mortality in low- and middle-income countries. Their findings attributed 0.695 million premature deaths and preterm births globally to air pollution, identifying it as the fifth leading cause of death in India in 2010(9).

Xiao et al. (2016) examined surface ozone and nitrogen oxides at urban, suburban, and rural sites in Ningbo, China. Results showed that peak daily surface ozone levels occurred in the afternoon, while nitrogen oxide concentrations peaked in the morning. Surface ozone exhibited a positive correlation with temperature but a negative correlation with relative humidity and ambient nitrogen oxides (10).

Previous studies employing satellite data have explored the spatiotemporal dynamics of atmospheric pollutants. For instance, Shami et al. (2020) used Sentinel-5P data to document a temporary decline in NO_2 concentrations across Iran's major cities during the COVID-19 lockdown, underscoring the direct influence of human activity on this pollutant. Similarly, Abdolazimi et al. (2023) in Shiraz identified a distinct seasonal pattern in NO_2, with peak concentrations occurring in autumn. In another context, Xiao et al. (2016) in Ningbo, China, demonstrated that NO_2 levels peaked during early morning hours—a pattern aligned with traffic rhythms and meteorological conditions. (3,10&11)

Tehran's high population density, expanding ground transportation network, and industrial growth have created unique conditions conducive to the accumulation of NO_2. Given the rising incidence of respiratory and cardiovascular illnesses in recent years, understanding the dispersion patterns of NO_2—particularly during cold seasons when meteorological conditions suppress pollutant dispersion—is critically important.

The specific objectives of this study are: a) to investigate and analyze the compound risk associated with NO_2 concentrations in different parts of Tehran metropolis and its suburbs during cold seasons and b) to prepare spatial distribution maps of NO_2 to support environmental and public health planning by identifying urban air quality conditions.

Accordingly, the present study aims to conduct an integrated hazard analysis of the spatial distribution of NO_2 during cold seasons across the Tehran metropolitan area and its suburban zones. This study seeks to answer the question of what are the spatiotemporal patterns of NO_2 distribution across Tehran and its peri-urban areas during cold seasons, and which natural and urban factors contribute to the formation of this compound hazard?

The study area

Tehran is located between 51°09′ and 51°60′ east longitude and 35°37′ and 35°83′ north latitude. The city lies on the central plateau, on the southern slopes of the Alborz Mountains, with a general slope direction from north to south, situated on a relatively flat plain. It covers an area of approximately 730 square kilometers and has a population of about 13.2 million. Tehran features a semi-arid climate, primarily influenced by the central Alborz mountain ranges. The average annual precipitation in this region is 333 millimeters(1). According to the 2016 National Population and Housing Census (1395 in the Iranian calendar), Tehran County had a population of 8,737,000. Including the populations of other counties within Tehran province (4,530,000) and Alborz province (2,712,000), the total population reaches at least 15,979,000. Given Tehran's area of 730 square kilometers, this results in a population density of approximately 21,889 persons per square kilometer. Despite this extremely high population density, Tehran has only 540 kilometers of highways and arterial roads (covering an area of 22,662,000 square meters), around 3,000 traffic routes, and 231 kilometers of metro lines. With approximately 18 million trips and 23.1 million passenger movements occurring daily, public transportation (buses and metro) accounts for only 36.4% of total trips, while roughly 3,500,000 vehicles operate within the city (5).

Given the close interrelationship among human activities, urban development, and air pollution, the scope of this study is confined exclusively to Tehran County. This selection is justified by the fact that Tehran not only serves as the country's primary metropolitan and demographic center but also functions as the core of the regional urban system due to its rapid population growth, high concentration of industrial and service-sector activities, extensive transportation network expansion, and pivotal role in traffic patterns and pollutant emissions. Consequently, examining the spatiotemporal variations of NO_2 concentrations within Tehran County enables a more precise analysis of air pollution trends and their linkages with urban form, demographic dynamics, and transportation-related factors.

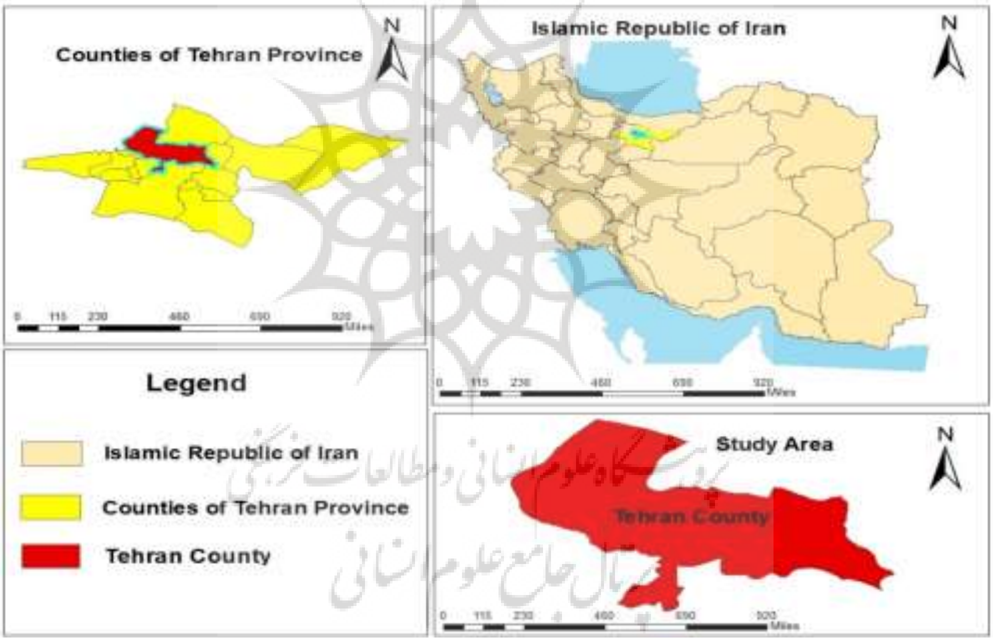

Figure 1. Geographic location of the study area (Source: authors, 2025)

Methods

This research employs a mixed-methods approach and is of a descriptive–analytical nature. It aims to investigate the spatiotemporal variations in NO_2 concentrations across Tehran County during the winter season over a seven-year period (2018–2024). The primary objective of the study is to analyze the long-term trends of this key air pollutant as an indicator of urban air quality and to assess the influence of anthropogenic activities and environmental conditions over the past decade.

The data used in this study consist of surface-level NO_2 concentrations derived from Sentinel-5P satellite imagery acquired by the TROPOMI sensor. These data are publicly available through the Copernicus Open Access Hub platform. The temporal scope of the study encompasses the winter season (from December 22 to March 20) for each year within the specified period. The spatial extent is limited to Tehran County, which serves as the capital of Tehran province and is among the most populous metropolitan areas globally.

Satellite images were provided in raster format as daily GeoTIFF files. Following acquisition, the data were processed within a Geographic Information System (GIS) environment. To precisely delineate the study area, a vector layer representing the official administrative boundaries of Tehran County was employed. This boundary layer—compiled from data provided by Iran's National Cartographic Center and Tehran Municipality—was used as a spatial mask to ensure that only pixels falling within Tehran County were included in the analyses.

Subsequently, daily NO_2 values for each year were aggregated into monthly averages and then further averaged across the winter months to obtain seasonal means. To conduct statistical analyses at the county level, the zonal statistics operation was applied, enabling the calculation of descriptive statistics—including mean, maximum, minimum, and standard deviation of NO_2 concentrations. This process facilitated the examination of temporal trends and the identification of intra-urban spatial patterns.

To visualize the spatial distribution of NO_2 concentrations, seasonal average raster data were converted into vector layers. In this conversion, adjacent pixels with similar values were grouped into homogeneous polygons, with the mean NO_2 concentration assigned as an attribute to each polygon. Finally, seasonal average NO_2 distribution maps were generated for each year of the study period. Using color classification techniques, these maps were analyzed to interpret both spatial and temporal variations in pollutant concentrations across Tehran County.

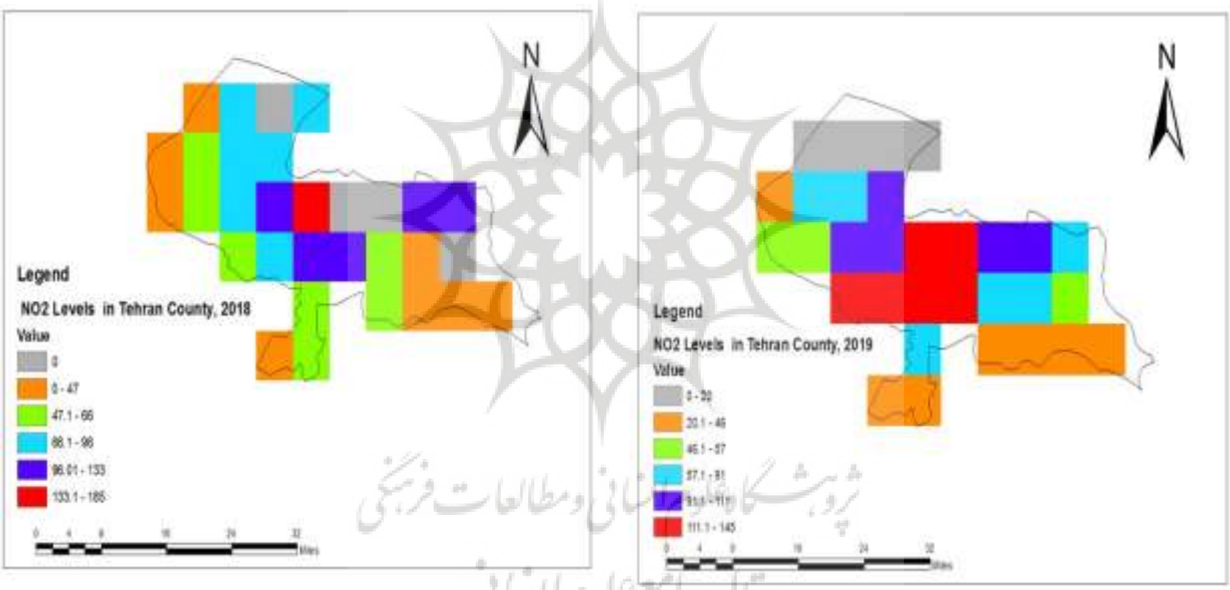

Figure 2. Spatial distribution maps of seasonal average NO_2 concentrations in 2018 and 2019 (Source: authors, 1404).

Findings

This section presents the results obtained from the analysis of Sentinel-5P satellite data, aimed at identifying the spatial and temporal patterns of NO_2 concentrations during the winter season over a seven-year period (2018–2024) in Tehran County. Using raster image processing techniques—including spatial clipping, seasonal averaging, and conversion to vector layers—the NO_2 data were analyzed specifically for Tehran County. The findings are presented as maps illustrating the seasonal average spatial distribution of NO_2 for each year, enabling the identification of distinct spatial patterns and temporal variations in pollution levels.

Figure 2 illustrates the spatial distribution maps of seasonal average NO_2 concentrations for the years 2018 and 2019 in Tehran County. A detailed analysis of these maps reveals a significant transformation in the pollution pattern between these two years.

In 2018, NO_2 concentrations ranged from 0 to 185 µg/m^3 and were classified into six color-coded categories: gray (0–47), light blue (48–66), green (67–91), orange (92–111), purple (112–

133), and red (134–185). The highest concentrations—indicated by red hues (134–185 µg/m³)—were predominantly observed in the central districts of Tehran County. This reflects the intense concentration of pollution sources such as dense transportation networks, industrial zones, and commercial hubs in the urban core. Moderate to high pollution levels (purple: 112–133 µg/m³; orange: 92–111 µg/m³) also appeared in parts of the northern and eastern regions. In contrast, the southern and western areas of the county were represented by green (67–91 µg/m³), light blue (48–66 µg/m³), and even gray (0–47 µg/m³), indicating significantly lower NO_2 concentrations. Overall, the spatial pattern in 2018 exhibited a centralized, core-periphery structure, with pollution levels decreasing from the city center toward the southern and western peripheries.

By 2019, the maximum NO_2 concentration range had decreased to 0–145 µg/m³, with the following color classification: gray (0–20), light blue (20.1–46), green (47–66), orange (67–91), purple (92–111), and red (112–145). Despite this overall reduction in concentration range, the spatial pattern of pollution underwent a profound shift. The central area of Tehran County no longer exhibited the highest NO_2 levels; instead, it was depicted in purple and orange, corresponding to concentrations of 92–111 µg/m³ and 67–91 µg/m³, respectively. This relative decline in the city center may be attributed to traffic control policies, temporary industrial restrictions, or changes in commuting patterns.

Conversely, a new hotspot emerged in the northwestern part of the county—encompassing sections of the northern and western districts—which was identified as the area with the highest NO_2 concentrations in 2019. Marked in red, this zone recorded values between 112 and 145 µg/m³. Although this region already experienced elevated pollution levels in 2018 (112–185 µg/m³), it exhibited a notable spatial expansion toward the west and north in 2019, suggesting a shift or intensification of emission sources within the county.

Simultaneously, the southern and eastern regions also experienced a marked increase in NO_2 concentrations. Areas that were previously shown in green or light blue (indicating low pollution) in 2018 had transitioned to purple and even red in 2019, reflecting a substantial rise in pollution levels. These changes are likely driven by population growth, urban expansion, increased vehicular traffic, and intensified industrial activities across broader parts of the county.

In summary, the comparison between 2018 and 2019 reveals a clear transition in the spatial distribution of NO_2 in Tehran County—from a centralized pattern focused on the urban core and northeastern sectors in 2018 to a more dispersed and widespread pattern in 2019. Under this new configuration, northwestern, southern, and eastern districts now account for a significant share of air pollution. This evolution underscores that air pollution is no longer confined to the city center but has become a pervasive spatial challenge affecting multiple regions across Tehran County. These findings strongly highlight the need for a fundamental reassessment of urban air quality management strategies and urban planning policies. Measures targeting only the central city are no longer sufficient; instead, integrated, region-wide interventions must be implemented across the entire county to effectively address this growing environmental concern.

Figure 3 presents the spatial distribution maps of seasonal average NO_2 concentrations for the years 2020 and 2021 in Tehran County. A comparative analysis of these maps reveals substantial shifts in both the magnitude and spatial configuration of NO_2 pollution between the two years.

In 2020, NO_2 concentrations in Tehran County ranged from 7 to 27 µg/m³ and were classified into six color categories: gray (7–8 µg/m³), orange (8.1–10 µg/m³), green (10.1–15 µg/m³), light blue (15.1–18 µg/m³), purple (18.1–22 µg/m³), and red (22.1–27 µg/m³). The highest concentrations—depicted in red and purple—were concentrated in the central districts and northeastern parts of the county, indicating levels between 22.1 and 27 µg/m³ and 18.1–22 µg/m³, respectively. This pattern reflects the presence of dense pollution sources such as heavy traffic corridors, industrial activities, and commercial centers in the urban core and northeastern sectors. In contrast, the southern and western peripheries exhibited lower concentrations, represented by green (10.1–15 µg/m³) and orange (8.1–10 µg/m³), with the lowest values (gray: 7–8 µg/m³) observed at the extreme southern and western edges of the county. Overall, the 2020 spatial pattern was centralized and core-dominated, with peak pollution levels clearly anchored in the central and northeastern zones.

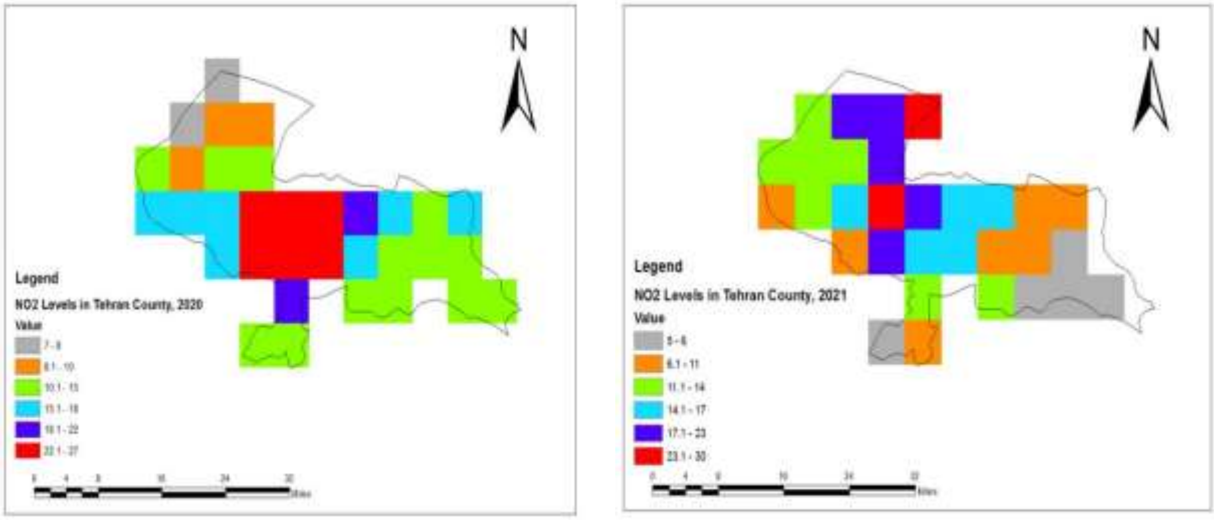

Figure 3. Spatial distribution maps of seasonal average NO_2 concentrations in 2020 and 2021 (Source: Authors, 1404).

By 2021, the NO_2 concentration range expanded slightly to 5–30 µg/m³, with the following classification: gray (5–6 µg/m³), orange (6.1–11 µg/m³), green (11.1–14 µg/m³), light blue (14.1–17 µg/m³), purple (17.1–23 µg/m³), and red (23.1–30 µg/m³). Despite the higher maximum value compared to 2020, the spatial distribution of pollution underwent a dramatic transformation. Most of Tehran County was now represented by orange (6.1–11 µg/m³) and green (11.1–14 µg/m³), indicating generally low to moderate NO_2 levels. Notably, the central area—previously a major pollution hotspot in 2020 (red and purple)—shifted to orange and green in 2021, reflecting a sharp decline in NO_2 concentrations (from 22.1–27 µg/m³ down to 6.1–14 µg/m³) .

However, limited zones in the northwestern and southeastern parts of the county emerged as areas with relatively higher concentrations, displayed in light blue (14.1–17 µg/m³), purple (17.1–23 µg/m³), and red (23.1–30 µg/m³). Although these values represent a significant reduction compared to 2020 levels in the city center, they remain above the county-wide average, suggesting persistent localized emission sources. Overall, the 2021 pattern is more dispersed and characterized by generally lower pollution levels across most of the county.

A detailed comparison of the 2020 and 2021 maps highlights a major shift: in 2020, peak NO_2 concentrations (up to 27 µg/m³) were concentrated in the central and northeastern districts; by 2021, these areas experienced a drastic reduction (to 6.1–14 µg/m³), while pollution became more diffused, with isolated hotspots appearing in the northwest and southeast (reaching up to 30 µg/m³). This transformation likely reflects a temporary decline in anthropogenic activities—particularly in transportation and industrial sectors—possibly due to factors such as pandemic-related restrictions, reduced mobility, temporary shutdowns, or targeted air quality control measures.

Nevertheless, the persistence of elevated NO_2 levels in specific peripheral zones underscores that certain areas remain under significant pollution pressure despite the overall improvement. These findings emphasize the critical need for continuous monitoring and adaptive, intelligent urban air quality management in Tehran County. A general decline in average concentrations should not lead to complacency; instead, attention must be directed toward sensitive and residual hotspots to ensure equitable and effective environmental governance across all urban districts.

Figure 4 displays the spatial distribution maps of seasonal average NO_2 concentrations for the years 2022 and 2023 in Tehran County. A comparative analysis of these maps reveals a striking contrast in both pollution intensity and spatial structure between the two years.

In 2022, NO_2 concentrations across Tehran County ranged from 0 to 189 µg/m³ and were classified into six color categories: gray (0 µg/m³), orange (0–45 µg/m³), green (45.1–63 µg/m³), light blue (63.1–81 µg/m³), purple (81.1–129 µg/m³), and red (129.1–189 µg/m³).

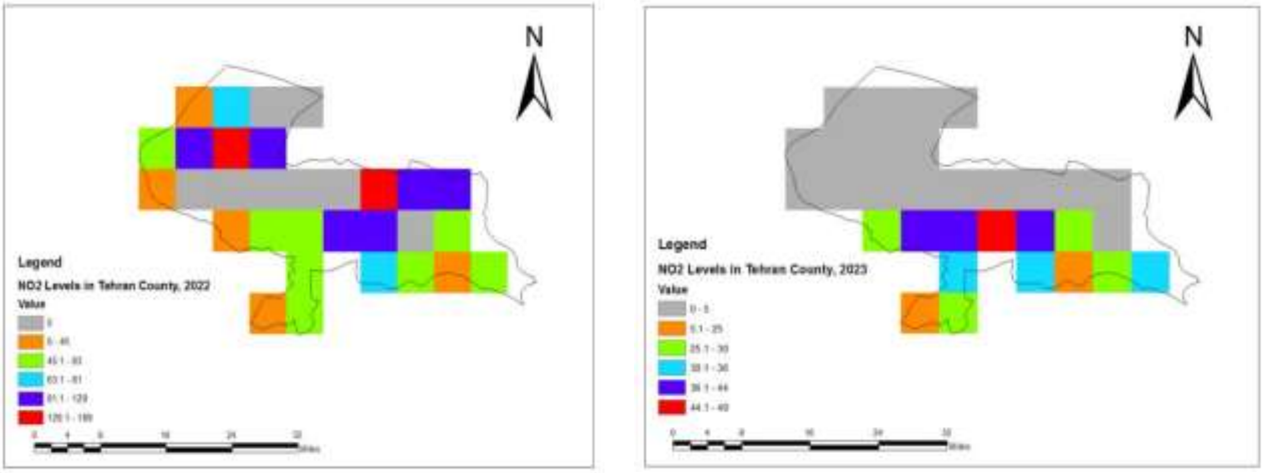

Figure 4. Spatial distribution maps of seasonal average NO_2 concentrations in 2022 and 2023 (source: authors, 1404)

This pattern reflects the persistent influence of dense anthropogenic sources, including heavy traffic networks, industrial operations, and commercial activity in the urban core and northeastern sectors. In contrast, the southern and western peripheries exhibited lower concentrations, represented by green (45.1–63 µg/m³) and orange (0–45 µg/m³), with some areas at the extreme edges shown in gray (0 µg/m³), indicating minimal or undetectable NO_2 levels. Overall, the 2022 spatial pattern was strongly centralized, with peak pollution levels anchored in the central and northeastern zones.

By 2023, NO_2 concentrations dropped dramatically, with a new range of 0–49 µg/m³ and the following classification: gray (0–5 µg/m³), orange (5.1–25 µg/m³), green (25.1–30 µg/m³), light blue (30.1–36 µg/m³), purple (36.1–44 µg/m³), and red (44.1–49 µg/m³). Despite the significantly reduced upper limit compared to 2022, the spatial configuration of pollution underwent a profound transformation. The majority of the county was now depicted in orange (5.1–25 µg/m³) and green (25.1–30 µg/m³), indicating generally low to moderate NO_2 levels. Notably, the central area—previously a major hotspot in 2022 (red and purple)—shifted to orange and green in 2023, reflecting a drastic decline in NO_2 concentrations.

Only limited zones in the southeastern part of the county exhibited relatively higher values, displayed in light blue (30.1–36 µg/m³), purple (36.1–44 µg/m³), and red (44.1–49 µg/m³). These areas recorded concentrations between 30.1 and 49 µg/m³—substantially lower than 2022 levels but still above the county-wide average. Overall, the 2023 pattern is markedly more dispersed and characterized by significantly lower pollution levels across nearly all districts.

A detailed comparison between 2022 and 2023 highlights a dramatic shift: in 2022, NO_2 concentrations peaked in the central and northeastern districts (up to 189 µg/m³), forming a classic core-periphery pollution structure. By 2023, this pattern collapsed—central concentrations plummeted to 5.1–30 µg/m³, and pollution became more evenly distributed, with only minor hotspots remaining in the southeast (up to 49 µg/m³). This sharp decline may be attributed to a combination of factors, including stricter traffic regulations, reduced industrial emissions, improved fuel standards, or broader environmental policies implemented during this period.

Nevertheless, the persistence of elevated NO_2 levels—even at reduced magnitudes—in specific southeastern zones indicates that localized emission sources remain active and warrant targeted attention. These findings underscore the importance of sustained air quality monitoring and adaptive, spatially informed policy interventions. While the overall improvement in 2023 is encouraging, it should not lead to the neglect of residual hotspots. Effective urban air quality management in Tehran County requires a balanced strategy that maintains progress in central areas while proactively addressing emerging or persistent pollution challenges in peripheral districts.

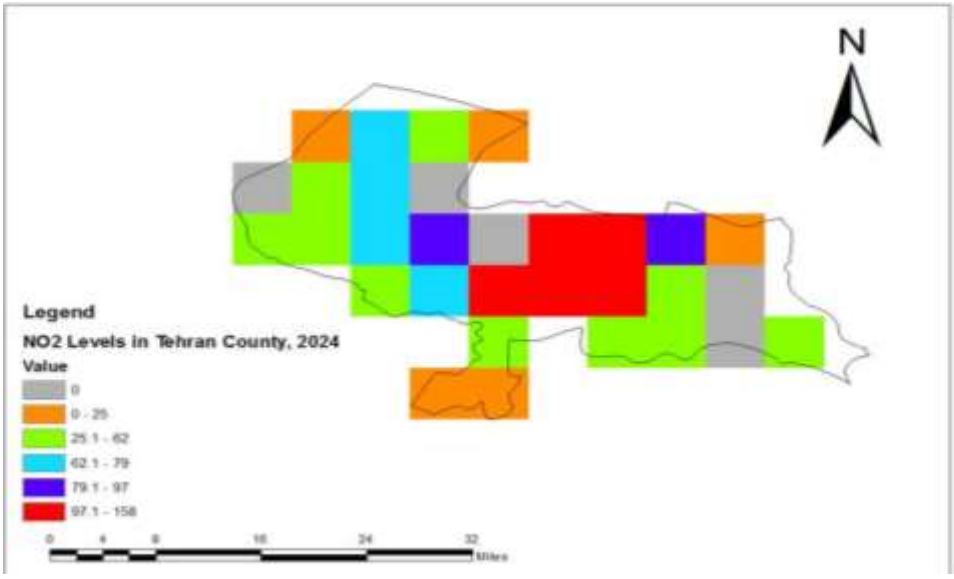

Figure 5. Spatial distribution map of seasonal average NO_2 concentrations in 2024 (source: authors, 2025)

Figure 5 illustrates the spatial distribution of seasonal average NO_2 concentrations across Tehran County in 2024. NO_2 levels ranged from 0 to 158 µg/m³ and were classified into six color categories: gray (0 µg/m³), orange (0–25 µg/m³), green (25.1–62 µg/m³), light blue (62.1–79 µg/m³), purple (79.1–97 µg/m³), and red (97.1–158 µg/m³). The highest concentrations—depicted in red and purple—were concentrated in the central districts and northeastern parts of the county, corresponding to levels of 97.1–158 µg/m³ and 79.1–97 µg/m³, respectively. This pattern reflects the persistent presence of dense anthropogenic emission sources, including heavy traffic networks, industrial activities, and commercial hubs in the urban core and northeastern sectors. In contrast, the southern and western peripheries exhibited lower concentrations, represented by green (25.1–62 µg/m³) and orange (0–25 µg/m³), with some areas at the extreme edges shown in gray (0 µg/m³), indicating minimal or undetectable NO_2 levels. Overall, the 2024 spatial pattern is strongly centralized, with peak pollution levels clearly anchored in the central and northeastern zones—reminiscent of pre-pandemic conditions.

Discussion and Conclusion

This study analyzed Sentinel-5P satellite data to identify the spatiotemporal patterns of NO_2 concentrations during the winter season across a seven-year period (2018–2024) in Tehran County. Using raster image processing, spatial clipping, seasonal averaging, and vector conversion techniques, seasonal average NO_2 maps were generated for each year, revealing distinct spatial configurations and temporal trends in pollution levels.

In 2018, NO_2 concentrations ranged from 0 to 185 µg/m³, with the highest values (134–185 µg/m³, red) concentrated in the central districts—driven by dense transportation networks, industrial zones, and commercial activity. Northern and eastern areas showed moderate-to-high levels (purple and orange), while southern and western peripheries exhibited lower concentrations (green, light blue, and gray). The pattern was distinctly core-centered.

By 2019, the maximum concentration decreased to 145 µg/m³, and the spatial structure shifted significantly. The city center no longer held the highest values; instead, it appeared in purple and orange (67–111 µg/m³), suggesting reduced emissions—possibly due to traffic control policies or temporary industrial restrictions. A new hotspot emerged in the northwestern sector (112–145 µg/m³, red), with notable spatial expansion toward the west and north. Simultaneously, southern and eastern districts experienced rising pollution levels, indicating urban sprawl, population growth, and increased vehicular and industrial activity. This marked a transition from a centralized to a more dispersed pollution pattern.

The years 2020 and 2021 witnessed a dramatic decline in NO_2 levels—ranging from 7–27 µg/m³ and 5–30 µg/m³, respectively—coinciding with pandemic-related restrictions. In

2020, the central and northeastern zones remained the primary hotspots (22.1–27 µg/m³), maintaining a core-periphery structure. However, in 2021, the entire county shifted to low-to-moderate concentrations (mostly orange and green), with only limited elevated zones in the northwest and southeast (up to 30 µg/m³). This sharp reduction reflects the temporary suppression of human activities, particularly in transport and industry—a finding consistent with studies by Shami et al. (2020) and Abdolazimi et al. (2023) (3,11)

In 2022, NO_2 levels surged again, reaching up to 189 µg/m³, with a return to a strongly centralized pattern—red and purple zones reappeared in the center and northeast. This resurgence signals a post-pandemic rebound in urban activity, traffic volume, and industrial operations. By 2023, concentrations dropped significantly (0–49 µg/m³), and the spatial pattern became more diffuse, with only minor hotspots in the southeastern periphery (e.g., Eslamshahr and Qods), reflecting ongoing urban expansion into these areas.

In 2024, NO_2 concentrations rose once more—peaking at 158 µg/m³—with the central and northeastern districts again emerging as dominant hotspots. Concurrently, elevated levels extended into southern and eastern suburbs, confirming the spatial expansion of pollution sources beyond the urban core.

Collectively, these findings demonstrate that NO_2 pollution in Tehran County has evolved from a centralized urban problem into a widespread spatial challenge affecting multiple districts. This transformation underscores the direct influence of anthropogenic activities—particularly transportation and industry—on air quality. Compounding this issue are Tehran's semi-arid climate and frequent winter temperature inversions, which trap pollutants in the lower atmospheric layers and prevent dispersion. This combination of natural meteorological constraints and intense human pressure renders Tehran a textbook example of a "compound hazard".

Therefore, a fundamental reassessment of urban air quality management and spatial planning strategies is urgently needed. Policies focused solely on the city center are no longer sufficient. Instead, integrated, region-wide interventions must be implemented across the entire county. Continuous satellite-based monitoring, intelligent zoning, and proactive identification of emerging hotspots are essential to address residual pollution and ensure equitable environmental protection for all residents.

In conclusion, it must be said that the seven-year analysis (2018–2024) reveals that NO_2 pollution in Tehran County is highly dynamic, shaped by the interplay of human activity and seasonal meteorological conditions. While temporary declines occurred during pandemic years, long-term trends show a concerning return—and even intensification—of pollution, now extending beyond the urban core into suburban districts. This evolution demands a paradigm shift: from reactive, center-focused policies to proactive, integrated, and spatially inclusive strategies that recognize air pollution as a metropolitan-scale challenge.

The researchers recommend that satellite data be integrated into urban planning, and that Sentinel-5P and similar remote sensing datasets should be systematically incorporated into urban decision-making as scientific tools for air quality management, spatial planning and environmental policy design. Public transport and traffic reduction should also be expanded, as increasing the share of clean and efficient public transport – especially metro and electric bus networks – can significantly reduce greenhouse gas emissions and vehicle congestion. Industrial activities should also be regulated and stricter environmental controls should be applied in sensitive and peripheral areas, with particular attention to industrial clusters in the southern and eastern suburbs. Finally, public awareness and citizen participation should be increased, as regular dissemination of air quality data and health advice can empower residents to modify their behavior and support pollution reduction initiatives.

Compliance with Ethical Guidelines

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Author's Contributions

This article is based on Naser Bay idea at RCS at Golestan province, who was responsible for conducting the research, collecting, and analyzing the data; and the other authors, Ali Asghar Abdollahi, Sadegh Karimi, Masoud Ahmadi, Nader Oveisi, Hadi Ghanizadeh, were responsible for the design, supervision, and methodology. However, Sadegh Karimi was responsible for correspondence and editing the final manuscript submitted to the journal.

Conflict of Interests

The authors declare no conflict of interest.

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