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Comparative Analysis of NO_2, SO_2, CO, HCHO, and Aerosol Variations in Baghdad and Damascus Using Sentinel-5P and Giovanni Data via Google Earth Engine

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ABSTRACT

Objective: This study aims to assess and analyze the distribution and levels of key atmospheric pollutants NO_2, SO_2, CO, HCHO, and Aerosols in Baghdad and Damascus from 2019 to 2022, exploring the impact of urbanization, industrial activities, and climatic conditions on air quality.
Methods: Remote sensing data from Sentinel-5P (TROPOMI) and Giovanni NASA through Google Earth Engine (GEE) were utilized to monitor atmospheric pollutants at a regional scale, providing high-resolution data for comprehensive analysis of pollutant concentration trends.
Results: The study reveals significantly higher levels of air pollution in Baghdad compared to Damascus, primarily due to its higher population density, intense industrial activities, and limited vegetation cover. Seasonal variations in pollutant levels were observed, with higher concentrations in colder months. Land use maps highlight urban sprawl in both cities, with Baghdad experiencing more extreme temperature variations and poorer air quality due to limited green spaces. Wind dynamics and runoff data further illustrate the role of climatic and geographical conditions in shaping pollutant distribution and water management needs.
Conclusion: The findings underscore the complex relationship between urbanization, pollution, and environmental factors in Baghdad and Damascus. While both cities face significant environmental challenges, Baghdad's rapid urbanization and industrial activities make it more vulnerable to pollution. The study emphasizes the need for sustainable urban planning, effective pollution management strategies, and the integration of green spaces to mitigate environmental degradation and improve air quality. Remote sensing tools are essential for monitoring and managing pollution levels in both cities.

1. Introduction

Air pollution is one of the most critical environmental and health challenges faced by major cities worldwide. Key pollutants such as nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon monoxide (CO), formaldehyde (HCHO), and aerosols are emitted into the atmosphere from various anthropogenic and natural sources (Sicard et al., 2023). NO_2 and SO_2 primarily result from fossil fuel

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combustion and industrial processes, while CO mainly originates from motor vehicle emissions and incomplete combustion of organic matter (Sicard et al., 2023). HCHO, a volatile organic compound (VOC), is released from industrial activities, combustion processes, and organic material degradation (Xia et al., 2024). Aerosols, suspended particles in the atmosphere, not only affect air quality but also have implications for climate change.

In recent years, satellite technology has become a crucial tool for monitoring air pollutants globally. Satellites such as Sentinel-5P from the European Space Agency (ESA) and analytical platforms like Giovanni NASA have become essential in monitoring air quality and identifying changes in atmospheric pollutants (Yilmaz et al., 2023). The Sentinel-5P satellite, with its TROPOMI sensor, is capable of collecting data on various atmospheric pollutants, including NO_2, SO_2, CO, and HCHO, on a global scale (Jamei et al., 2022). These data are invaluable for assessing air quality, understanding pollutant distribution, and evaluating their impact on public health and the environment (Jamei et al., 2022).

Additionally, Google Earth Engine serves as a powerful platform for processing satellite and geospatial data, offering comprehensive tools for spatiotemporal analysis. This platform enables access to a vast repository of satellite data, which can be processed and analyzed over various temporal and spatial scales (Ghasempour et al., 2021). Combining satellite data from sources like Giovanni and Sentinel-5P using tools such as Google Earth Engine provides a more accurate and effective (Omokpariola et al., 2024) means of assessing pollutant changes in specific regions, such as Baghdad and Damascus.

Baghdad and Damascus, as two major cities in the Middle East, face unique air pollution challenges due to factors like high population density, industrial activity, and extensive transportation networks. These cities are significantly affected by air pollution, which can lead to severe health and environmental consequences (Rabee, 2015; Meslmani, 2004). Furthermore, climate changes and political developments in these regions may influence pollutant characteristics and their variation over time. Therefore, precise monitoring and assessment of air pollutants using satellite technologies are crucial to mitigating risks and improving the quality of life in these areas. Air pollution, particularly in large urban areas, is a significant environmental and public health concern worldwide. The accumulation of harmful pollutants in the atmosphere, including nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon monoxide (CO), formaldehyde (HCHO), and aerosols, has been linked to various respiratory and cardiovascular diseases, as well as broader environmental issues such as climate change and acid rain. Cities in the Middle East, including Baghdad and Damascus, are particularly vulnerable to these pollutants due to high population densities, industrial activities, transportation emissions, and political instability that may affect environmental management efforts (Rabee, 2015; Meslmani, 2004).).

Satellite-based remote sensing technologies, such as Sentinel-5P and tools like Giovanni NASA, provide valuable opportunities for overcoming these challenges. These technologies allow for the continuous monitoring of atmospheric pollutants over vast areas and can provide crucial data for understanding pollution dynamics. However, despite the availability of satellite data, a comprehensive comparison of air pollution trends, including NO_2, SO_2, CO, HCHO, and aerosols, using these platforms in regions such as Baghdad and Damascus, has not been sufficiently explored. Existing studies primarily focus on individual pollutants or limited geographical areas, with little emphasis on comparing data from different satellite sources or analyzing temporal variations within urban environment (Omokpariola et al., 2024; Rana et al., 2023).

Numerous studies have utilized satellite-based remote sensing and advanced analytical platforms to monitor and assess atmospheric pollutants. These studies provide insights into pollutant distribution, temporal variations, and the utility of different satellite tools.

Maurya et al. (2022) demonstrated the effectiveness of Sentinel-5P in capturing spatial and temporal variations in air pollutants, emphasizing its role in urban air quality assessments. Similarly, studies have validated the accuracy of TROPOMI measurements against ground-based data, showcasing its reliability for pollution monitoring in regions with limited ground infrastructure (Ialongo et al., 2020).

Giovanni NASA, an online visualization and analysis tool, has also been widely used for processing and analyzing satellite data. The platform enables researchers to explore trends in atmospheric pollutants across various temporal and spatial scales. For instance, Sharma et al. (2024) used Giovanni to investigate long-term trends in NO_2 and SO_2 levels across Asian cities, highlighting the impact of industrialization and policy interventions on air quality.

While significant advancements have been made in air pollution monitoring, most studies have been limited to specific pollutants or regions and have rarely integrated multiple data sources. Moreover, comparative studies between different satellite platforms, such as Giovanni NASA and Sentinel-5P, are scarce, particularly for Middle Eastern cities like Baghdad and Damascus. This lack of comprehensive analysis limits the understanding of pollution dynamics and their health and environmental implications in these cities.

Building upon the findings of previous research, this study addresses the gaps in the literature by integrating and comparing data from Giovanni NASA and Sentinel-5P to evaluate trends in NO_2, SO_2, CO, HCHO, and aerosols in Baghdad and Damascus. This approach not only provides a more holistic understanding of air pollution in these cities but also demonstrates the potential of satellite tools for overcoming monitoring challenges in data-scarce regions. The primary objective of this study is to evaluate and compare changes in the concentrations of key atmospheric pollutants, including nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon monoxide (CO), formaldehyde (HCHO), and aerosols, in two major Middle Eastern cities Baghdad and Damascus. By leveraging satellite data from Giovanni NASA and Sentinel-5P through the Google Earth Engine platform, this study aims to provide a comprehensive understanding of pollutant dynamics in these regions over time.

Specific Objectives of this study are:

- To analyze temporal and spatial variations in the concentrations of NO_2, SO_2, CO, HCHO, and aerosols in Baghdad and Damascus using data from Sentinel-5P and Giovanni NASA.
- To compare the outputs of the two satellite-based platforms in terms of pollutant measurement accuracy, coverage, and usability.
- To identify seasonal trends and potential sources of pollutants in these cities, such as industrial activities, transportation, and natural events (e.g., dust storms).
- To assess the effectiveness of combining satellite datasets with cloud-based platforms like Google Earth Engine for air quality monitoring in data-scarce regions.

Research Questions:

- How have NO_2, SO_2, CO, HCHO, and aerosol concentrations changed over time in Baghdad and Damascus?
- What similarities and differences can be observed in the data provided by Giovanni NASA and Sentinel-5P for the selected pollutants?
- What are the major factors driving the observed spatial and temporal variations in pollutant concentrations in these cities?
- How can the integration of satellite data and Google Earth Engine improve the monitoring and management of air quality in urban areas of the Middle East?

A comparative analysis of Giovanni NASA and Sentinel-5P data will demonstrate complementary strengths, with Sentinel-5P providing higher spatial resolution and Giovanni NASA offering broader temporal datasets, thereby enabling a more comprehensive understanding of air pollution dynamics in the study regions. This research is valuable as it addresses critical gaps in air pollution monitoring for data-scarce regions like Baghdad and Damascus. By leveraging satellite data from Giovanni NASA and Sentinel-5P, the study provides comprehensive insights into the spatial and temporal dynamics of key pollutants, which are often difficult to assess using traditional ground-based methods. The results of this study will support policymakers in developing targeted strategies to manage air quality and mitigate its health and environmental impacts. Furthermore, the integration of satellite datasets with advanced platforms like Google Earth Engine introduces an innovative and scalable methodology for environmental monitoring, which can be applied to other urban regions globally. Given the increasing environmental and public health challenges in the Middle East, this research contributes to a deeper understanding of pollution dynamics, aiding sustainable urban planning and enhancing environmental resilience in the region.

2. Material and Methods

This chapter outlines the data sources, tools, and methodological approach employed in this study to analyze and compare atmospheric pollutants in Baghdad and Damascus.

2.1 Data Sources

The study utilizes satellite-based datasets from two primary sources:

- Sentinel-5P (TROPOMI): High-resolution data on atmospheric pollutants such as NO_2, SO_2, CO, HCHO, and aerosols, retrieved from the European Space Agency (ESA) (Ghasempour et al., 2021).
- Giovanni NASA: A web-based platform providing temporal and spatial datasets of atmospheric pollutants for trend analysis and visualization (Le et al., 2024).

Both data sources provide global coverage, enabling a robust comparison of pollutant concentrations in the study regions.

2.2 Study Area

The analysis focuses on Baghdad (Iraq) and Damascus (Syria), two urban centers in the Middle East characterized by high population densities, extensive industrial activities, and significant pollution challenges (Ali & Mashee 2014; Rain, 2009). These cities were selected due to their environmental relevance and the availability of satellite data (Fig. 1).

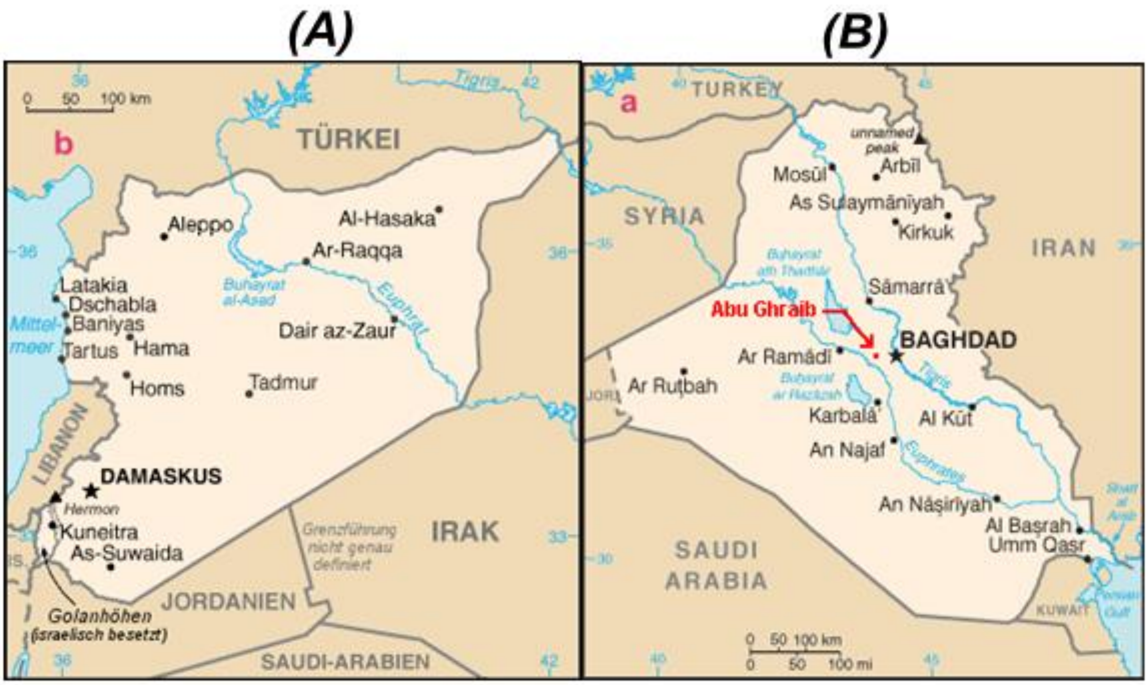

Fig.1 – Study area Damascus (A) and Baghdad (B)

2.3 Methodological Framework

The methodological approach consists of the following steps:

- Data Collection and Preprocessing:

Satellite datasets from Sentinel-5P and Giovanni NASA were collected for NO_2, SO_2, CO, HCHO, and aerosols. Data were preprocessed for compatibility, including regridding, unit standardization, and cloud contamination removal.

- Geospatial Analysis in Google Earth Engine:

The Google Earth Engine platform was used to process, visualize, and analyze satellite data. This cloud-based tool facilitated the extraction of spatial and temporal trends in pollutant concentrations.

- Comparative Analysis:

The study compared pollutant levels observed in the two datasets, focusing on spatial resolution, temporal trends, and regional variations. Seasonal and annual patterns were also evaluated to identify key drivers of pollution.

3. Results

3.1. Comprehensive Analysis of Pollutants in Baghdad and Damascus

The Fig.2 shows the concentration and distribution of five key pollutants, including Aerosol, HCHO (Formaldehyde), NO_2 (Nitrogen Dioxide), CO (Carbon Monoxide), and SO_2 (Sulfur Dioxide), in the cities of Baghdad and Damascus.

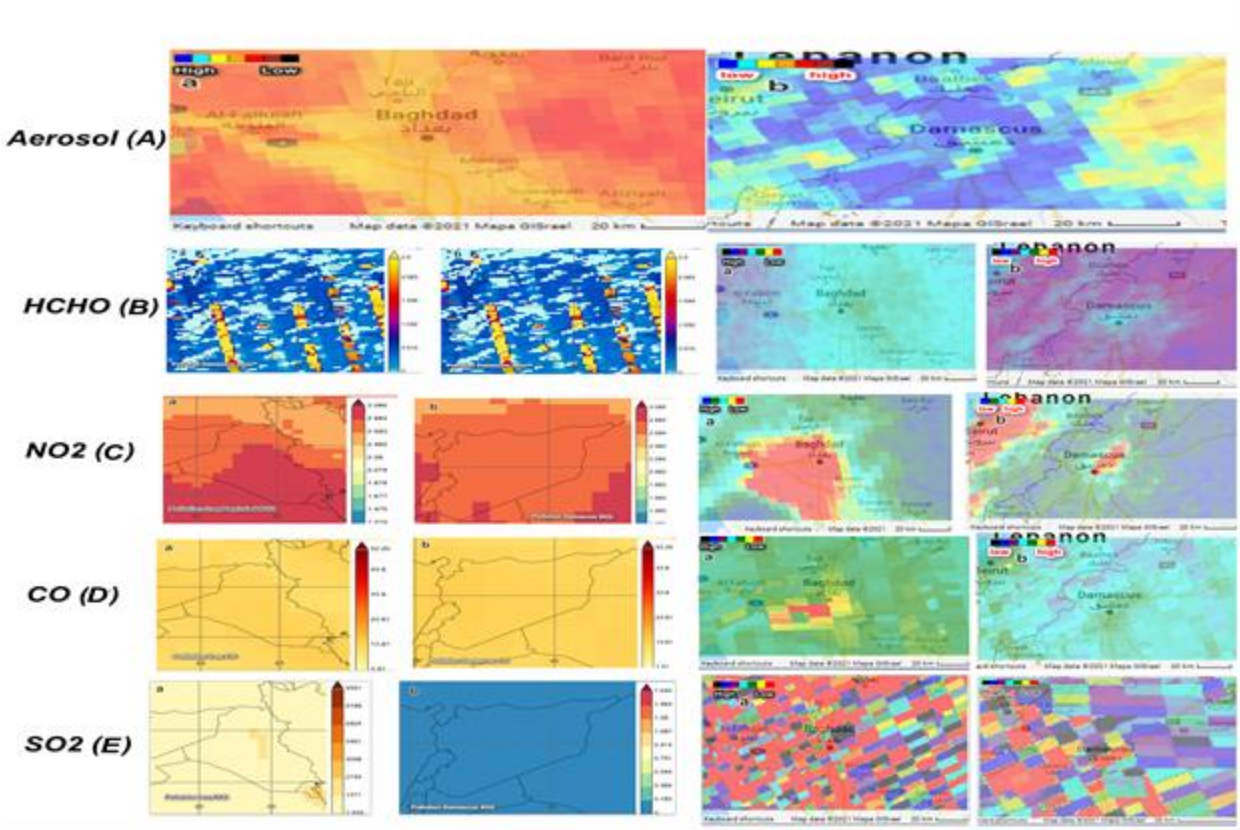

Fig.2 - Spatial distribution of UVAerosol, HCHO, NO_2, CO, and SO_2 pollutants over Baghdad (a) and Damascus (b)

The analysis of each pollutant in these areas is presented separately:

1. Aerosol

Baghdad (a): The aerosol concentrations are significantly higher compared to Damascus. This is evident in both urban and surrounding areas, where the intensity of aerosols indicates widespread pollution sources. The high values are likely attributed to a combination of factors, including intense industrial activity, vehicular emissions, and frequent dust storms, which are prevalent due to Baghdad's arid environment. The outskirts of the city also show elevated aerosol levels, suggesting the influence of desert dust and agricultural activities. These high aerosol levels pose serious environmental and health risks, particularly respiratory and cardiovascular diseases.

Damascus (b): Damascus exhibits considerably lower aerosol levels. The concentrations are generally more localized, with relatively mild intensity even in the urban center. This difference is likely due to the city's smaller industrial base, lower vehicular density, and possibly different meteorological conditions that limit aerosol accumulation. Furthermore, the surrounding areas of Damascus show negligible aerosol presence, highlighting the lack of significant external sources such as desert dust or industrial emissions.

2. HCHO (Formaldehyde)

Baghdad (a):

In Baghdad, the concentration of HCHO shows a relatively uniform distribution, but higher levels are observed in the central urban areas. This distribution pattern is likely due to urban activities such as transportation, fossil fuel combustion, and industrial activities.

Damascus (b):

Damascus also experiences increased concentrations of HCHO in central areas. The intensity of pollution in densely populated urban areas is higher, which appears to be related to the high density of vehicles and the use of low-quality fuels.

3. NO_2 (Nitrogen Dioxide)

Baghdad (a):

The concentration of NO_2 in Baghdad is higher than in Damascus. This is likely due to the higher density of vehicles, heavy industries, and the use of non-clean fuels. Areas with higher population density in the city center show the highest levels of this pollutant.

Damascus (b):

The concentration of NO_2 in Damascus shows a more even distribution across various areas. However, central areas still experience the highest pollution levels. The lower concentration in the suburbs reflects the lesser impact of human activities in these regions.

4. CO (Carbon Monoxide)

Baghdad (a):

In Baghdad, the concentration of CO is higher in urban areas. This pollutant is primarily produced by incomplete combustion of fossil fuels in vehicles and power plants. The high CO concentration in Baghdad indicates significant issues related to fuel quality and transportation systems.

Damascus (b):

The CO distribution pattern in Damascus is similar to Baghdad, but the intensity appears to be lower. This difference may be related to the smaller population and more limited industrial activities in Damascus.

5. SO_2 (Sulfur Dioxide)

Baghdad (a):

Baghdad shows significant concentrations of SO_2, especially in industrial areas and near power plants. This pollutant is primarily released from the burning of sulfur-containing fuels in industries and power plants.

Damascus (b):

SO_2 levels in Damascus are lower, but still noticeable in densely populated urban areas. This pattern suggests that the main sources of SO_2 in Damascus are traffic and the burning of non-standard fuels.

The results indicate that both cities face serious air pollution challenges. However, the intensity and distribution of pollutants in Baghdad are more severe due to the higher population density and industrial activities. The comparison of the data shows that remote sensing tools (such as Sentinel-5P and Giovanni) are valuable for monitoring pollution and provide useful information about the sources and severity of pollution. These findings can assist policymakers in making informed decisions to reduce pollution.

3.2. Comprehensive Analysis of Pollutants in Baghdad and Damascus (2019–2022)

The Fig.3 includes charts depicting changes in pollutants such as the UV Aerosol Index, HCHO (Formaldehyde), NO_2 (Nitrogen Dioxide), CO (Carbon Monoxide), and SO_2 (Sulfur Dioxide) in the cities of Baghdad and Damascus from 2019 to 2022.

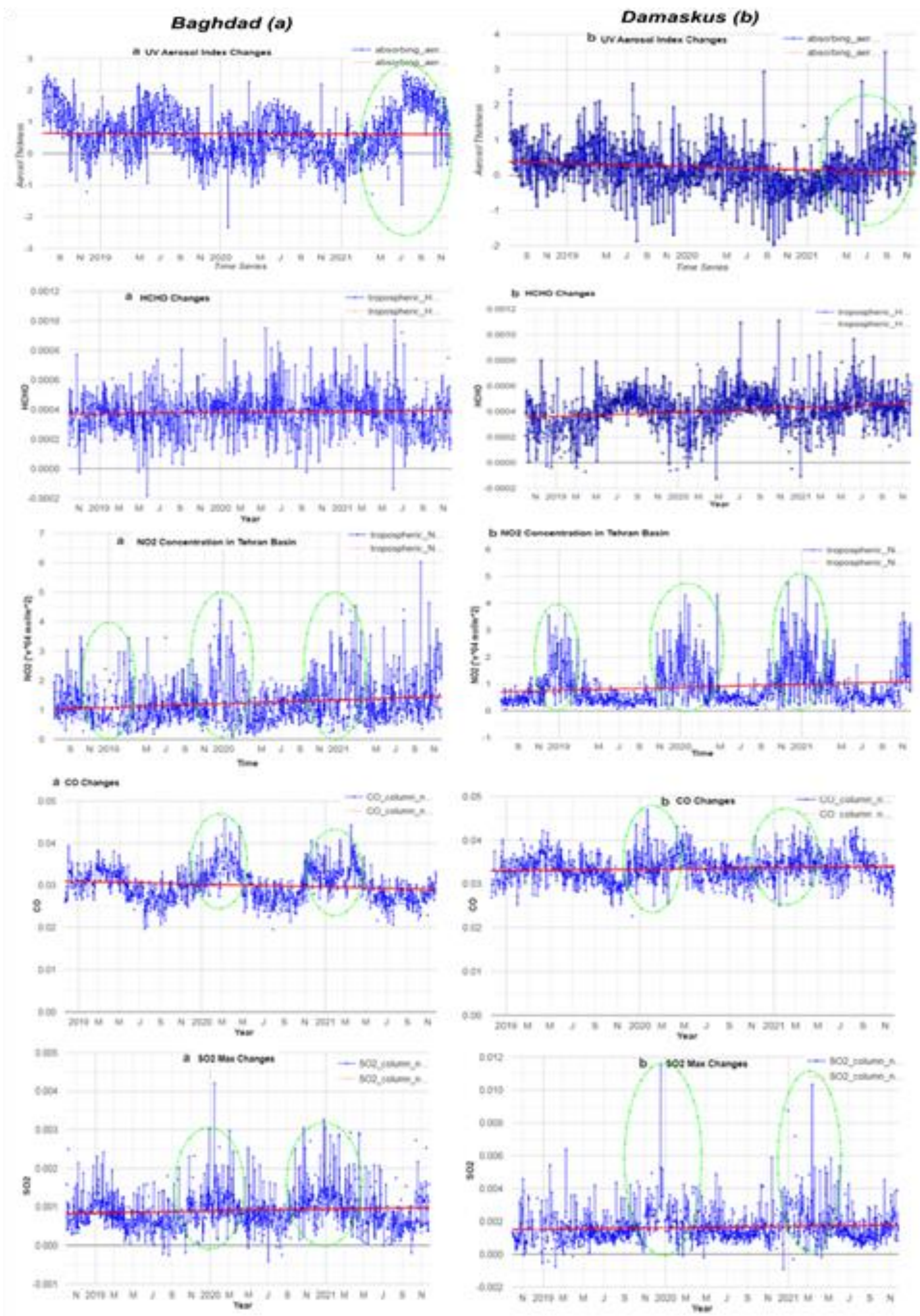

Fig.3 - Temporal variations of UV Aerosol Index, HCHO, NO_2, CO, and SO_2 in Baghdad (a) and Damascus (b) during 2019–2022

Below, each pollutant is examined separately for each city:

1. UV Aerosol Index

Baghdad (a):

The changes in the UV Aerosol Index in Baghdad show a relatively stable trend, with a significant increase observed during specific periods in 2021 (indicated by the green circle). This increase may be associated with events such as dust storms or an upsurge in industrial activities.

Damascus (b):

The chart for Damascus shows a similar pattern, but the fluctuations are less intense. However, higher values during similar periods in 2021 suggest regional effects similar to those in Baghdad.

2. HCHO (Formaldehyde)

Baghdad (a):

The HCHO changes in Baghdad show fluctuations, with higher concentrations observed during the warmer months, such as summer. This could be due to human activities and weather conditions related to increased sunlight exposure.

Damascus (b):

In Damascus, the levels of HCHO are lower compared to Baghdad, and the fluctuation pattern appears more uniform, likely due to lower population density and more limited human activities.

3. NO_2 (Nitrogen Dioxide)

Baghdad (a):

The concentration of NO_2 in Baghdad notably increases during the colder months (winter). This increase could be linked to the use of heating fuels and the phenomenon of temperature inversion.

Damascus (b):

A similar pattern is observed in Damascus, but the overall levels are lower. This suggests less impact from transportation and industrial activities compared to Baghdad.

4. CO (Carbon Monoxide)

Baghdad (a):

CO levels in Baghdad show a slight decline over the period under review, but seasonal increases are observed in the winter months due to incomplete combustion of fossil fuels.

Damascus (b):

The CO changes in Damascus are similar to those in Baghdad but with lower concentrations and fewer fluctuations, indicating less dense emission sources.

5. SO_2 (Sulfur Dioxide)

Baghdad (a):

The SO_2 concentration in Baghdad shows intermittent increases, peaking during specific periods of the year, such as winter. This is likely due to the use of sulfur-containing fuels in power plants and industries.

Damascus (b):

Damascus shows lower SO_2 levels, but similar peaks are observed during certain periods. This pattern suggests that transportation and the use of low-quality fuels in the region contribute to SO_2 emissions.

The charts indicate that both cities are influenced by human activities and weather conditions, but the pollution intensity in Baghdad is higher due to the greater population density and industrial activities. Seasonal variations in all pollutants are evident, highlighting the importance of managing pollutants in relation to weather conditions and different seasons.

3.3. Land Use Analysis of Baghdad and Damascus: Urban Expansion and Limited Vegetation

The land use maps of Baghdad and Damascus reveal similar patterns in the distribution and types of land use (Fig. 4). The red areas, representing urban zones, dominate both maps. These zones include completed buildings and those under construction, highlighting the concentrated urban development and expansion of residential and commercial infrastructure. Another significant observation is the minimal vegetation cover in both cities. This indicates a noticeable lack of green spaces and natural resources, likely due to the rapid urban expansion. Such limited vegetation can lead to several challenges, including increased environmental temperatures, reduced air quality, and loss of biodiversity. These trends emphasize the importance of sustainable urban planning in Baghdad and Damascus. There is a need to balance development with the creation and preservation of green spaces. Initiatives like urban greening projects, protecting natural resources, and raising public awareness about environmental issues can help address these challenges effectively.

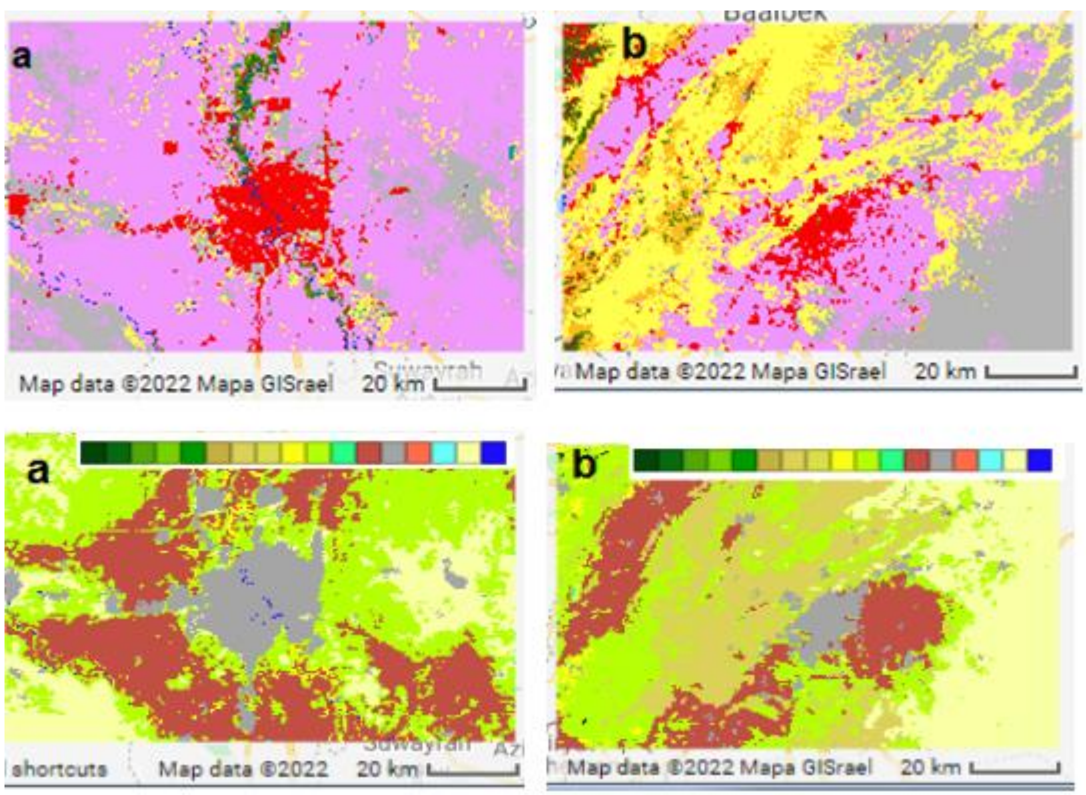

Fig.4 – Land use Baghdad (a) and Damascus (b)

3.4. NDVI

In Baghdad, the arid and hot climate results in sparse vegetation cover, while Damascus benefits from a more abundant vegetation cover due to its relatively humid conditions. This highlights the role of moisture availability in influencing vegetation growth. In Baghdad, the distribution of vegetation is concentrated near the Tigris River, where water availability supports plant growth. In contrast, Damascus shows higher vegetation density, largely attributed to its proximity to the Mediterranean Sea, which provides more favorable conditions for dense vegetation growth (Fig. 5). This analysis underscores the interplay between climatic factors, water availability, and vegetation cover, which collectively impact land surface temperature patterns in these regions.

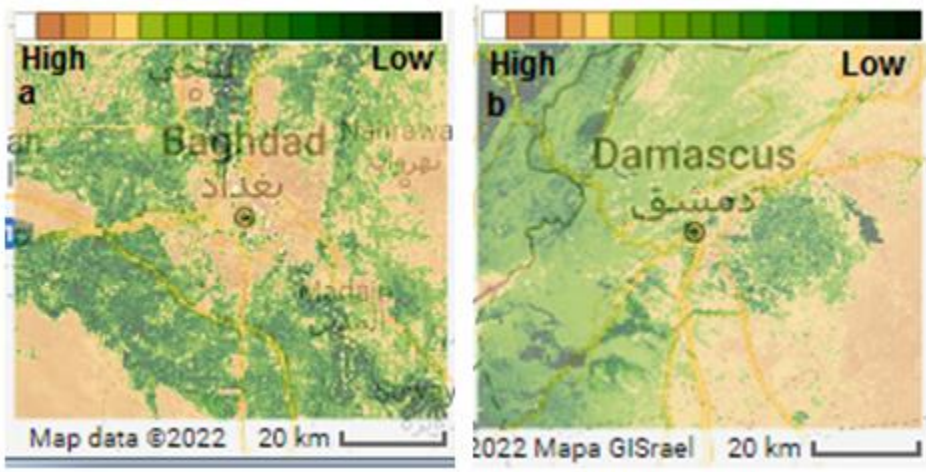

Fig. 5- NDVI Baghdad (a) and Damascus (b)

3.5. Runoff Variations in Baghdad and Damascus (2000–2020): A Comparative Analysis

The runoff maps for Baghdad and Damascus from 2000 to 2020 illustrate differences in runoff levels influenced by their distinct climatic and geographical settings (Fig. 6). Damascus, being near the Mediterranean Sea, experiences slightly higher runoff compared to Baghdad, which lies in a hot and arid region. The data also reveal temporal fluctuations in runoff. Notably, Damascus recorded higher runoff in 2003 and 2012, likely due to increased precipitation or specific hydrological conditions during those years. Conversely, Baghdad experienced higher runoff in 2016 and 2019, potentially influenced by localized rainfall events or other climatic factors. These variations highlight the dynamic nature of runoff influenced by climate, geography, and temporal factors in both cities. Understanding these patterns is critical for effective water resource management and urban planning in the region.

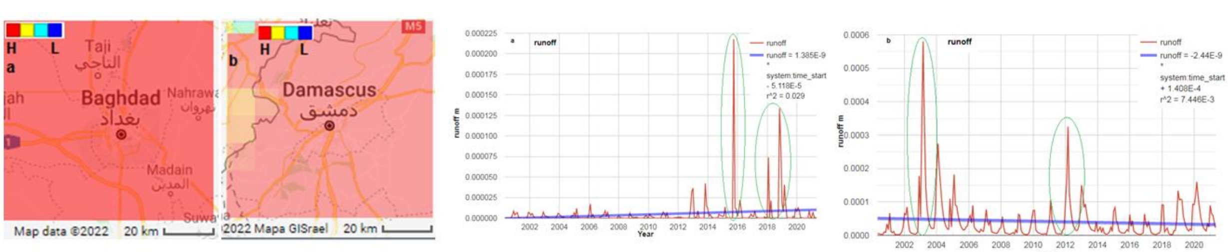

Fig.6 - Runoff Patterns in Baghdad (a) and Damascus (b) (2000–2020)

3.6. Windrose Analysis of Baghdad and Damascus: Dominant Wind Directions and Speeds

In the windrose for Baghdad, the strongest winds, exceeding 20 meters per second, are observed from the southeast, specifically from the direction of Iran and Ahvaz. This region experiences intense winds that may be influenced by regional weather systems and topography. Additionally, the prevailing wind in Baghdad is from the northwest, coming from Turkey and Syria, indicating the primary wind direction in this area. For Damascus, the windrose reveals that the strongest winds originate from the southwest, coming from Iraq and Jordan. These winds also reach high speeds, likely driven by local and regional climatic factors. The prevailing wind direction in Damascus is from the northeast, flowing from Turkey, which influences the general atmospheric circulation patterns in the region. These wind patterns highlight the unique climatic conditions affecting both cities and their surrounding environments, with varying wind strengths and prevailing directions based on their geographical locations and regional influences. Understanding these wind dynamics is essential for urban planning, climate studies, and environmental management in both cities.

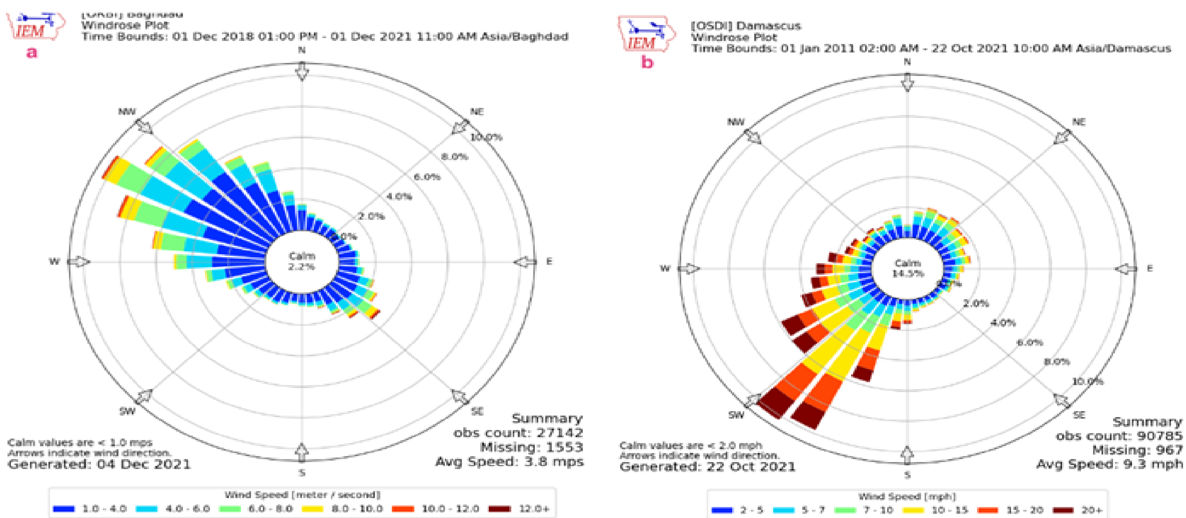

Fig.7- Windrose Analysis of Baghdad and Damascus: Dominant Wind Directions and Speeds

3.7. Population Distribution and Density in Baghdad and Damascus

Figure 8 illustrates the population distribution and density in the cities of Baghdad (b) and Damascus (a) from 2019 to 2021. The map shows that while the overall population distribution in Baghdad is more spread out, Damascus exhibits a higher population density. This indicates that Baghdad has a larger geographical area with a lower concentration of people, whereas in Damascus, a smaller area is densely populated, particularly in urban and central areas. The differences in population distribution and density between the two cities have significant implications for several environmental factors, including air quality, land surface temperature, and vegetation cover:

Air Pollution: In cities with higher population density, like Damascus, pollution tends to be more concentrated, especially in central areas. The increased number of vehicles, industries, and residential activities in these areas leads to higher emissions of pollutants, contributing to poorer air quality. In contrast, Baghdad's more spread-out population distribution results in slightly lower concentrations of pollutants, although the overall pollution may still be significant due to other factors like industrial activity and traffic.

Land Surface Temperature (LST): Areas with higher population density often experience elevated land surface temperatures due to increased human activity, construction, and a reduction in vegetation cover. Damascus, with its higher population density, is likely to experience higher localized temperatures in urban areas compared to Baghdad. The large, spread-out population in Baghdad means there are more open or underdeveloped areas, which may help mitigate the heat island effect to some extent, though these areas are still impacted by urbanization.

Vegetation Cover: Urban areas with higher population density, like Damascus, often face greater pressure on green spaces and natural resources. This pressure leads to a reduction in vegetation cover as more land is developed for housing and commercial purposes. In contrast, the more dispersed population in Baghdad means that there may be relatively larger areas of undeveloped land, but urban sprawl still encroaches on natural areas, limiting the extent of green spaces and vegetation cover.

Infrastructure Strain: The higher population density in Damascus places greater strain on infrastructure, including waste management, water supply, and energy resources. This often exacerbates environmental issues such as pollution and unsustainable resource use. In Baghdad, although the population is more spread out, rapid urban growth and infrastructure demands still create significant environmental challenges, including increased waste generation and resource consumption. In summary, the population distribution and density in Baghdad and Damascus have direct and indirect effects on various environmental factors. While Damascus faces the challenges of managing a dense urban population with higher levels of pollution and temperature, Baghdad must contend with issues related to urban sprawl and the pressure on resources and green spaces. Both cities must focus on sustainable urban planning to address these challenges and minimize their environmental impacts.

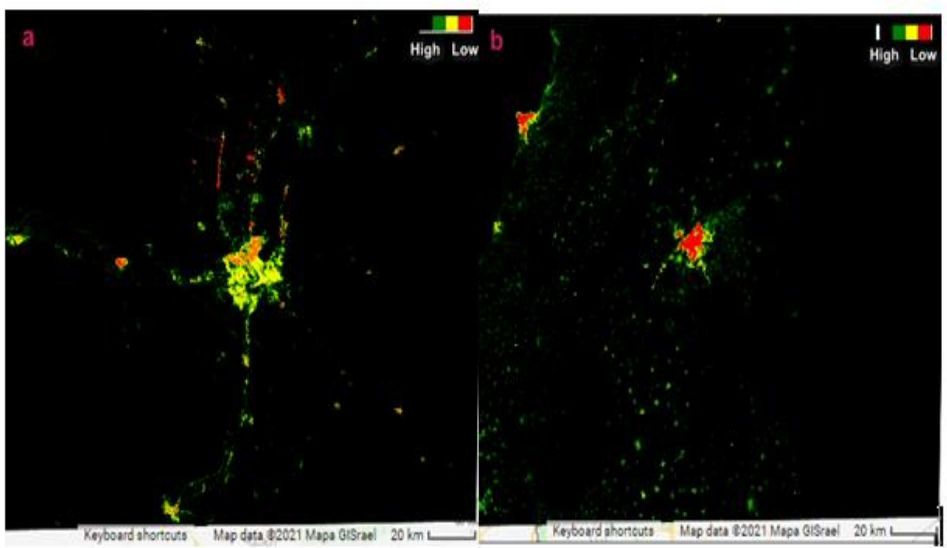

Fig. 8 - Population Distribution and Density in Baghdad and Damascus (2019-2021)

3.8. Analysis of NO2 and PM2.5 Concentrations in Baghdad and Damascus during 2020

Fig. 9 shows the 15-day moving average concentrations of nitrogen dioxide (NO2) and particulate matter (PM2.5), along with the daily AQI, from January to June 2020. The data reveals a marked reduction in pollution levels during the quarantine period (indicated by the green zone), particularly in relation to the COVID-19 pandemic, which led to global lockdowns and restrictions on transport and industrial activities. These restrictions reduced emissions from vehicles, factories, and other sources of air pollution.

The graph illustrates that the concentrations of NO2 (in green) and PM2.5 (in blue), as well as the AQI values (in red), fluctuated significantly in both cities. In particular, while the reduction in pollution was noticeable across both Baghdad and Damascus during the quarantine period, Baghdad exhibited consistently higher levels of pollutants. This is likely due to its more concentrated urban development and industrial activity, even during restricted periods.

The findings also highlight that the Ramadan period (marked in yellow) had an impact on pollutant levels in cities with significant Muslim populations. These findings underscore the role of human activity and governmental policies in influencing air quality. The temporary decline in pollution during quarantine offers valuable insight into how limiting transportation and industrial activity can reduce air pollution levels. However, it is evident that Baghdad, with its more intense urbanization, remains more vulnerable to higher pollutant levels compared to Damascus, even during such exceptional circumstances.

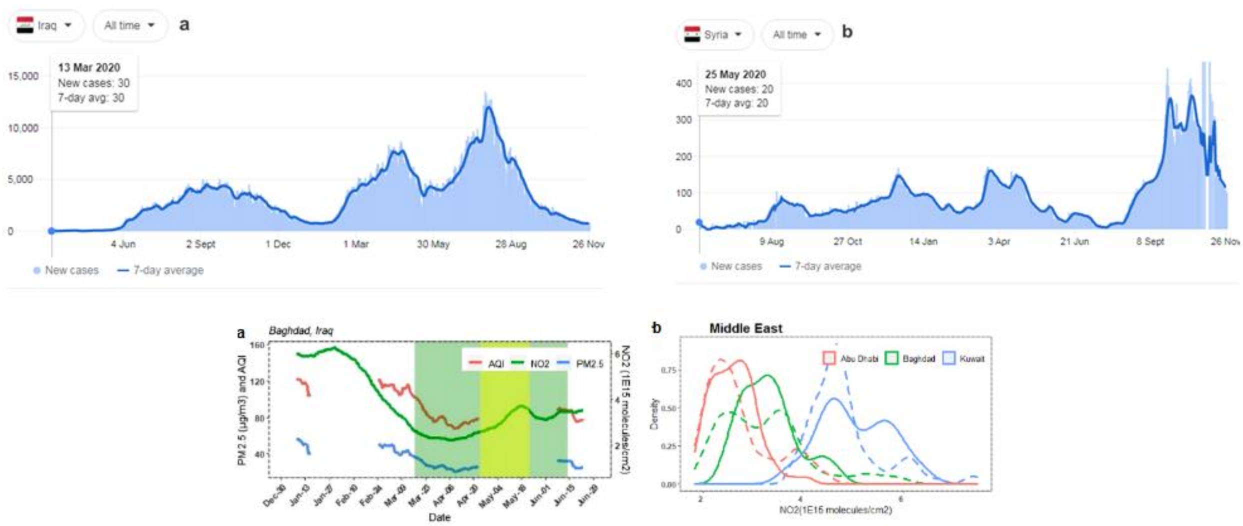

Fig. 9 -Average 15-Day NO2 Concentrations and Daily PM2.5 Density in 2020

4. Discussion

In this study the primary objective of this study is to assess and analyze the levels and distribution of key atmospheric pollutants, including nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon monoxide (CO), formaldehyde (HCHO), and aerosols in the cities of Baghdad and Damascus, over the period from 2019 to 2022. These pollutants were selected due to their significant impact on air quality and public health, as well as their sensitivity to human activities such as urbanization, transportation, and industrial processes.

To achieve this, remote sensing data was employed as a vital tool to monitor and analyze these pollutants at a regional scale. Specifically, two main data sources were used: Sentinel-5P (TROPOMI) and Giovanni NASA, which are capable of providing high-resolution atmospheric data for pollutant concentration analysis.

The results of this study highlight significant differences in air pollution levels, land use, vegetation cover, and other environmental factors between the cities of Baghdad and Damascus. While both cities face pressing environmental challenges, the intensity and distribution of pollutants are more severe in Baghdad, primarily due to its higher population density and the expansion of industrial activities. These findings underscore the critical need for informed policy decisions and sustainable urban development practices to mitigate pollution and improve environmental quality.

One of the key observations from the data is the prominent role of human activities in influencing air quality. The analysis of pollutant levels, including UV Aerosol Index, HCHO (formaldehyde), NO_2 (nitrogen dioxide), CO (carbon monoxide), and SO_2 (sulfur dioxide), reveals that Baghdad experiences higher levels of pollution across all indicators compared to Damascus. This disparity can be attributed to several factors, including the greater industrial activity in Baghdad, which is a major source of air pollutants, as well as the higher population density and associated vehicular emissions. In contrast, Damascus exhibits a more modest level of pollution, which may reflect less industrialization and a relatively lower population density.

Moreover, seasonal variations in pollutant levels were observed in both cities, with higher concentrations during colder months, likely due to increased heating demand and the phenomenon of atmospheric inversion. Such seasonal patterns reinforce the importance of considering climate and weather conditions in pollution management strategies. These findings align with previous studies that have highlighted the seasonal nature of urban air pollution, particularly in regions with cold winters and high heating demands (Soleimanpour et al., 2023).

The role of vegetation and climate in shaping the environmental landscape of both cities is also critical. The land use maps of Baghdad and Damascus show striking similarities in their urban expansion, with large red areas indicating the dominance of urban zones that include both completed buildings and those under construction. This urban sprawl, especially in Baghdad, puts considerable pressure on the limited green spaces, which are already sparse in both cities. The minimal vegetation cover in both cities is a key factor contributing to higher urban heat island effects, poorer air quality, and the loss of biodiversity. This pattern is consistent with studies on rapid urbanization and its impacts on environmental quality (Zarin & Esraz-Ul-Zannat, 2023).

In Baghdad, the arid and hot climate results in even more limited vegetation, with plant growth concentrated near the Tigris River where water availability supports vegetation. In contrast, Damascus benefits from relatively more favorable climatic conditions, including higher moisture availability due to its proximity to the Mediterranean Sea. These differences in vegetation density significantly influence the land surface temperature patterns, with Baghdad experiencing more extreme temperature variations due to the scarcity of vegetation. Similar findings have been reported in studies examining the relationship between urbanization, climate, and vegetation cover (Li et al., 2020).

The analysis of runoff data between 2000 and 2020 further illustrates the distinct climatic and geographical conditions of the two cities. Damascus, located near the Mediterranean, experiences slightly higher runoff compared to Baghdad, which is situated in a hot and arid region. However, both cities show temporal fluctuations in runoff, indicating the dynamic nature of hydrological conditions influenced by factors such as precipitation and local climatic conditions. These findings are essential for understanding water management needs in both cities, as runoff levels directly affect water resources and urban planning.

Wind dynamics, as illustrated by the windrose diagrams for Baghdad and Damascus, reveal significant regional differences. In Baghdad, the strongest winds come from the southeast (Iran and Ahvaz) and northwest (Turkey and Syria), which reflect both local and regional climatic influences. Similarly, Damascus experiences strong winds from the southwest (Iraq and Jordan) and the northeast (Turkey), driven by varying regional factors. These wind patterns play a crucial role in the dispersion of pollutants, affecting air quality in different parts of each city. Understanding these wind dynamics is vital for urban planning, air quality management, and climate studies in both regions.

The impact of the Ramadan period on air pollution levels in both cities highlights the influence of human activity on pollution. During this period, marked by reduced industrial and transportation activities, there was a noticeable decrease in pollutant levels, particularly in areas with significant Muslim populations. This suggests that limiting human activity, such as during lockdowns or specific policy interventions, can have a positive effect on reducing pollution. However, it is important to note that Baghdad, with its higher levels of urbanization, remains more susceptible to higher pollution levels than Damascus, even under such exceptional circumstances.

In summary, the findings from this study underscore the complex relationship between urbanization, pollution, vegetation cover, and climate in Baghdad and Damascus. While both cities face significant environmental challenges, Baghdad's more intense urbanization, coupled with its industrial activities and limited green spaces, makes it more vulnerable to air pollution and other environmental issues. Conversely, Damascus, though still impacted by pollution and urbanization, benefits from a more favorable climatic setting and relatively better vegetation cover, which provides some respite from the urban heat island effect.

These results reinforce the importance of sustainable urban planning and the need to incorporate green spaces and environmental considerations into development strategies. Both cities should focus on improving air quality, protecting natural resources, and promoting public awareness about environmental issues. The role of remote sensing tools, such as Sentinel-5P and Giovanni, in monitoring pollution is invaluable in providing insights into the sources and severity of pollution, enabling better management and decision-making. Moreover, the importance of seasonal variations, wind patterns, and runoff dynamics in shaping urban environmental conditions should not be overlooked. Through a combination of effective policy, technological solutions, and sustainable development practices, both cities can work towards reducing their environmental impact and improving the quality of life for their residents.

5. Conclusion

This study provides a comprehensive analysis of atmospheric pollutants in the cities of Baghdad and Damascus from 2019 to 2022, using remote sensing data from Sentinel-5P (TROPOMI) and Giovanni NASA. The findings highlight significant differences in pollution levels between the two cities, with Baghdad experiencing more severe pollution due to its higher population density, greater industrialization, and rapid urban expansion. Seasonal variations in pollutant concentrations were also observed, with higher levels during colder months, emphasizing the need to factor in climate and weather conditions in air quality management strategies.

The study further underscores the critical role of vegetation cover and climatic conditions in shaping the environmental landscape. Baghdad's arid climate and limited green spaces contribute to more extreme temperature variations and poorer air quality, whereas Damascus benefits from more favorable conditions for vegetation growth, reducing some of the environmental stresses. Additionally, the analysis of runoff data and wind dynamics reveals the influence of both geographic and climatic factors on water resources and pollutant dispersion in these cities.

The Ramadan period’s impact on pollution levels demonstrates how human activities, such as reductions in industrial and transportation activities, can effectively lower pollutant concentrations, further highlighting the role of policy interventions in improving air quality. In conclusion, while both cities face significant environmental challenges, the results emphasize the need for sustainable urban planning, enhanced green spaces, and the use of remote sensing tools for better pollution monitoring and management. The findings contribute valuable insights for policymakers seeking to mitigate pollution and improve the overall quality of life for residents in both cities.

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