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Spatial Analysis of Atmospheric Pollutants in An-Najaf Governorate Based on Sentinel-5 Satellite Observations

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Abstract:
Sentinel-5P satellite imagery, in combination with Geographic Information Systems (GIS), was utilized to analyze the spatial distribution of the atmospheric pollutant gases—ozone (O_3), sulfur dioxide (SO_2), and carbon monoxide (CO)—across An-Najaf Governorate in central Iraq. The study aimed to assess patterns of pollutant concentration and identify the anthropogenic and environmental factors influencing their distribution. Sentinel-5P satellite data were processed and analyzed using ArcMap 10.8, qualifying high-resolution mapping of pollutant levels across the governorate's nine districts with varying land uses. Results showed that CO concentrations peaked in Abbasiya, Al-Hurriyah, Al-Kufa, and Al-Qadisiyah, while SO_2 concentrations were highest in Al-Hurriyah, Abbasiya, and Haidariyah. Elevated levels of O_3 were recorded in Al-Hurriyah, Abbasiya, Haidariyah, and An-Najaf Center. Furthermore, the Normalized Difference Built-up Index (NDBI) was employed to explore the correlations between pollutant levels and urban development, revealing a strong positive relationship between gas concentrations and building density. Pearson correlation coefficients confirmed that areas with dense human activity, industrial presence, and power generation facilities experience significantly higher pollutant emissions. The study underscores the critical role of remote sensing in environmental monitoring and highlights the urgent need for sustainable urban planning to mitigate air pollution and its associated health, environmental, and economic impacts.
Keywords: Sentinel-5p, ArcMap, An-Najaf, Correlation, Air Pollution, Ozone.

التحليل المكاني لملوثات الغلاف الجوي في محافظة النجف بناءً على بيانات القمر الصناعي سنتنل-5

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الخلاصة:
استُخدمت صور القمر الصناعي Sentinel-5P، بالاشتراك مع نظم المعلومات الجغرافية (GIS)، لتحليل التوزيع المكاني للغازات الملوثة للهواء (الأوزون (O_3) وثاني أكسيد الكبريت (SO_2) وأول أكسيد الكربون)

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(CO) في محافظة النجف بوسط العراق. هدفت الدراسة إلى تقييم أنماط تركيز الملوثات وتحديد العوامل البشرية والبيئية المؤثرة على توزيعها. جرت معالجة بيانات القمر الصناعي Sentinel-5P وتحليلها باستخدام برنامج ArcMap 10.8، مما أتاح رسم خرائط عالية الدقة لمستويات التلوث في مختلف مناطق المحافظة التسع ذات الاستخدامات المتنوعة للأراضي. أظهرت النتائج أن تركيزات أول أكسيد الكربون بلغت ذروتها في العباسية والحرية والكوفة والقادسية، بينما كانت تركيزات ثاني أكسيد الكبريت أعلى ما يمكن في الحرية والعباسية والحيدرية. وسُجلت مستويات مرتفعة من الأوزون في الحرية والعباسية والحيدرية ووسط النجف. علاوة على ذلك، استُخدم مؤشر الفرق المعياري للمناطق المبنية (NDBI) لاستكشاف العلاقات بين مستويات الملوثات والتنمية الحضرية، وكشف عن وجود علاقة إيجابية قوية بين تركيزات الغازات وكثافة المباني. وأكدت معاملات ارتباط بيرسون أن المناطق ذات الكثافة السكانية العالية والوجود الصناعي ومرافق توليد الطاقة، تشهد انبعاثات ملوثات أعلى بكثير. وتؤكد هذه الدراسة على الدور الحاسم للاستشعار عن بُعد في الرصد البيئي، وتُبرز الحاجة المُلحة إلى تخطيط حضري مستدام للتخفيف من تلوث الهواء وما يرتبط به من آثار صحية وبيئية واقتصادية.

1-Introduction:

The problem of pollution, both present and global, is one of the most destructive factors affecting air quality, posing a significant challenge to health organizations and the general public [1], particularly in developed and developing countries. Humans inhale daily from the air the necessary quantities of oxygen for their survival [2] but with those quantities enter proportions of other gases and suspended particles present in the air that cause pollution [3] which negatively affects human health [4], as research has shown that adverse health effects do not result from exposure Adverse health effects do not result from sudden exposure to polluting gases. However, they may occur with continuous consumption over time. It was found that continuous exposure may reduce a person's lifespan by approximately eight months on average and more than two years in the most polluted cities worldwide [5]. Studies have shown that urban and air pollution may be attributed to two factors: natural factors and human factors [6]. Natural factors include forest burning, dust storms, volcanoes, and others. The second factor, which constitutes the largest percentage, is the human factor, referring to the means of transportation, waste disposal, and the burning of fossil fuels, such as natural gas and oil, to produce energy, as well as the generation of waste. Industrial and fuel use for cooking, heating, and other activities that produce dust and suspended particles are all the results of human practices that have not been thoroughly studied from a health and environmental perspective [5]. The increasing population momentum in the city increases energy consumption and the increase in the number of cars and other means that lead to increased emissions of polluting gases into the air, in addition to the desertification factor due to dry climatic conditions, all of which affect human health in one way or another [5]. Urban expansion, climate change, and other factors have led to the removal of forests and green agricultural areas, soil degradation and poor Agricultural management, natural disasters, and the removal of forests and orchards to establish residential and commercial complexes and projects have led to the loss of biodiversity and diversity of land cover, which has also affected, to some extent, the increase in air pollution [7]. According to reports and research published by the World Health Organization (WHO), air pollution is the pollution of the internal or external environment as a result of chemical, physical, or biological factors that result in changes in the composition and nature of the air surrounding humans, which harms their health and the health of other living organisms [8]. Secondly, the problem of air pollution is more severe in cities and industrial and commercial areas than in rural areas, as these institutions and the polluting emissions they produce, in addition to the means of transportation within these cities and the emissions of heating and cooking methods, are a primary source of impurities, whether the emissions of primary gases of materials or secondary gases resulting from the interaction of primary materials, where more than 9% of the world's forms live in areas with high concentrations of chemicals in the air [9]. According to this organization, seven million deaths occur annually due to continuous exposure to air pollution and also fuel smoke; some studies have confirmed that there is a direct relationship between diseases and pollution resulting from industrial and traffic waste [10], especially in developing cities, where their outputs of CO_2, O_3, SO_2, other gases, and suspended particles affect effects leading to the deterioration of respiratory diseases[11], cardiovascular diseases, and even fertility diseases [12]. Ground-based pollution measurement stations are one of the most effective methods for measuring pollution. However, due to the problems of the short distance they cover, the costs of installation and maintenance, the complexity of pollution monitoring mechanisms and processes, and the possibility of errors in measurements and the appearance of results and non-representative spatial pattern s [1], there is an urgent need to use remote sensing [13]Geographic information systems [14], as these current methods and techniques have evolved and been applied in numerous disciplines, including air quality research, allow the study of the current state of cities and the assessment and solutions of the issues they face [15] because they offer the required spatial data and spatial analysis tools that facilitate the identification of regional trends and their properties. According to the US Geological Survey, the accuracy of spatial data refers to the degree to which the outputs closely resemble the actual values or values presumed to be accurate. The satellite data have shown a high potential for meeting the requirements for monitoring pollution using remote sensing techniques [16]. It is a satellite dedicated to monitoring the atmosphere using a high-resolution spectrometer system [17]. It was launched in 2017 and carries the TROPOMI spectrometer, an atmospheric monitoring instrument [18]. The study aimed to assess (CO, SO_2, O_3) gases concentration over the An-Najaf study area, [19] [20] analyze the causes that contribute to increased emission of these gases, and study the effect of geographical and demographical factors on atmospheric gases concentration using Sentinel-5p data [21] [22].

2- Study area:

The study area is situated in An-Najaf Governorate (Fig. 1), which is located in the central western part of Iraq. The study area covers most of the districts of the governorate. The study site covers an area of approximately 28,824 m^2. Geographically, it extends from latitude 32°01′44″N to longitude 44°20′23″E. The governorate is strategically bordered by Saudi Arabia to the south, Anbar Governorate to the west, Babylon and Karbala to the north, and Al-Qadisiyah and Al-Muthanna to the east. Najaf exhibits diverse land use patterns, including expansive agricultural zones, densely populated residential and commercial districts, and various industrial areas.

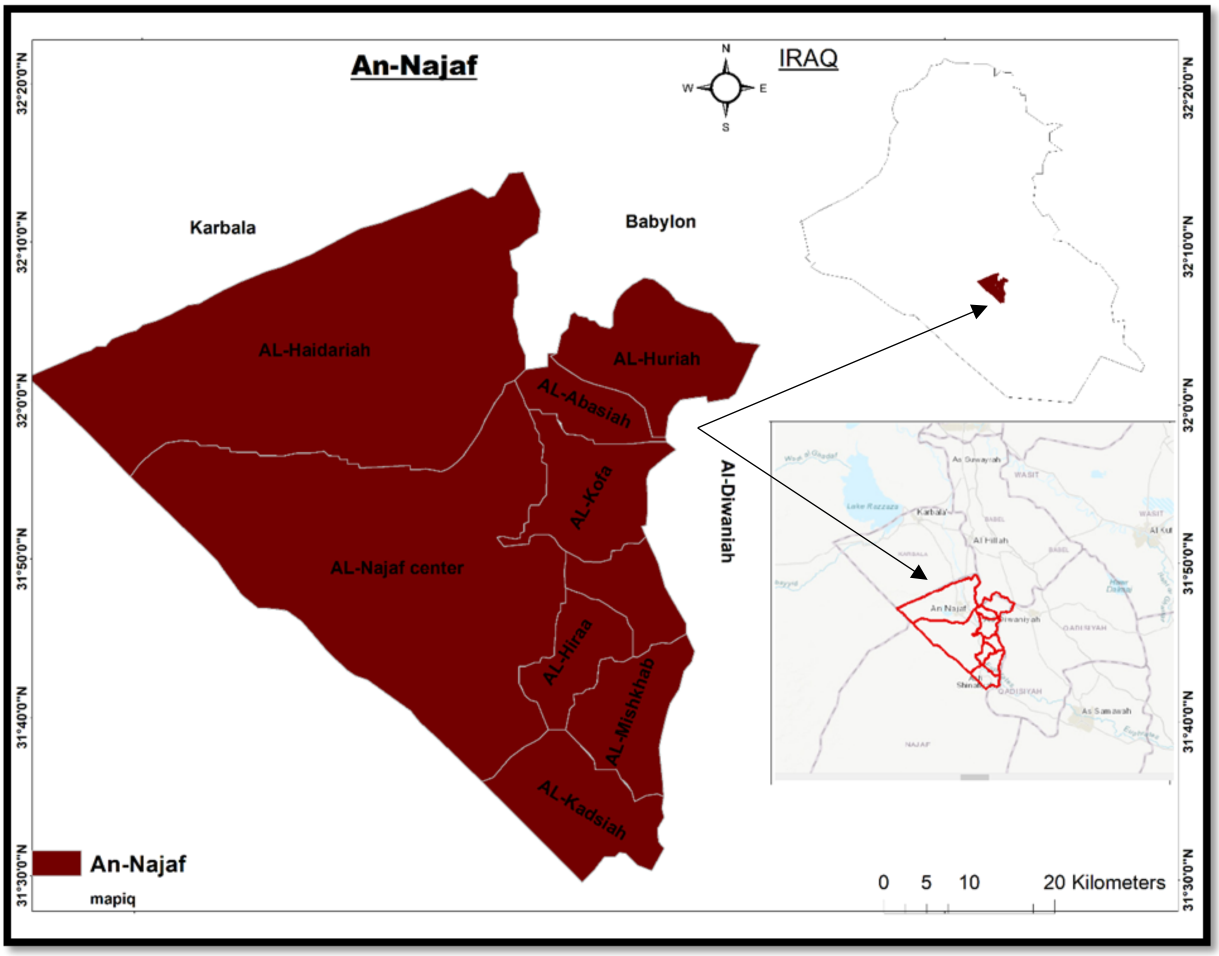

Figure 1: The administrative study area map and surrounding areas.

3-Methodology:

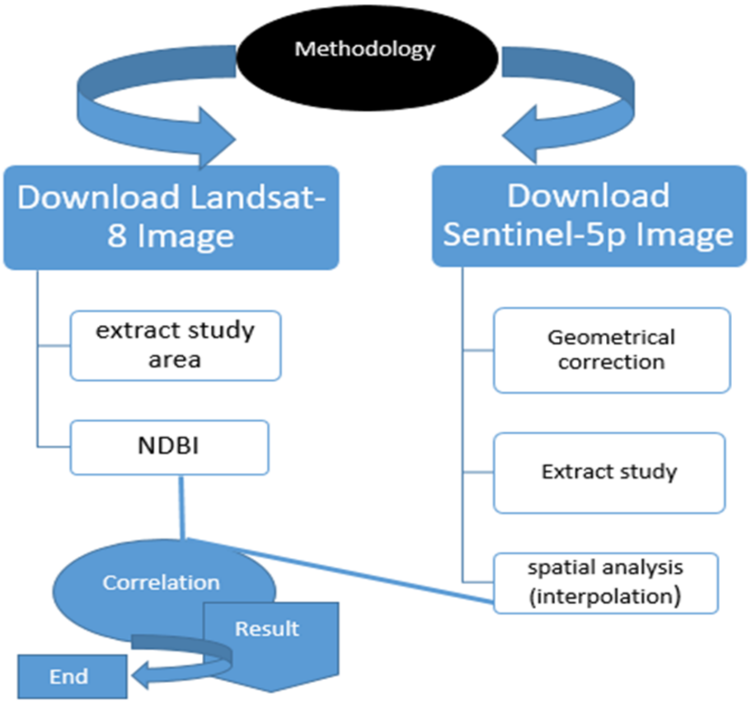

Figure 2: A flowchart illustrates the steps of the study producer.

High-resolution satellite data from Sentinel-5P, an advanced satellite operated by the European Space Agency (ESA) and equipped with the TROPOMI (Tropospheric Monitoring Instrument), were used. This instrument offers a spatial resolution between 3.5 and 5.5 km², enabling the precise tracking of key pollutants such as carbon monoxide (CO), sulfur dioxide (SO_2), and ozone (O_3) [23]. The data, freely accessible through the Copernicus Open Access Hub, were collected on September 28, 2024, and used to assess air quality in the study area.
The methodological workflow included several key steps:
1. Data Acquisition: Raw satellite images were downloaded in formats requiring geographic correction to ensure spatial accuracy.
2. Geographic Correction: QGIS and ArcMap software were utilized to correct and align the satellite data with actual geographic coordinates, explicitly targeting the Najaf monitoring station.
3. Spatial Analysis: Using ArcMap version 10.8, the corrected data were analyzed to extract pollutant concentrations from the identified pixel locations corresponding to the monitoring station.
4. Map Production: Spatial distribution maps were generated to visualize pollutant levels across the study area, helping to identify concentration hotspots and potential sources of pollution.
5. Urbanization Impact Assessment: The Normalized Difference Built-up Index (NDBI) was applied to evaluate the influence of urban expansion on the increase in air pollutant levels.

3.1 Normalized difference built-up index:

The Normalized Difference Built-up Index (NDBI) is an index for built-up areas created using remote sensing images. It is necessary to classify the different types of built-up areas in the research region using the NDBI to distinguish the inhabited region from other types of land cover, such as soil, plants, and water. The range of the (NDBI) value is -1 to 1 [24]. This index requires images in order to produce accurate results. Images captured by Landsat-8 (Landsat data are used for classification). The amount of land used for building and the percentage of built-up land raise the NDBI [25]. The NDBI is calculated using the equation: [26]

$$NDBI = (Blue - NIR) / (Blue + NIR) \qquad \ldots\ldots\ldots\ldots (1)$$

Where;
Blue is a blue band (B2) in Landsat 8
NIR is a near-infrared band (B5) in Landsat -8

4- Results and Discussion:

Table 1: Satellite data acquired.

Contaminant	Satellite	Tool	The province	Date of catching	Time
CO	Sentinal-5p	Tropomi	AL-Najaf	2024/9/28	10:47:00
SO2	Sentinal-5p	Tropomi	AL-Najaf	2024/9/28	10:47:39
O3	Sentinal-5p	Tropomi	AL-Najaf	2024/9/28	10:47:39

-Points were identified along lines of longitude and latitude, called stations. The concentration of the gases under study was measured at each station, and then analyses were carried out, and the results were extracted.

Table 2: The concentrations of gases (CO, SO2, and O3) measured by (mol/m^2) for the stations.

FID	O3	CO	SO2	longitude	latitude
1.	0.126202	0.03291	0.000148-	44° 28' 51.300" E	32° 12' 4.121" N
2.	0.1254	0.032894	0.000351	44° 25' 49.699" E	32° 12' 4.121" N
3.	0.125347	0.032894	0.000216-	44° 22' 37.819" E	32° 11' 50.416" N
4.	0.12557	0.032282	0.000325-	44° 22' 10.408" E	32° 9' 50.491" N
5.	0.124966	0.032282	0.000337-	44° 26' 13.684" E	32° 8' 45.389" N
6.	0.12405	0.032282	0.000114-	44° 26' 44.522" E	32° 5' 2.671" N
7.	0.125368	0.032184	0.000359-	44° 26' 37.669" E	32° 1' 57.644" N
8.	0.124129	0.032184	0.001053-	44° 22' 58.378" E	32° 1' 16.527" N
9.	0.12574	0.032282	0.000784	44° 23' 12.084" E	32° 5' 2.671" N
10.	0.124796	0.031485	0.000426-	44° 19' 8.808" E	32° 8' 55.668" N
11.	0.124694	0.033275	0.000567-	44° 19' 39.645" E	32° 11' 16.151" N
12.	0.124378	0.027471	0.000903	44° 14' 7.282" E	32° 8' 45.389" N
13.	0.12525	0.027471	0.000026-	44° 14' 34.694" E	32° 4' 28.407" N
14.	0.124391	0.031485	0.000247	44° 18' 0.279" E	32° 4' 24.981" N
15.	0.124617	0.031498	0.000403	44° 18' 10.558" E	32° 1' 2.822" N
16.	0.12476	0.028937	0.000235	44° 13' 53.577" E	32° 0' 59.395" N
17.	0.124145	0.028937	0.000701	44° 14' 34.694" E	31° 58' 4.648" N
18.	0.125507	0.031624	0.000016	44° 17' 22.588" E	31° 57' 13.251" N
19.	0.12472	0.031803	0.000606	44° 22' 48.099" E	31° 57' 40.663" N
20.	0.124776	0.032184	0.000606	44° 24' 37.744" E	31° 58' 14.927" N
21.	0.124539	0.027471	0.000377-	44° 11' 2.255" E	32° 7' 19.728" N
22.	0.125315	0.027471	0.000197-	44° 11' 9.108" E	32° 4' 48.966" N
23.	0.12478	0.027471	0.000365	44° 7' 12.685" E	32° 4' 48.966" N
24.	0.124712	0.027471	0.000354	44° 7' 46.949" E	32° 7' 2.596" N
25.	0.123748	0.029431	0.000373	44° 2' 21.439" E	32° 4' 4.422" N
26.	0.123871	0.029431	0.000372	43° 58' 55.853" E	32° 3' 19.879" N
27.	0.124174	0.029431	0.000796	43° 57' 37.046" E	32° 1' 13.101" N
28.	0.123495	0.030575	0.000161	43° 54' 21.740" E	32° 0' 42.263" N
29.	0.123516	0.030756	0.000614	43° 58' 25.016" E	31° 57' 33.810" N

4.2 Carbon Monoxide:

Carbon monoxide (CO) is a colorless, odorless gas primarily produced by the incomplete combustion of fossil fuels, including natural gas, coal, and emissions from vehicle exhausts and power generators. Human activities are the dominant source of this pollutant. Figure (3) illustrates the spatial distribution of carbon monoxide concentrations across the governorate.
The western part of the governorate recorded the lowest CO levels, which can be attributed to its predominantly agricultural landscape, vast open desert areas, and prevailing wind patterns that aid in dispersing pollutants. In contrast, higher concentrations were observed in the eastern parts, particularly in Al-Hurriya and Al-Abbasiya (a sub-district of the Kufa district), where levels reached approximately 0.033 mol/m^2. This increase is closely linked to urban expansion, dense residential development, and intensified traffic, all of which contribute significantly to emissions from vehicles and generators.

Elevated CO levels, around 0.0305 mol/m², were also detected in the central part of the governorate near Lake Najaf. This area is characterized by high population density, industrial zones, and the presence of religious shrines that attract large numbers of visitors, all of which contribute to increased emissions from human activities. Similarly, the center of the Al-Kufa district displayed two distinct zones: one area with high pollutant concentrations of approximately 0.03205 mol/m², encompassing densely populated neighborhoods, universities, government institutions, commercial hubs, and healthcare facilities; and another zone with noticeably lower concentrations due to the presence of orchards and the scattered distribution of residential areas, which reduces traffic congestion and related emissions.

In the southeastern regions of the governorate, including areas such as Al-Mushkhab, Al-Qadisiyyah, and Al-Hirah (a sub-district of the Al-Manathira district), carbon monoxide levels were considerably lower. This can be attributed to the dominance of agricultural land use and lower population density, which results in fewer pollution sources. [27]

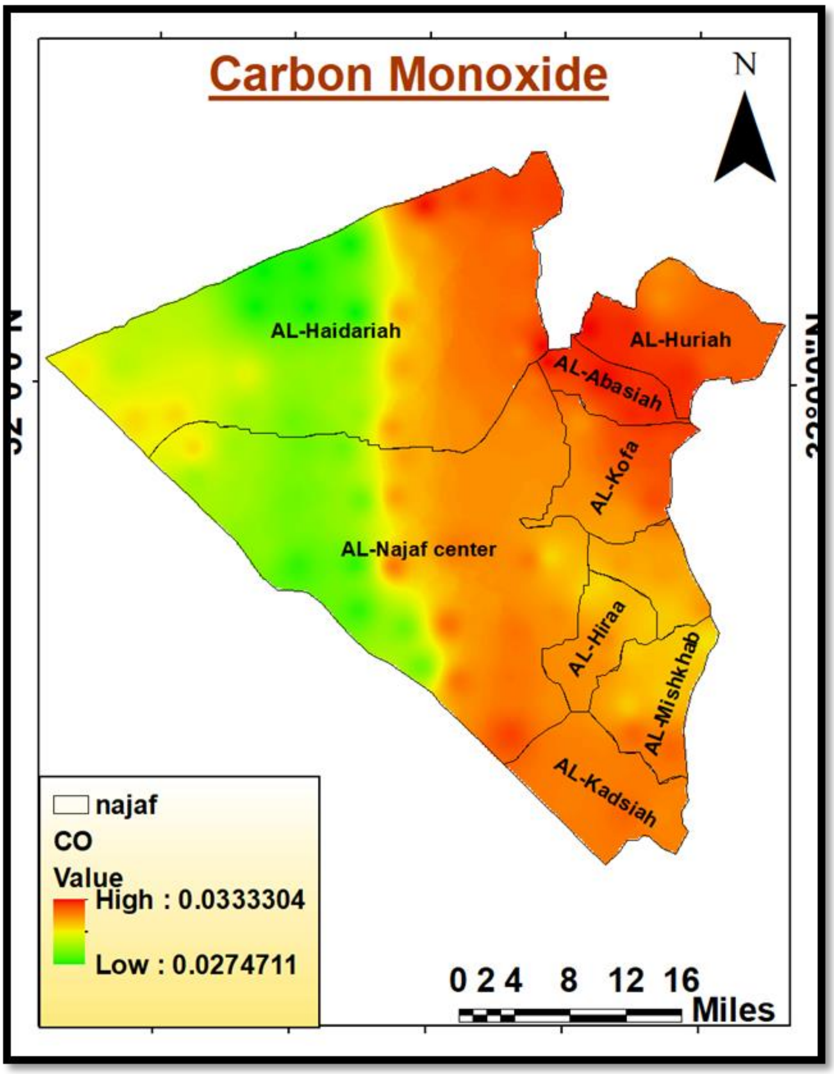

Figure 3: Carbon monoxide concentrations distributed in the study area.

4.3 Sulfur Dioxide:

Sulfur Dioxide (SO_2) is a colorless gas released from both natural sources—such as volcanic eruptions and forest fires—and anthropogenic activities, including industrial processes, power generation, waste burning, and other human-induced emissions. Figure (4) illustrates the spatial distribution of sulfur dioxide concentrations across the study area. The observed concentration values ranged from high (0.00119331 mol/m²) to low (-0.00105285 mol/m²), indicating significant spatial variability.

The highest concentrations were recorded in the Al-Haidariya area (a sub-district of An-Najaf district), where multiple emission sources are located, including the Al-Haidariya and Al-Haidariya Gas Power Stations, the An-Najaf Ashraf Tire Factory, the Al-Husseiniya Oil Field, and a lime brick factory. These industrial and energy production facilities contribute directly to SO_2 emissions, and the gas is further dispersed to adjacent areas due to prevailing wind patterns.

Elevated levels were also detected in the central part of the governorate, particularly near the An-Najaf Sea, where several power stations are concentrated, such as the Makrumah Station, Al-Jawahiri Station, Al-Najaf Secondary Power Station, and the An-Najaf Gas Power Station. Additionally, the presence of a rubber products factory intensifies emissions in this zone.

In the Al-Hurriya area, high sulfur dioxide levels were associated with dense population, ongoing construction activities, heavy traffic, and the burning of waste—all of which are known sources of SO_2. A noticeable rise in gas concentration was also observed in Al-Abbasiyah district, attributed to the presence of the Al-Abbasiyah Electricity Department and the Al-Abbasiyah Secondary Electricity Transformer Station.

Similar emission levels were detected in the Al-Kufa district due to the operation of the Kufa Cement Factory. Likewise, the northern part of the Al-Hiraa sub-district exhibited elevated SO_2 levels, which were attributed to the Sitom Power Station, the Najaf Asphalt Factory, and the Spico Najaf Asphalt Factory.

On the other hand, the lowest concentrations of sulfur dioxide were found in the southern and southeastern regions—specifically in Al-Mushkhab, Al-Hiraa, and Al-Qadisiyah—where agricultural land dominates and the presence of dense orchards and limited industrial activities contributes to the overall reduction in pollutant levels.

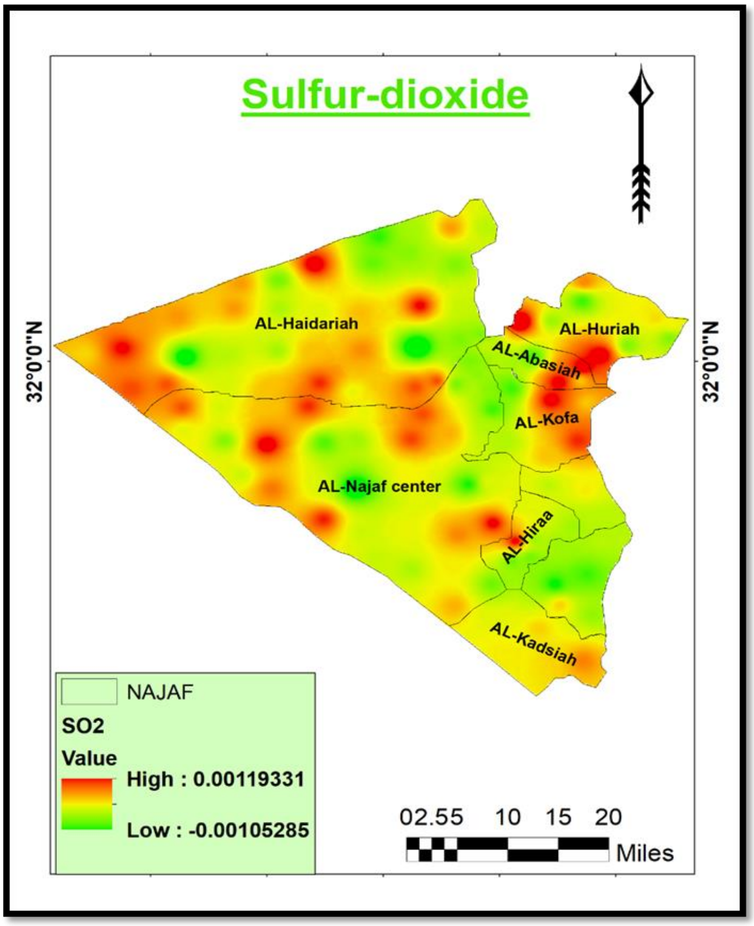

Figure 4: Sulfur dioxide concentrations distributed in the study area.

4.4 Ozone:

This gas was classified as a secondary pollutant, formed through chemical reactions involving primary pollutants in the atmosphere. It poses a rapid and serious threat to human health, with asthma, particularly among children, being one of the most notable health conditions linked to its exposure. Figure (5) illustrates the spatial distribution of this gas within the study area, revealing that its overall concentration across the governorate is relatively low. This can be attributed to the prevalence of open spaces, agricultural lands, and desert terrain in Najaf, particularly toward its western side. Moreover, prevailing wind patterns help disperse primary pollutants before they can combine to form higher concentrations of secondary gases.

The concentration values ranged up to 0.126817 mol/m², with the highest levels recorded in the northeastern part of Al-Haidariya. This area is home to major emission sources, including the Al-Haidariya Gas Power Station and the Al-Tahrir Quarry [28]. Elevated concentrations were identified in the southeastern part of Al-Hurriya, likely linked to emissions from a sewage treatment plant, as well as in southeastern Al-Mushkaf and Al-Manathera, due to the presence of the Al-Manathera Station.

Moderate concentrations were detected in the central areas of the governorate, which have a dense population, commercial centers, and industrial activity. In contrast, the lowest concentrations were observed in the western and southern regions, where the landscape is dominated by agriculture and open desert lands, and human activities and hence pollution levels are minimal.

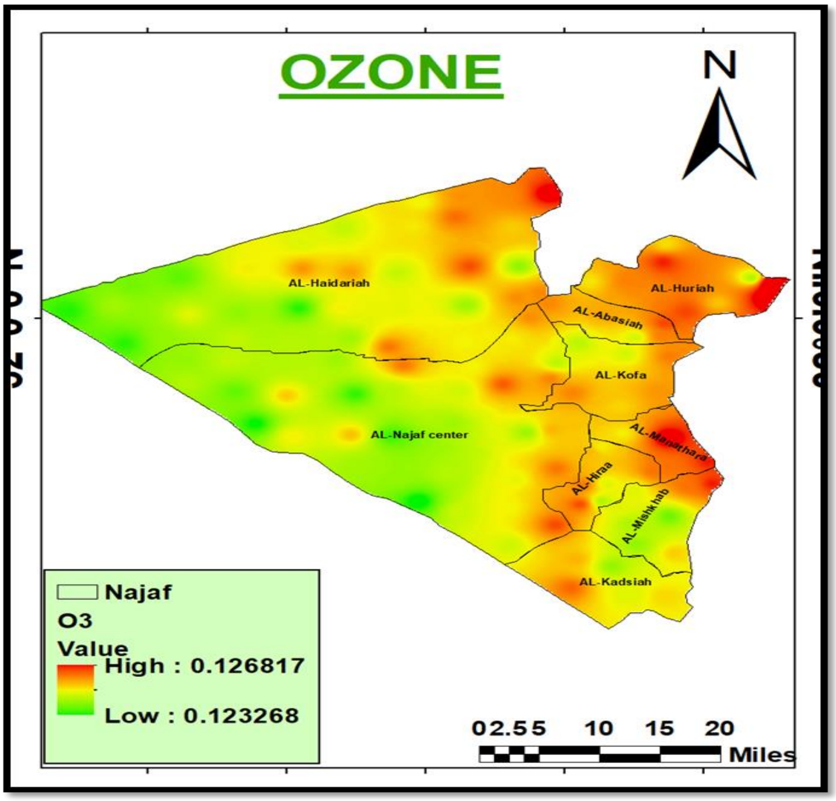

Figure 5: Ozone concentrations distributed in the study area.

Table (3) shows the concentration of polluting gases within Al-Najaf in several nations globally. It showed that the concentration of CO gas in Al-Najaf is relatively lower compared to Ukraine [29], which may be due to the burning operations practiced by Ukrainian farmers or the use of heating methods in winter in Ukraine. However, compared to North Macedonia [18] and Mazandaran [30], the concentration in Al-Najaf is relatively close due to the nature of these regions, which have high population density and industrial activity. As for the SO2 gas, it was higher in Al-Najaf than in Ukraine and Mazandaran; this is due to the increased proliferation of power generation stations, which were considered among the most significant causes of this gas's emission in areas with high pollution levels. Meanwhile, the highest concentration of O3 gas was found in Mazandaran compared to Al-Najaf because that region has many factories and plants, which increase the emissions of primary gases that generate this gas.

Table 3: Concentration of polluting gases in An-Najaf governorate compared to some global cities [18] [29] [30]:

Cities name	CO Concentration	SO2 Concentration	O3 Concentration
Alhira	0.031525995	0.000284	**0.125124189**
Alkadsiah	0.032158516	0.000131	**0.124902574**
Almanathera	0.031501864	0.000182	**0.125425664**
Almishkhab	0.03153272	0.000199	**0.124759775**
Alabasiah	0.033207799	0.000353	**0.125195909**
Alhuria	0.032742619	0.000334	**0.125388974**
Alhaidariah	0.0305011	0.000274	**0.124599665**
alnajaf center	0.030546887	0.000259	**0.124468439**
Alkofa	0.032051895	0.0001381	**0.124970448**
Ukrin	0.04	0.00046	**--------------------**
north macedonia	0.036	--------------------	**--------------------**
Mazandaran	0.03	0.00048	**0.14**

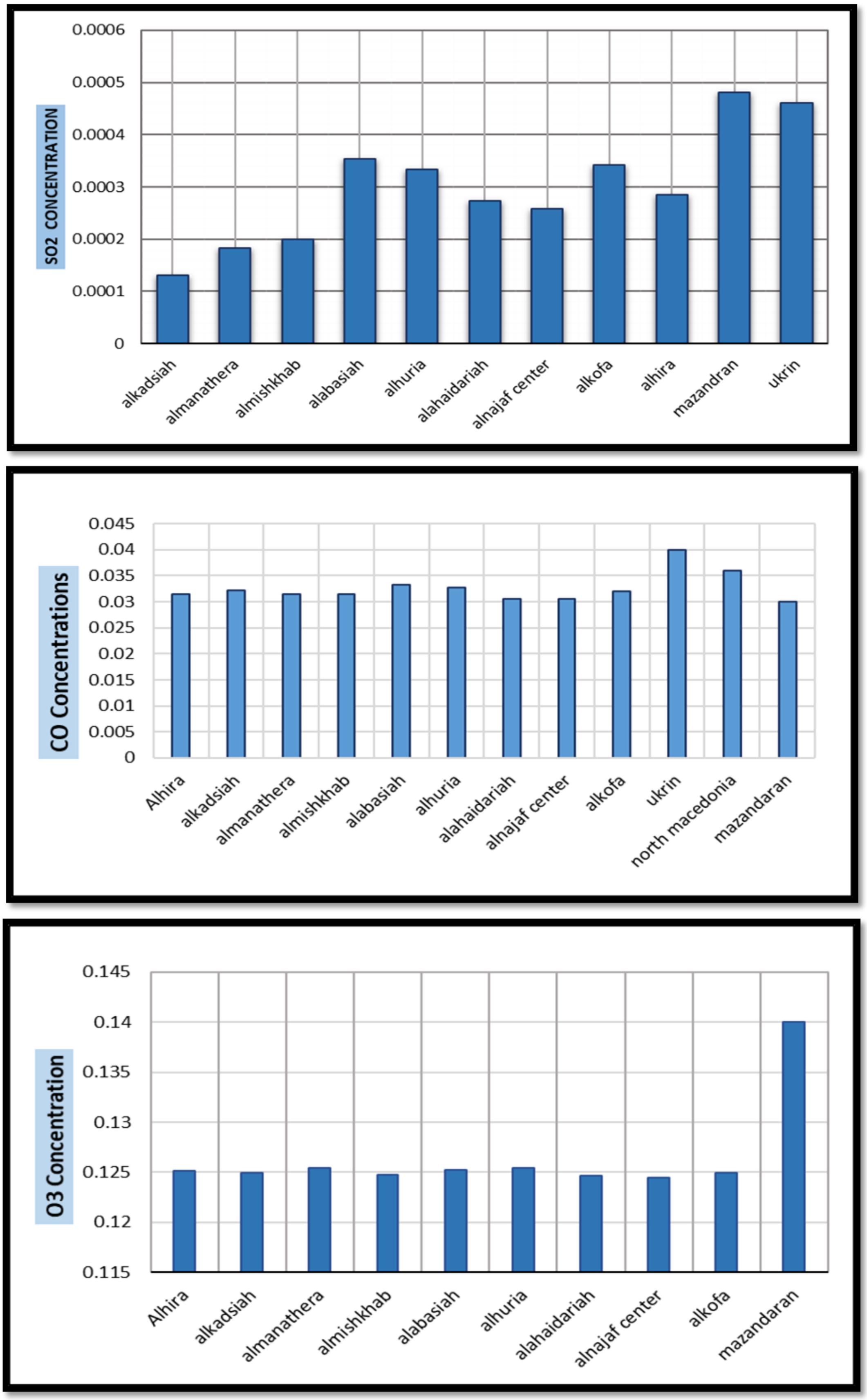

Figure 6 : Comparing the gas concentrations (measured by mol/m^2) in the study area with several worldwide regions.

4-4 NDBI:

The Normalized Difference Built-up Index (NDBI) is a widely used remote sensing indicator designed to detect and quantify built-up and residential areas. This index operates by measuring the difference in spectral reflectance between urban surfaces—such as buildings and paved areas—and other types of land cover, including vegetation, water bodies, and bare soil. Buildings typically reflect more shortwave infrared (SWIR) radiation than near-infrared (NIR) radiation [31], allowing NDBI to distinguish urbanized regions from non-urban surfaces effectively.

As illustrated in Figure (7), NDBI values range from a maximum of 10.26130 to a minimum of -0.507153. The brown-toned areas on the map represent high NDBI values, indicating dense built-up zones. These high values are primarily concentrated around Lake Najaf and in the surrounding central, commercial, and residential districts, reflecting the high intensity of urban development.

Conversely, low NDBI values correspond to agricultural lands, open spaces, and desert areas, which exhibit different reflective properties compared to built environments.

Overall, NDBI serves as an essential tool in land cover classification, urban mapping, and monitoring urban expansion, offering a clear spatial representation of the distribution and intensity of built-up areas within the study region.

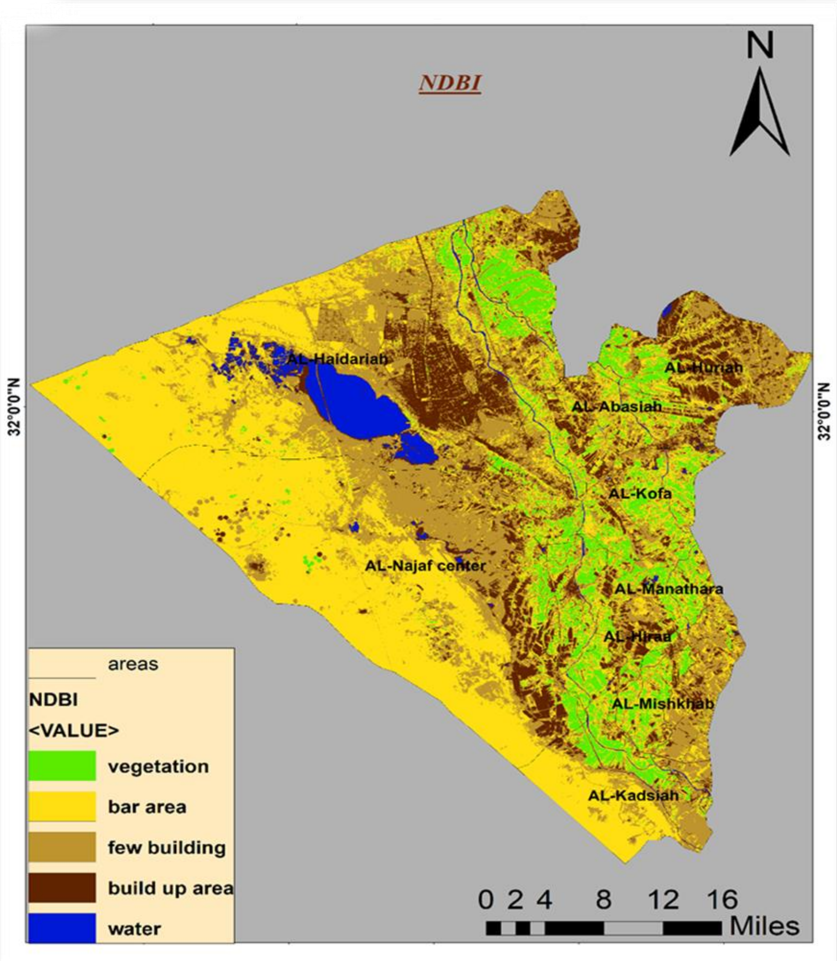

Figure 7: NDBI of the study area

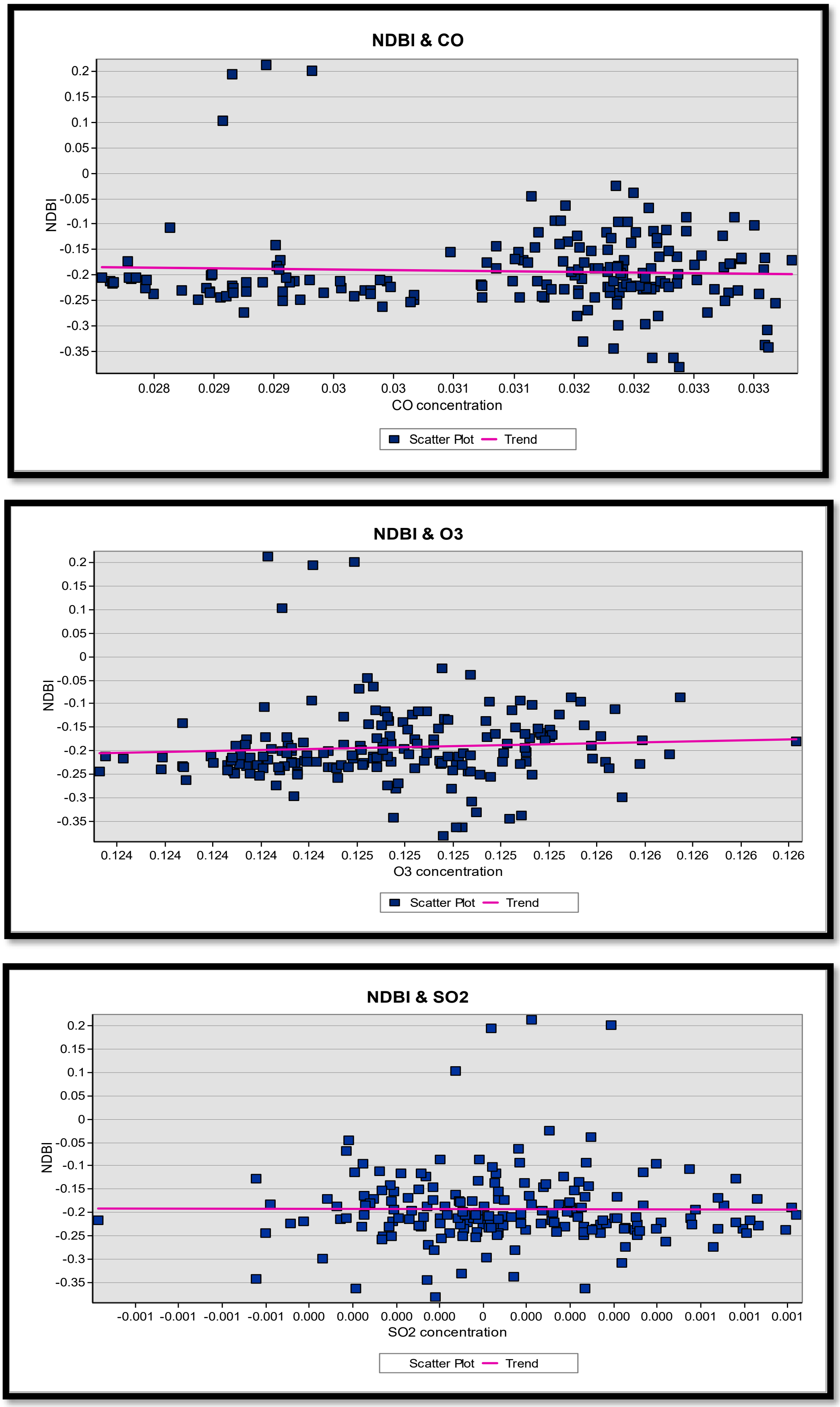

Figure 8 : Scatter plot of NDBI correlation with CO, SO_2, and O_3 concentration (mol/m^2) at Al-Najaf governance.

Figure (8) presents a linear regression model illustrating the relationship between the explanatory variable (NDBI) and the response variables (CO, SO_2, and O_3). This model is used to investigate the impact of urban expansion, as measured by NDBI, on the concentration levels of these atmospheric pollutants.

The regression analysis reveals a positive linear relationship between NDBI and CO, suggesting that the increase in built-up areas is associated with a rise in carbon monoxide concentrations. This can be attributed to human activities prevalent in urban areas, such as vehicle emissions and generator use, which are common sources of CO.
However, the data indicate a relatively weak correlation between NDBI and both SO_2 and O_3 concentrations. This weak relationship may be because the primary sources of SO_2 and O_3 were not directly linked to residential expansion, but rather to power plants, industrial zones, fuel combustion, and waste burning—all of which emit pollutants independently of the built-up density measured by NDBI.
The regression coefficients (R^2 values) further support this interpretation:
•NDBI and CO: $R^2 = 0.0096$
•NDBI and SO_2: $R^2 = 0.0022$
•NDBI and O_3: $R^2 = 0.0314$
These values confirm that while there is a slight influence of urban expansion on CO levels, the relationship with SO_2 and O_3 is minimal, indicating that other factors beyond built-up land cover are more responsible for their distribution.

5- Conclusion:
Data obtained from the Sentinel-5P satellite demonstrated high effectiveness in assessing the concentrations of carbon monoxide (CO), sulfur dioxide (SO_2), and ozone (O_3) across the Najaf Governorate. The analysis revealed a statistically significant relationship between elevated levels of these pollutants and areas characterized by persistent traffic congestion, high building density, industrial and commercial activities, and other anthropogenic influences.

The results indicated that CO concentrations reached up to 0.03333304 mol/m² in key urban areas with intense human activity. In comparison, SO_2 levels were recorded at approximately 0.000119331 mol/m², primarily attributed to the widespread presence of electric power stations, which serve as the primary sources of this gas throughout the governorate. O_3 concentrations were found to be around 0.126817 mol/m², likely resulting from the interaction of its precursor gases—mainly CO and NOx—under the influence of solar radiation.

Conversely, significantly lower pollutant concentrations were observed in agricultural zones, areas with abundant green cover, regions with low population density, and open desert landscapes. These findings suggest a spatial contrast in air quality across the governorate, directly influenced by land use and human activities.
Based on the applied methodology, the study concludes that Najaf Governorate exhibits relatively high air pollution levels compared to global benchmarks in similar geographic and climatic settings. Furthermore, this research emphasizes the transformative role of remote sensing technologies, particularly data from the Sentinel-5P satellite, in providing a reliable, cost-effective, and precise means of monitoring air quality.
Ultimately, the study underscores the potential of satellite-based monitoring in supporting environmental management strategies. By identifying pollution hotspots and their sources, these tools can significantly contribute to mitigating the adverse impacts of air pollution on human health and ecosystems.

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