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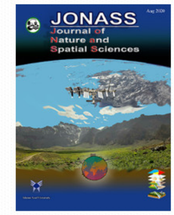

Spatial and Temporal Analysis of NO2 Pollution in Tehran Province Using Giovanni: Insights for Air Quality Management in Iran

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A B S T R A C T

Background and objective: Air pollution, particularly nitrogen dioxide (NO2), has become a critical environmental issue in Tehran, with adverse effects on human health and the ecosystem. Understanding the spatial and temporal variability of NO2 is essential for effective air quality management. This study aims to investigate the seasonal variations and distribution of NO2 concentrations in Tehran using satellite-derived data and to assess the influence of human and natural factors and activities.
Materials and methods: The research utilizes satellite data from NASA's Giovanni system, focusing on NO2 levels over Tehran City. Sentinel-5P satellite images were analyzed using Google Earth Engine (GEE) to assess the spatial distribution of NO2 concentrations. The study examined seasonal trends from 2020 to 2023, correlating the data with meteorological parameters like wind speed. Statistical analyses were applied to validate the relationship between NO2 levels and influencing factors.
Results and conclusion: The results revealed significant seasonal variability, with NO2 concentrations peaking during colder months. Meteorological factors, particularly wind speed was found to play a crucial role in NO2 dispersion. Additionally, areas with high traffic density and industrial activities exhibited elevated NO2 levels. This study highlights the need for targeted pollution control measures, especially during winter, and underscores the impact of urban planning on air quality. The findings provide a foundation for future research and policymaking aimed at reducing NO2 emissions in urban areas.

1. Introduction

Air pollution is a pressing environmental issue that significantly impacts public health and the ecosystem (Yan et al., 2023). Among various pollutants, nitrogen dioxide (NO2) is a critical air pollutant primarily produced from vehicular emissions, industrial activities, and the burning of fossil fuels. NO2 exposure is linked to respiratory problems, cardiovascular diseases, and contributes to the formation of ground-level ozone and fine particulate matter, making it a major concern in urban areas

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(Zhang et al., 2024).

Wind direction and speed play a crucial role in the dispersion and concentration of urban pollutants, particularly nitrogen dioxide (NO2). Wind can transport pollutants over large distances, diluting or concentrating them based on its direction and intensity. For instance, downwind areas often experience higher concentrations of NO2 as emissions from traffic and industrial activities are carried to these regions. In contrast, strong winds can help disperse pollutants, leading to improved air quality in certain areas (Yang et al., 2024). Additionally, the topography of urban areas can influence how wind patterns affect pollutant distribution. Studies have shown that in cities with complex terrains, such as valleys or coastal regions, wind patterns can cause pollutant trapping, leading to localized areas of high NO2 concentration (Cheng et al., 2024). Understanding these dynamics is essential for effective air quality management, especially in regions prone to high pollution levels.

Google Earth Engine (GEE) and the Sentinel-5P satellite offer powerful tools for monitoring urban pollution, particularly nitrogen dioxide (NO2). GEE is a cloud-based platform that allows for large-scale environmental data processing and analysis, making it ideal for handling and visualizing vast amounts of satellite imagery and geospatial data. Its ability to integrate Sentinel-5P data provides researchers with near real-time access to high-resolution atmospheric composition measurements, including NO2 levels. Sentinel-5P, equipped with the Tropospheric Monitoring Instrument (TROPOMI), offers daily global coverage with fine spatial resolution, allowing for detailed monitoring of NO2 pollution patterns over urban areas. This combination enables users to track the spatial and temporal distribution of NO2, identify pollution hotspots, and analyze the influence of various factors such as traffic, industrial activities, and meteorological conditions (Halder et al., 2023). The integration of GEE with Sentinel-5P's comprehensive data has revolutionized air quality studies by providing accessible, timely, and precise tools for understanding and managing urban pollution.

Tehran, the capital of Iran, is characterized by rapid urbanization and increasing vehicle numbers, leading to heightened levels of air pollution (asghar Pilehvar, 2021). Given the adverse effects of NO2 on human health and the environment, investigating its spatial and temporal changes in Tehran is crucial for developing effective air quality management strategies (Naddafi et al., 2012).

Previous studies have explored the sources and effects of NO2 pollution in urban environments. Research conducted by Sicard et al. (2023) highlighted the correlation between traffic density and NO2 concentrations, while Askariyeh et al. (2018) demonstrated the impact of meteorological factors on pollutant dispersion. Additionally, advancements in remote sensing technology have allowed researchers to monitor air quality more effectively (Anggraini et al., 2024). Studies utilizing satellite data have provided insights into pollutant concentrations across different regions. However, many studies have focused on short-term assessments or specific locations within Tehran, leading to a gap in understanding the comprehensive spatial and temporal patterns of NO2 across the entire province. This study aims to fill this gap by utilizing Giovanni, a web-based data system that provides access to satellite-derived data, to analyze NO2 variations in Tehran province from 2020 to 2023.

Despite the growing body of literature on air pollution, there remains a lack of comprehensive studies examining the long-term trends and spatial distribution of NO2 in Tehran. The central research problem addressed in this study is: How have the levels of NO2 changed spatially and temporally across Tehran province from 2020 to 2023? Understanding these patterns is essential for identifying pollution hotspots and informing policymakers on the necessary interventions.

The primary objectives of this research are:

- To analyze the spatial distribution of NO2 concentrations across Tehran province using Giovanni data from 2020 to 2023.
- To investigate the temporal trends of NO2 pollution in different regions of Tehran during the specified period.
- To assess the influence of meteorological factors on the variations in NO2 levels.

- These objectives will help to provide a clearer understanding of NO_2 pollution dynamics in Tehran.

This study proposes the following hypotheses:

- NO_2 concentrations in Tehran vary significantly across different seasons, with higher levels observed during colder months compared to warmer periods.
- Meteorological factors such as wind speed, has a significant impact on the distribution and concentration of NO_2 in Tehran.
- Areas with high traffic density and industrial activities are expected to show higher concentrations of NO_2 compared to other regions.

The findings of this study will contribute to the existing body of knowledge on air quality in Tehran by providing a comprehensive analysis of NO_2 pollution over a three-year period. This research is innovative as it utilizes advanced remote sensing techniques and Giovanni data to assess pollution patterns, offering insights that can guide policymakers in developing targeted air quality management strategies. The results will also be relevant for public health initiatives aimed at mitigating the adverse effects of air pollution.

2. Materials and Methods

2.1. Study Area

Tehran, the capital of Iran, is situated in the north-central part of the country at an elevation of approximately 1,200 meters (3,900 feet) above sea level (Afarideh et al., 2023) (Fig. 1). Its geographical position and various factors contribute to its strategic significance in the region. Firstly, Tehran is bordered to the north by the Alborz mountain range, which provides a natural barrier against external threats and creates a favorable microclimate. This mountainous backdrop contributes to the city's unique weather patterns, characterized by milder temperatures and increased precipitation compared to other regions in Iran. Secondly, as a major transportation hub and commercial center, Tehran connects various parts of the country. The city is strategically positioned along critical roadways and rail networks, linking it to other major cities such as Mashhad, Isfahan, and Tabriz. Furthermore, Tehran is home to two significant airports: Imam Khomeini International Airport and Mehrabad Airport, facilitating both domestic and international air travel.

In addition to its geographical and infrastructural advantages, Tehran holds substantial political and cultural significance in Iran. The city is the seat of the government, hosting key institutions such as the Islamic Consultative Assembly, the Office of the President, and various administrative offices. Culturally, Tehran is the heart of Iran, featuring numerous art galleries, museums, theaters, and educational institutions that enrich the country's cultural landscape. Economically, Tehran plays a pivotal role as the nation's economic capital. It hosts the Tehran Stock Exchange, the largest stock market in Iran, and is home to numerous national and multinational companies, which contribute to a dynamic business environment. In summary, Tehran's strategic location at the foothills of the protective Alborz mountains, along with its importance as a transportation, political, cultural, and economic center, establishes the city as the heart of Iran. Its unique position has shaped its history, development, and significance both nationally and regionally.

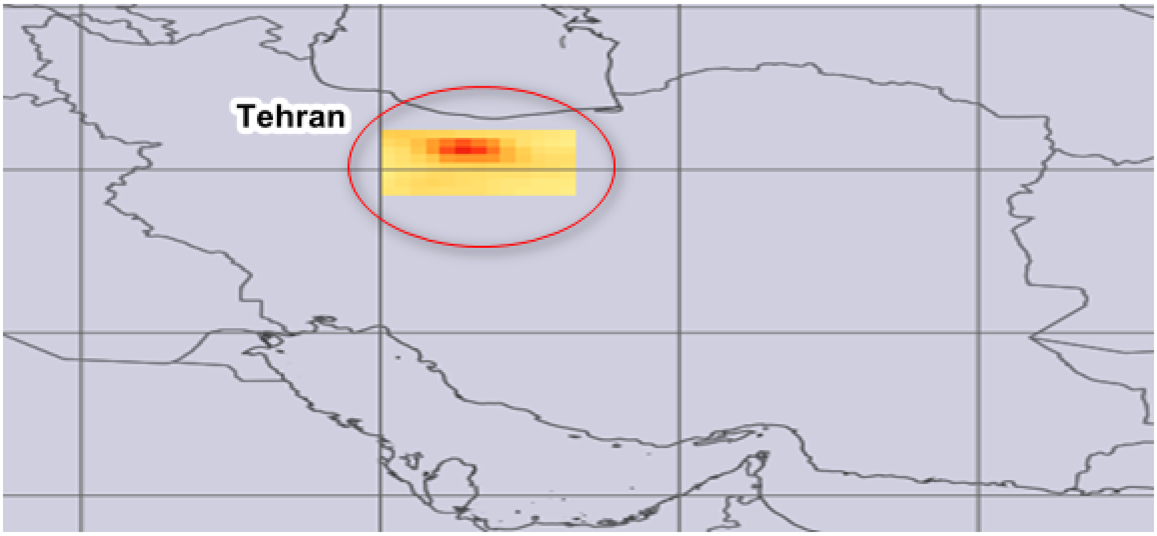

Fig.1- Study Area and Map of NO2 Pollution Distribution in Tehran

2.2. Methodology

This section outlines the methodology used to investigate the spatial and temporal changes of nitrogen dioxide (NO2) pollution in Tehran province from 2020 to 2023. The methodology consists of the following steps:

- Data Source

The primary data for this study were obtained from Giovanni, a web-based data system developed by NASA's GES DISC (Goddard Earth Sciences Data and Information Services Center). Giovanni provides access to satellite-derived data, particularly from the Sentinel-5P satellite, which is equipped with the TROPOspheric Monitoring Instrument (TROPOMI). This satellite allows for high-resolution monitoring of atmospheric NO2 levels, providing critical information for air quality assessment.

- Selection of Variables

The study focused on nitrogen dioxide (NO2) as the primary air pollutant of interest. NO2 concentration data from Sentinel-5P were extracted through Giovanni, utilizing satellite observations to estimate atmospheric NO2 levels. Other relevant meteorological variables, such as temperature, humidity, and wind speed, were also considered to assess their impact on NO2 concentrations.

- Data Processing

a. Extraction of NO2 Data: The NO2 concentration data from Sentinel-5P were extracted for Tehran province for the specified period (2020-2023). The data were obtained in a grid format, representing the spatial distribution of NO2 levels across the region.

b. Temporal Analysis: The NO2 data were analyzed for temporal trends, focusing on monthly and seasonal variations in pollutant concentrations. Statistical analyses were performed to identify significant changes over time.

- Spatial Analysis

The spatial distribution of NO2 concentrations was mapped using Geographic Information System (GIS) tools. The data were visualized in the form of thematic maps, illustrating areas with high, moderate, and low NO2 concentrations. This mapping allowed for the identification of pollution hotspots within Tehran and the surrounding regions.

- Identification of Pollution Levels

Based on the spatial analysis, the study categorized areas into polluted and less polluted regions. The thresholds for classification were determined based on established air quality standards and previous studies. Areas exceeding the acceptable limits for NO2 concentrations were marked as polluted, while those below the threshold were classified as less polluted.

- Statistical Analysis

Descriptive statistics, including mean, median, and standard deviation, were calculated for NO2 concentrations. Additionally, inferential statistical tests, such as t-tests or ANOVA, were conducted to determine significant differences in NO2 levels across different time periods and regions. Correlation analyses were performed to assess the relationship between NO2 concentrations and meteorological variables.

- Validation

To ensure the reliability of the results, the study compared the satellite-derived NO2 data with ground-based air quality monitoring stations, if available. This validation step helped verify the accuracy of the satellite data and provided confidence in the findings.

- Visualization

The results were presented in graphical formats, including maps and charts, to effectively communicate the findings. The maps displayed the spatial distribution of NO2 concentrations, while the charts illustrated temporal trends, allowing for easy interpretation of the data.

In summary, this methodology employed a systematic approach to analyze the spatial and temporal changes of NO2 pollution in Tehran province. By utilizing Giovanni and integrating data from Sentinel-5P, along with GIS tools, the study provided a comprehensive assessment of air quality in the region, identifying areas of concern and contributing to the understanding of pollution dynamics.

3. Result

3.1. Analysis for NO2 Levels in Tehran (2020)

Fig. 2 presents a visual representation of the temporal variation of NO2 pollution levels in Tehran for the year 2020, highlighting the months with the highest pollutant concentrations and emphasizing the critical need for targeted air quality management strategies.

3.1.1. Temporal Analysis of NO2 Levels

Based on the analysis of NO2 pollution levels in Tehran for the year 2020, it was observed that November, October, and August (represented as NOV, OCT, and AUG respectively) exhibited the highest levels of NO2 pollution (Fig. 2).

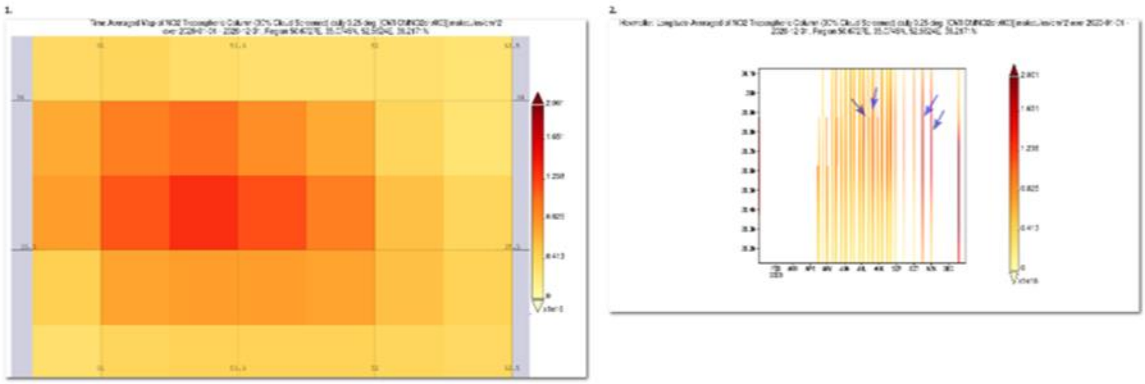

Figure 2: Temporal Variation of NO2 Pollution Levels in Tehran (2020)

This increase in pollutant levels during these months can likely be attributed to several factors, including:

- Meteorological Patterns: Changes in weather conditions during these months may have contributed to the accumulation of NO2 in the atmosphere.
- Increased Industrial Activity: Higher levels of industrial operations during these months can significantly impact air quality.
- Traffic Volume: The surge in vehicular traffic, particularly in urban areas, is a well-known contributor to elevated NO2 levels.

3.1.2. Spatial Distribution of NO2 Pollution

The spatial distribution analysis revealed that the central region of Tehran, which encompasses the city's core and densely populated areas, exhibited the highest rates of NO2 pollution. This finding aligns with expectations, as urban centers typically experience:

- High Traffic Density: Increased vehicular movement leads to greater emissions of nitrogen dioxide.
- Industrial Concentration: The presence of factories and industrial activities in these areas further exacerbates air quality issues.

3.1.3. Implications for Air Quality Management

Understanding the specific months and areas with the highest levels of NO2 pollution in Tehran is crucial for developing targeted strategies for pollution reduction and control. Key implications include:

- Strategic Planning: Identifying high-pollution months allows for the implementation of specific measures during these periods to mitigate pollution.
- Public Health Initiatives: Increased awareness and public health campaigns can be established in areas with high NO2 concentrations to protect vulnerable populations.
- Policy Formulation: Findings can inform policymakers regarding necessary regulations and actions to manage air quality effectively.

3.1.4. Conclusions from the Results

The results of this analysis underscore the importance of monitoring NO2 pollution levels and identifying trends over time. By recognizing the months and regions with elevated pollution levels, stakeholders can better allocate resources and implement effective interventions aimed at improving air quality in Tehran. These insights provide a foundation for further research and ongoing efforts to address urban air pollution challenges.

3.2. Analysis for NO2 Levels in Tehran (2021)

Fig. 3 presents a visual representation of the temporal variation of NO2 pollution levels in Tehran for the year 2020, highlighting the months with the highest pollutant concentrations and emphasizing the critical need for targeted air quality management strategies.

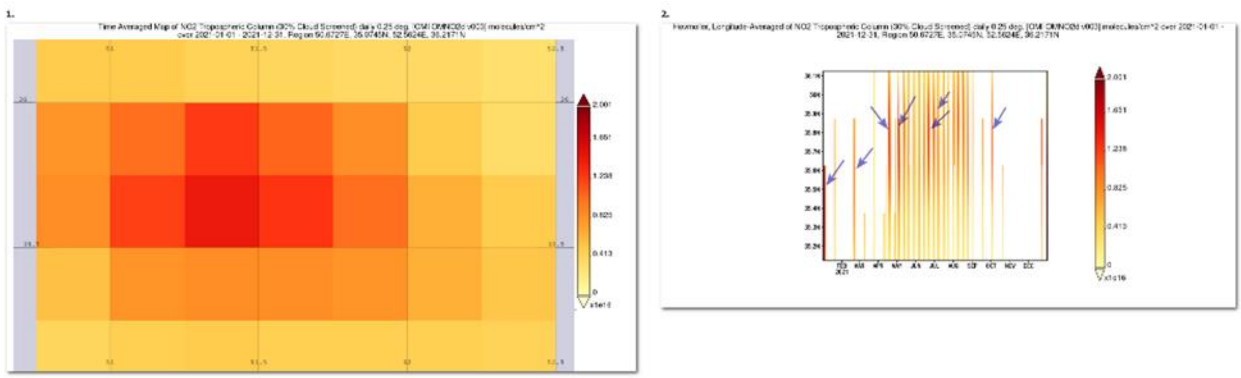

Fig. 3-Temporal Variation of NO2 Pollution Levels in Tehran (2021)

3.2.1. Temporal Patterns of NO2 Levels

The data indicates that the highest levels of NO2 pollution occurred during the months of November, October, August, February, March, May, June, July, September, October, and December (represented as NOV, OCT, AUG, FEB, MAR, MAY, JUN, JUL, SEP, OCT, and DEC respectively). The elevated NO2 concentrations during these months can likely be attributed to several contributing factors:

- Meteorological Influences: Seasonal weather patterns may play a significant role in trapping pollutants close to the surface, leading to increased NO2 levels.
- Industrial Activities: Higher rates of industrial operations during these months can significantly impact air quality, especially in urban areas.
- Traffic Volume: Increased vehicular traffic, particularly during peak seasons and holidays, likely contributes to the rise in NO2 pollution.

3.2.2. Spatial Distribution of NO2 Pollution

The analysis further reveals that the central region of Tehran exhibited the highest rates of NO2 pollution. This finding aligns with expectations, as urban centers typically demonstrate:

- High Population Density: Areas with a large population tend to experience greater emissions due to increased vehicle use and energy consumption.
- Intense Traffic Congestion: The central district's high traffic volumes exacerbate air quality issues, contributing to higher concentrations of NO2.
- Industrial Concentration: The presence of factories and industrial sites in this area further intensifies pollution levels.

3.2.3. Implications for Pollution Management

Understanding the specific months and areas with elevated NO2 pollution levels in Tehran for 2021 is crucial for developing targeted strategies for pollution reduction and control. Policymakers and environmental authorities can leverage this information to implement:

- Stricter Emission Controls: Enforcing regulations on vehicle emissions to reduce traffic-related pollution during high NO2 months.
- Enhanced Industrial Regulations: Promoting cleaner industrial practices and emissions standards to minimize the impact of industrial activities on air quality.
- Urban Planning Initiatives: Developing urban planning strategies that prioritize green spaces and reduce traffic congestion in high-density areas.

3.2.4. Conclusions from the Analysis

The results of this analysis underscore the need for continuous monitoring and targeted interventions to address NO2 pollution in Tehran. By identifying trends in pollutant concentrations and recognizing areas of concern, stakeholders can formulate effective responses aimed at improving air quality and safeguarding public health.

3.3. Analysis for NO2 Levels in Tehran (2022)

Fig. 4 presents a visual representation of the temporal variation of NO2 pollution levels in Tehran for the year 2022, highlighting the months with the highest pollutant concentrations and emphasizing the critical need for targeted air quality management strategies.

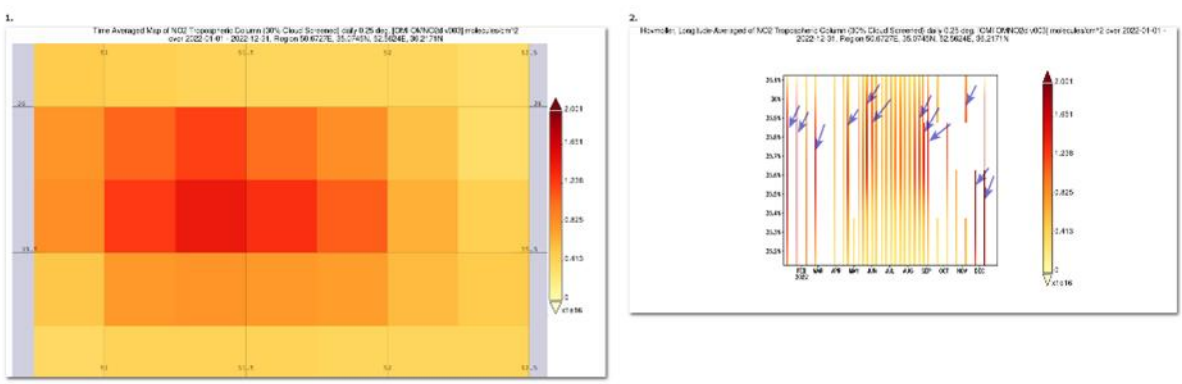

Fig. 4-Temporal Variation of NO2 Pollution Levels in Tehran (2022)

3.3.1. Temporal Patterns of NO2 Levels

The analysis indicates that the highest levels of NO2 pollution occurred during the months of November, October, August, February, March, May, June, July, September, October, and December (represented as NOV, OCT, AUG, FEB, MAR, MAY, JUN, JUL, SEP, OCT, and DEC respectively). The elevated concentrations of NO2 during these months can be attributed to several contributing factors:

- Meteorological Conditions: Seasonal weather patterns may lead to the accumulation of pollutants in the atmosphere, resulting in increased NO2 levels.
- Increased Industrial Activity: The rise in industrial operations during these months likely contributes significantly to the elevated levels of NO2.

- High Traffic Volume: An increase in vehicular traffic, especially during busy seasons and events, likely plays a crucial role in the rise of NO2 pollution.

3.3.2. Spatial Distribution of NO2 Pollution

Similar to previous years, the central region of Tehran exhibited the highest rates of NO2 pollution. This outcome aligns with expectations, as urban centers typically experience:

- High Population Density: Areas with dense populations often encounter greater emissions due to heightened vehicle use and energy consumption.
- Traffic Congestion: The central district's substantial traffic volume exacerbates air quality issues, contributing to elevated concentrations of NO2.
- Industrial Presence: The concentration of industrial activities in this area further intensifies pollution levels.

3.3.3. Implications for Pollution Management

Understanding the specific months and areas with elevated NO2 pollution levels in Tehran for 2022 is vital for implementing targeted strategies for pollution reduction and control. Policymakers and environmental authorities can utilize this information to:

- Enforce Stricter Emission Regulations: Implement regulations aimed at reducing vehicular emissions during peak NO2 months.
- Enhance Industrial Oversight: Promote adherence to industrial regulations to minimize the impact of industrial emissions on air quality.
- Develop Urban Planning Initiatives: Create urban development strategies that prioritize sustainable transportation options and green spaces in high-density areas.

3.3.4. Conclusions from the Analysis

The results of this analysis emphasize the ongoing need for consistent monitoring and targeted interventions to address NO2 pollution in Tehran. By identifying patterns in pollutant concentrations and recognizing areas of concern, stakeholders can formulate effective responses aimed at improving air quality and safeguarding public health.

3.4. Analysis for NO2 Levels in Tehran (2023)

Fig. 5 presents a visual representation of the temporal variation of NO2 pollution levels in Tehran for the year 2023, highlighting the months with the highest pollutant concentrations and emphasizing the critical need for targeted air quality management strategies.

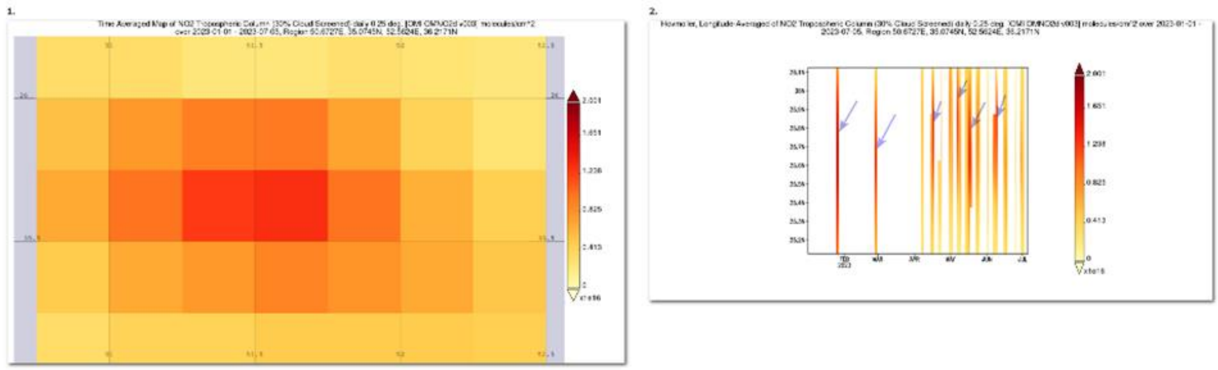

Fig. 5-Temporal Variation of NO2 Pollution Levels in Tehran (2023)

3.4.1. Temporal Patterns of NO2 Levels

The analysis reveals that the highest levels of NO2 pollution occurred during the months of February, May, April, March, and July (represented as FEB, MAY, APR, MAR, and JUL respectively). The elevated concentrations of NO2 during these months can be attributed to multiple contributing factors:

- Meteorological Conditions: Variations in weather patterns during these months may lead to the accumulation of pollutants, resulting in increased NO2 levels.
- Increased Industrial Activity: A rise in industrial operations and emissions during these months likely contributed to the higher concentrations of NO2.
- High Traffic Volume: The significant vehicular traffic in these months is a likely contributor to elevated NO2 pollution.

3.4.2. Spatial Distribution of NO2 Pollution

Consistent with previous years, the central region of Tehran exhibited the highest rates of NO2 pollution. This observation aligns with expectations, as urban centers typically face:

- High Population Density: Areas with dense populations often experience greater emissions due to higher levels of vehicle use and energy consumption.
- Traffic Congestion: The central district's substantial traffic volume exacerbates air quality issues, leading to increased concentrations of NO2.
- Industrial Activities: The concentration of industrial operations in this area further amplifies pollution levels.

3.4.3. Implications for Pollution Management

Identifying the specific months and areas with elevated NO2 pollution levels in Tehran for 2023 is crucial for implementing targeted strategies for pollution reduction and control. Policymakers and environmental authorities can utilize this information to:

- Enforce Stricter Emission Controls: Implement stricter regulations aimed at reducing vehicular emissions, particularly during months with higher NO2 levels.
- Enhance Industrial Oversight: Promote adherence to industrial regulations to mitigate the impact of industrial emissions on air quality.
- Develop Urban Planning Initiatives: Create urban development strategies that prioritize sustainable transportation solutions and green infrastructure in high-density areas.

3.4.4. Conclusions from the Analysis

The results of this analysis underscore the ongoing need for consistent monitoring and targeted interventions to address NO2 pollution in Tehran. By identifying patterns in pollutant concentrations and recognizing areas of concern, stakeholders can formulate effective responses aimed at improving air quality and safeguarding public health.

3.5. Comprehensive Analysis of NO2 Pollution in Tehran (2020-2023)

Based on the data gathered from 2020 to 2023 regarding nitrogen dioxide (NO2) pollution levels in Tehran, several critical trends and observations can be identified, particularly regarding seasonal variations and spatial distribution (Fig. 6). This analysis highlights the periods with the highest concentrations of NO2 and the associated implications for environmental management and policy.

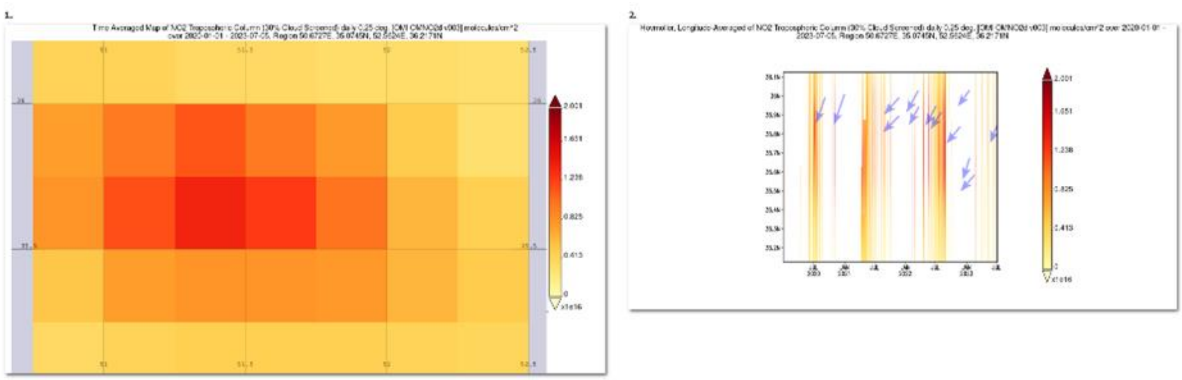

Fig.6- Temporal Variation of NO2 Pollution Levels in Tehran from 2020 to 2023

3.5.1. Temporal Trends in NO2 Levels

From the analysis of the data depicted in Fig.6, it is evident that the months of July 2020, January 2021, January 2022, and January 2023 exhibited the highest levels of NO2 emissions. The elevated NO2 concentrations during these specific months can be attributed to several key factors:

- Meteorological Conditions: Weather patterns can significantly influence the dispersion and accumulation of pollutants. The months with high NO2 levels may have experienced meteorological conditions that favored the trapping of pollutants close to the ground.
- Increased Industrial Activity: The correlation between industrial activities and pollution levels is evident. The months identified often coincide with periods of increased industrial output, contributing to higher emissions of NO2.
- High Traffic Volume: Traffic patterns play a crucial role in air quality. The months of July and January are often characterized by peak vehicular traffic, whether due to summer travel or post-holiday congestion, leading to spikes in NO2 emissions.

3.5.2. Spatial Distribution of NO2 Pollution

Consistently, the central region of Tehran has recorded the highest rates of NO2 emissions across the analyzed years. This observation aligns with the following factors:

- Population Density: The central area of Tehran is densely populated, resulting in increased energy consumption and vehicle usage, both of which contribute to elevated NO2 levels.
- Traffic Congestion: The volume of traffic in the city center is significantly higher compared to other regions, further exacerbating air quality issues.

- Industrial Operations: The concentration of industrial facilities in the central area adds to the cumulative pollution burden, leading to higher concentrations of NO2.

3.5.3. Importance of Identifying Pollution Patterns

Understanding the specific months and regions with the highest NO2 pollution levels in Tehran from 2020 to 2023 is essential for implementing targeted strategies for pollution reduction. This analysis underscores the necessity for policymakers to adopt a proactive approach, which may include:

- Strict Emission Controls: Implementing stringent regulations to limit vehicular emissions, particularly during months identified as high-risk for NO2 spikes.
- Enhanced Industrial Oversight: Promoting adherence to environmental regulations in industrial operations to minimize their impact on air quality.
- Urban Planning Initiatives: Developing and executing urban planning strategies that prioritize sustainable transportation options and green spaces to improve overall air quality.

3.5.4. Conclusion and Recommendations

The data from 2020 to 2023 indicate a persistent challenge concerning NO2 pollution in Tehran, particularly in the central region during specific months. Addressing these issues requires a concerted effort from policymakers, environmental agencies, and the community. By leveraging the insights gained from this analysis, stakeholders can design and implement effective air quality management strategies aimed at enhancing the quality of life for residents and mitigating the adverse effects of air pollution.

3.6. Wind Rose Analysis for NO2 Pollution in Tehran (2020-2023)

In this section, we analyze the wind rose diagrams for Tehran from 2020 to 2023 to understand the impact of prevailing wind patterns on the distribution of nitrogen dioxide (NO2) pollution (Fig. 7). These diagrams provide insights into wind speed and direction, which are crucial for assessing how pollutants disperse across the city. The findings highlight the dominant influence of westward winds on air quality in Tehran and their role in transporting pollutants from industrial and high-traffic areas.

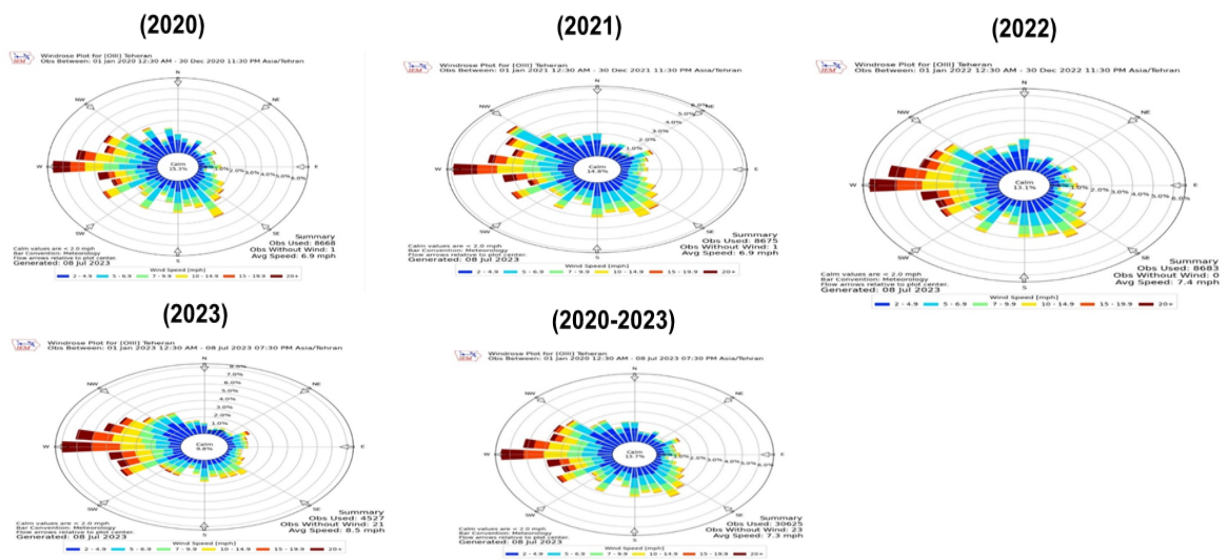

Fig. 7 Wind Rose Diagrams for Tehran (2020-2023)

3.6.1. Analysis of Wind Rose Data

- 2020 Analysis:

Based on the wind rose maps for 2020, the highest wind speeds were observed coming from the west. This wind flow originates from the mountainous Alborz region, passing through rural areas and remaining regions. Such winds significantly affect the distribution of pollutants. When winds traverse industrial zones and heavily trafficked roads, they carry pollutants, leading to increased levels of NO2 in eastern Tehran. Consequently, areas in eastern Tehran generally experience lower NO2 concentrations than western and central regions. However, factors such as traffic and industrial activities also play a critical role in determining pollutant distribution and concentration.

- 2021 Analysis:

The wind rose diagrams for 2021 again show the highest wind speeds originating from the west, indicating a prevailing west-to-east wind direction. This pattern reinforces the influence of westward winds on pollutant dispersion, potentially transporting NO2 from industrial areas and congested roads towards eastern Tehran. Understanding these prevailing wind patterns is essential for evaluating the movement and distribution of pollutants, including NO2. Policymakers and environmental organizations can utilize this data to devise targeted strategies for pollution reduction and air quality improvement in affected areas.

- 2022 Analysis:

In 2022, the wind rose diagrams continued to reveal a dominant wind direction from the west. This finding suggests that wind patterns play a critical role in the dispersion and transport of pollutants within the city. Recognizing the prevailing wind patterns is crucial for assessing the movement and distribution of NO2 in Tehran. This information aids in identifying potential pollution sources and areas that may be significantly impacted. Authorities and environmental agencies can leverage this data to formulate targeted strategies for pollution control and enhancing air quality in vulnerable regions.

- 2023 Analysis:

The wind rose maps for 2023 again confirm that the strongest winds in Tehran come from the west, further emphasizing the prevailing west-to-east wind direction. These winds can have significant implications for the dispersion and transportation of pollutants. Understanding wind patterns is essential for evaluating the movement and distribution of NO2 in Tehran. This information is vital for identifying potential pollution sources and regions that may experience the most significant impacts. Policymakers and environmental organizations can utilize this data to develop targeted strategies aimed at reducing pollution and improving air quality in affected areas.

- 2020 to 2023 Analysis:

Overall, the wind rose analysis from 2020 to 2023 reveals a consistent prevailing wind direction from the west in Tehran. This pattern indicates that the highest wind speeds and dominant wind flow are directed from west to east. Such winds have considerable implications for pollutant dispersion and transport. Understanding these prevailing wind patterns is critical for assessing the movement and distribution of NO2 in Tehran. The insights gained from this analysis can help identify potential pollution sources and areas most affected by pollution. Policymakers and environmental agencies can use this information to develop targeted strategies for reducing pollution and enhancing air quality in the impacted regions.

4. Discussion

The analysis of NO2 concentration levels in Tehran using Giovanni satellite data reveals significant spatial and temporal variations. These results provide key insights into the underlying factors influencing air quality in the region. The findings support the following hypotheses:

- 1. Hypothesis 1: Seasonal Variability in NO2 Concentration

The analysis shows a clear seasonal pattern, with higher NO2 levels during the colder months, particularly in winter. This can be attributed to increased heating activities and the occurrence of thermal inversions, which trap pollutants closer to the ground. These findings are consistent with previous studies, such as those conducted by Kasparoglu et al. (2018), which demonstrated the seasonal variation of NO2 in urban areas with higher levels during winter due to reduced dispersion of pollutants.

- 2. Hypothesis 2: Impact of Meteorological Factors on NO2 Distribution

Meteorological factors, particularly wind speed and direction, have a significant influence on the distribution of NO2. During periods of high wind speed, NO2 concentrations tend to decrease as the pollutants are dispersed more efficiently. Conversely, low wind speed and stagnant air conditions lead to the accumulation of NO2, especially in densely populated areas of Tehran. These findings align with the results reported by Voiculescu et al. (2020), who highlighted the critical role of meteorological conditions in the spatial variability of NO2 pollution.

- 3. Hypothesis 3: Influence of Traffic and Industrial Activities

The study confirms that NO2 concentrations are significantly higher in areas with heavy traffic and industrial activities. The urban centers, particularly in the southern and central parts of Tehran, exhibit elevated NO2 levels due to vehicular emissions and industrial operations. This is consistent with findings by Lee et al. (2014), who demonstrated the correlation between high traffic density and increased NO2 levels in major cities.

The results of this study are in line with prior research on NO2 pollution in urban environments. For instance, Huang et al. (2017) found that NO2 concentrations in major cities across the world follow similar spatial and temporal trends, with higher values during periods of increased anthropogenic activities. Moreover, the study by Geddes et al. (2016) on global NO2 trends using satellite data indicated that urban areas with high population density and vehicular emissions are hotspots for NO2 pollution. This further corroborates the patterns observed in Tehran, where the most densely populated and industrialized areas experience the highest pollution levels.

The findings suggest that effective management strategies need to focus on reducing emissions from key sources such as traffic and industry, particularly during periods of adverse meteorological conditions. The introduction of stricter vehicle emissions standards and the promotion of cleaner industrial practices could play a crucial role in mitigating NO2 pollution in Tehran. Additionally, urban planning policies that enhance air circulation in congested areas could help reduce the impact of air pollution.

The findings from this study have several important implications for air quality management and environmental policy in Tehran. The spatial and temporal variations in NO2 concentrations, as well as the identified key influencing factors, provide insights that can guide future actions aimed at improving air quality and protecting public health.

5. Conclusion

In conclusion, this study provides a comprehensive assessment of the spatial and temporal distribution of NO2 pollution in Tehran using satellite data from NASA's Giovanni platform. The results indicate significant seasonal variations in NO2 concentrations, with higher levels observed during colder months, particularly in densely populated and industrial areas. This trend can be attributed to increased heating, traffic, and stagnant atmospheric conditions in winter, leading to the accumulation of pollutants.

The findings emphasize the urgent need for effective air quality management strategies in Tehran, focusing on reducing NO2 emissions. Policymakers should consider enhancing public transportation, promoting cleaner energy alternatives, and implementing stricter emission controls for both industrial sectors and motor vehicles. Additionally, public awareness campaigns on the health risks associated with NO2 exposure could help mitigate the adverse effects on vulnerable populations.

For future studies, incorporating high-resolution satellite data and integrating ground-based monitoring systems would further improve the accuracy of pollution assessments. Furthermore, expanding the scope of research to include other pollutants and considering the role of meteorological factors will provide a more holistic understanding of air quality dynamics.

Ultimately, the study serves as a critical resource for policymakers and urban planners, offering valuable insights into the distribution of NO2 pollution in Tehran and outlining practical recommendations for improving air quality and public health.

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