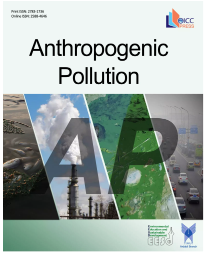

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Enhanced monitoring of air pollution in Asalouyeh, Iran using Sentinel-5 satellite imagery and Google Earth Engine

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Abstract:

Asalouyeh, a rapidly industrializing port city in Iran, faces significant environmental challenges due to air pollution resulting from extensive industrial activities. This study employs Sentinel-5 satellite data and the Google Earth Engine (GEE) platform to assess the spatial and temporal distribution of key air pollutants, including nitrogen dioxide (NO_2), carbon monoxide (CO), sulfur dioxide (SO_2), and aerosols, over the period from 2019 to 2023. By leveraging the advanced capabilities of remote sensing and cloud-based geospatial analysis, we processed satellite imagery to monitor atmospheric pollution levels and identify pollution hotspots. The findings indicate a notable increase in pollutant concentrations, particularly NO_2, CO, and SO_2. NO_2 levels increased from a range of $0.0022-0.0071$ μmol/m^2 in 2019 to $0.0025-0.0099$ μmol/m^2 in 2023, while CO concentrations rose from $0.63-0.88$ ppm in 2019 to $0.58-0.86$ ppm in 2023. Similarly, SO_2 concentrations increased significantly, from $0.008-0.04$ ppm in 2019 to $0.01-0.06$ ppm in 2023. Aerosol Optical Depth (AOD) values also showed an upward trend, reaching a peak of -0.034 to 0.8 in 2023 compared to -0.81 to 0.016 in 2019. The results demonstrate a clear correlation between increasing pollution levels and industrial expansion in Asalouyeh, with the highest concentrations observed near petrochemical complexes and transportation corridors. The identified pollution hotspots provide critical insights for policymakers, enabling targeted interventions such as emission control regulations, improved industrial waste management, and enhanced monitoring infrastructure. By integrating Sentinel-5 data with GEE's cloud-based processing capabilities, this study establishes a scalable and cost-effective framework for continuous air quality assessment in industrial zones, addressing the limitations of traditional ground-based monitoring. These findings contribute to a growing body of research on industrial air pollution in the Persian Gulf region, emphasizing the urgent need for stringent environmental policies and sustainable industrial practices to mitigate pollution-related health risks.

Keywords: Natural disasters; Floods; Damage ranking; Analytic hierarchy process; Flood insurance; Legal challenges

1. Introduction

Air pollution is one of the most pressing global environmental issues, posing significant risks to human health and ecosystems worldwide (Mayer, 1999; Kampa and Castanas, 2008; Hou et al., 2019; Li et al., 2020; Moghadam et al., 2021; Khoshand et al., 2024). As the world experiences rapid population growth and urbanization, the demand for energy and industrial activities has escalated, leading to increased emissions of harmful pollutants into the atmosphere (Ghaderi et al., 2024; Dockery et al., 1993). These pollutants, particularly airborne particles, can absorb and scatter radiation, thereby influencing weather patterns and cloud dynamics (Lohmann and Feichter, 2005; Mahowald, 2011; Stocker et al., 2013). Among the various environmental hazards, the World Health Organization (WHO) has identified particulate matter (PM) as a leading cause of morbidity and mortality, contributing to respiratory and cardiovascular diseases (WHO, 2016, 2024; Guo et al., 2019).

According to recent WHO reports, air pollution accounts for approximately 6.5 million premature deaths annually, with

99% of the global population exposed to air quality levels exceeding recommended limits (WHO, 2024; Campbell-Lendrum and Prüss-Ustün, 2019). This alarming trend emphasizes the urgent need for efficient air quality monitoring and mitigation strategies, particularly in regions undergoing rapid industrialization.

In the Middle East, air pollution has emerged as a critical environmental concern, exacerbated by industrial emissions, transportation, and natural dust storms (Weng et al., 2022). Iran, possessing some of the world's largest oil and gas reserves, faces severe air pollution challenges, particularly in industrial cities like Asalouyeh. This city, located on the northern shores of the Persian Gulf, is a major hub for Iran's petrochemical and natural gas industries. The rapid expansion of industrial and urban infrastructure in Asalouyeh has led to increased emissions of nitrogen dioxide (NO_2), carbon monoxide (CO), sulfur dioxide (SO_2), and aerosols, raising significant environmental and public health concerns (Alahverdi and Savabieasfahani, 2012; Keshmiri et al., 2018). The city's unique topography, bordered by the Persian Gulf to the south and the Zagros mountain range to the north, exacerbates air pollution by limiting airflow and facilitating pollutant accumulation (Abbasi et al., 2018).

Recent studies have highlighted the role of remote sensing and geospatial technologies in monitoring industrial air pollution. For instance, Weng et al. (2022) examined the effects of meteorological conditions on air pollution dispersion, emphasizing the importance of continuous monitoring. Similarly, Shikwambana et al. (2020) utilized satellite data to analyze pollution patterns in industrial regions of South Africa, demonstrating the potential of remote sensing for pollution assessment. The effectiveness of Sentinel-5P and Google Earth Engine (GEE) in large-scale air pollution monitoring has also been validated in studies focusing on pollution trends in industrial regions (Srivastava et al., 2025; Jodhani et al., 2024; Omar and Kumar, 2021).

Recent advancements in air pollution monitoring methodologies have demonstrated the increasing importance of integrating geospatial analysis with high-resolution satellite imagery. The use of Sentinel-5 data, coupled with Google Earth Engine, provides a scalable framework for assessing pollutant concentrations over time and space, enabling real-time monitoring of emissions. Previous studies have explored the spatial variation of industrial air pollution in other parts of the world, such as South Africa and China, utilizing similar remote sensing technologies (Safarianzengir et al., 2020; Shikwambana et al., 2020; Weng et al., 2022). Additionally, studies have applied numerical modeling techniques to validate satellite-derived air quality estimates, improving the accuracy of atmospheric pollution assessments (Jodhani et al., 2024; Duncan et al., 2014). This study builds on these developments by providing a comprehensive assessment of industrial pollution in Asalouyeh, leveraging geospatial tools to generate actionable insights for environmental management and policy implementation. By integrating recent methodologies, this research aims to enhance the precision and applicability of remote sensing data for air pollution monitoring in highly industrialized regions like Asalouyeh.

Moreover, research on the Persian Gulf region, particularly in Asalouyeh, remains limited. While previous studies have focused on air pollution in other Iranian industrial zones, such as Khuzestan (Ghaderi et al., 2024), this study fills a critical gap by providing a detailed spatial and temporal analysis of pollution trends in Asalouyeh over five years ($2019-2023$). By leveraging Sentinel-5 data and the GEE platform, this study offers high-resolution monitoring of key atmospheric pollutants, enabling policymakers to identify pollution hotspots and design effective mitigation strategies.

The health implications of elevated pollutant concentrations are severe, particularly in an industrially dense region like Asalouyeh. NO_2 is a precursor to ground-level ozone and particulate matter, both of which have been linked to respiratory diseases, cardiovascular conditions, and increased mortality rates (Bechle et al., 2013; WHO, 2024). Similarly, elevated CO levels pose serious risks due to their ability to impair oxygen delivery to bodily tissues (Alvim et al., 2021). Given these threats, it is crucial to implement systematic air quality monitoring frameworks and explore mitigation measures to reduce industrial emissions.

This study builds on the growing body of research utilizing remote sensing for air pollution assessment. The primary objectives of this study are:

To assess the spatial and temporal distribution of NO_2, CO, SO_2, and aerosols in Asalouyeh from 2019 to 2023 using Sentinel-5P satellite data.

To identify pollution hotspots and examine their correlation with industrial activities in the region.

To validate satellite-derived pollution data using statistical comparison techniques.

To provide actionable insights for air quality management and policy formulation in Iran's major industrial hub.

By addressing these objectives, this study contributes to the advancement of satellite-based air pollution monitoring techniques, demonstrating how GEE can be effectively utilized for continuous environmental assessments. The findings underscore the urgent need for enhanced air quality regulations and mitigation strategies to protect both the environment and public health in Asalouyeh and similar industrial regions worldwide.

2. Material and methods

2.1 Study area

Asalouyeh, located in the Bushehr province of Iran, lies on the northern shores of the Persian Gulf at coordinates 28°28′24.48″ N and 52°36′49.79″ E (Abbasi et al., 2018). It is an area of strategic economic and energy significance due to its proximity to the South Pars/North Dome Gas-Condensate field, one of the world's largest natural gas reserves (figure 1). Over the past two decades, Asalouyeh has evolved into a major industrial hub, hosting large-scale petrochemical complexes, refineries, and energy-intensive industries. However, this rapid industrialization has led to significant air pollution challenges, necessitating continuous environmental monitoring.

Asalouyeh is characterized by a complex topography, which plays a crucial role in the dispersion and accumulation of air pollutants. The city is flanked by the Persian Gulf to

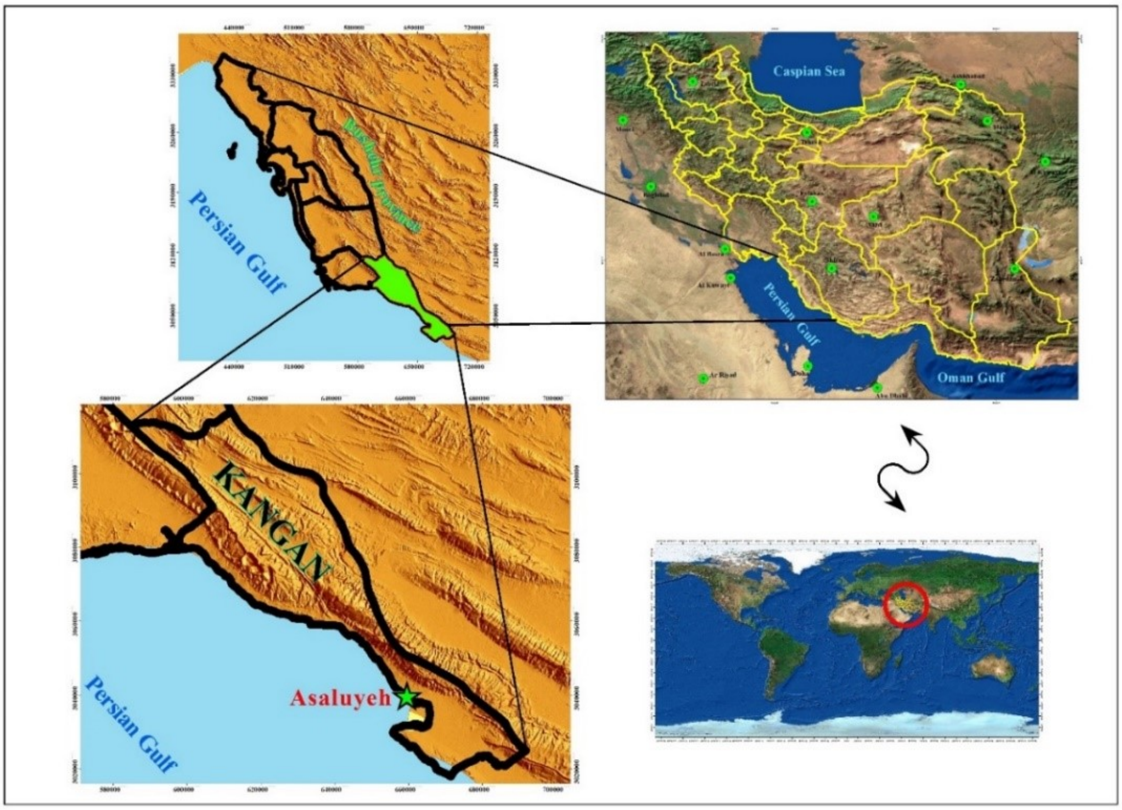

Figure 1. Map of the study area.

the south and the Zagros mountain range to the north, creating a semi-enclosed basin that restricts airflow. This topographical setting limits natural ventilation and contributes to pollutant stagnation, especially during periods of low wind activity. The elevation in the area varies from sea level at the coast to approximately 500 meters in the adjacent mountain ranges. These geographical constraints enhance the retention of industrial emissions, leading to prolonged exposure to pollutants in urban and industrial zones.
The climate of Asalouyeh is classified as hot desert (BWh) under the Köppen climate classification, with high temperatures, low annual rainfall, and high humidity levels due to its coastal location. The region experiences:
Hot summers with temperatures reaching 45 °C (113 °F) in peak months (June–August).
Mild winters with temperatures rarely falling below 10 °C (50 °F).
Low annual precipitation, averaging $150-200$ mm, mostly occurring during winter months.
High humidity levels, often exceeding 80%, can influence the formation of secondary pollutants such as ozone (O_3).
Frequent temperature inversions, especially in winter, trap pollutants near the surface and exacerbate air quality issues.
The soil composition in Asalouyeh is diverse and influenced by coastal, sedimentary, and desert environments. The region's soils exhibit the following characteristics:
Predominantly sandy and clayey soils with low organic matter due to the arid climate.
High salinity levels in coastal zones, affect vegetation cover and soil permeability.
Deposits of industrial pollutants, including heavy metals and petrochemical residues, have been detected in previous studies (Abbasi et al., 2018).
Erosion-prone due to strong coastal winds and minimal vegetation cover, contributing to dust storms that further degrade air quality.
These environmental conditions intensify the impact of air pollution, as poor soil retention, high temperatures (Khorrami et al., 2019), and weak atmospheric dispersion mechanisms facilitate the accumulation and long-range transport of industrial emissions.

2.2 Data sources

This study utilized data from the Sentinel-5 Precursor satellite, specifically the TROPOspheric Monitoring Instrument (TROPOMI), to monitor atmospheric pollutants over Asalouyeh. Sentinel-5P, launched on October 13, 2017, is dedicated to atmospheric monitoring and provides high-resolution data on various pollutants, including nitrogen dioxide (NO_2), carbon monoxide (CO), sulfur dioxide (SO_2), and aerosol optical depth (AOD) (sentiwiki. Copernicus.eu, 2024). The satellite offers daily global coverage with a spatial resolution of up to 7 km $\times$ 3.5 km, making it ideal for regional air quality assessments (Ghaderi et al., 2024; Jodhani et al., 2024).
Additionally, this study leveraged the capabilities of Google Earth Engine (GEE), a cloud-based geospatial analysis platform that provides access to a vast repository of satellite imagery and geospatial datasets. GEE facilitates the efficient processing and analysis of large volumes of data, allowing researchers to monitor temporal changes and gen-

erate spatial distribution maps of pollutants.

2.3 Remote sensing and image processing

Pre-Processing of Satellite Data

The initial step in this research involved pre-processing the Sentinel-5P data to ensure accuracy and reliability. This process included (Fig. 2):

1. Cloud Masking: Clouds can obscure satellite observations and affect the accuracy of data. A cloud mask algorithm was applied to the Sentinel-5P imagery to exclude cloudy pixels, ensuring that only clear-sky observations were used in subsequent analyses.

2. Geometric Correction: Geometric correction was performed to align the satellite images with the Earth's surface accurately. This step ensures that the spatial locations of features in the imagery correspond precisely to their real-world locations.

3. Radiometric Calibration: Radiometric calibration was conducted to correct any sensor-related errors and normalize the reflectance values across the images, facilitating consistent comparison over time.

4. Noise Reduction: A noise reduction filter was applied to remove any artifacts or noise present in the satellite data, enhancing the quality of the images for analysis.

2.3.1 Extraction of atmospheric pollutants

Using the GEE platform, atmospheric pollutants were extracted from the pre-processed Sentinel-5P data. The pollutants of interest in this study were:

1. Nitrogen Dioxide (NO_2): NO_2 is a key indicator of air pollution, primarily originating from combustion processes in vehicles and industrial activities. TROPOMI provides high-resolution measurements of NO_2 columns, which were analyzed to assess spatial distribution and temporal trends.

2. Carbon Monoxide (CO): CO is a toxic gas resulting from incomplete combustion. Its concentration was extracted and mapped to identify hotspots and temporal variations.

3. Sulfur Dioxide (SO_2): SO_2 emissions are predominantly from industrial processes, including fossil fuel combustion and refining activities. The spatial distribution of SO_2 was analyzed to assess industrial impacts on air quality.

4. Aerosol Optical Depth (AOD): AOD is a measure of aerosol concentration in the atmosphere. High AOD

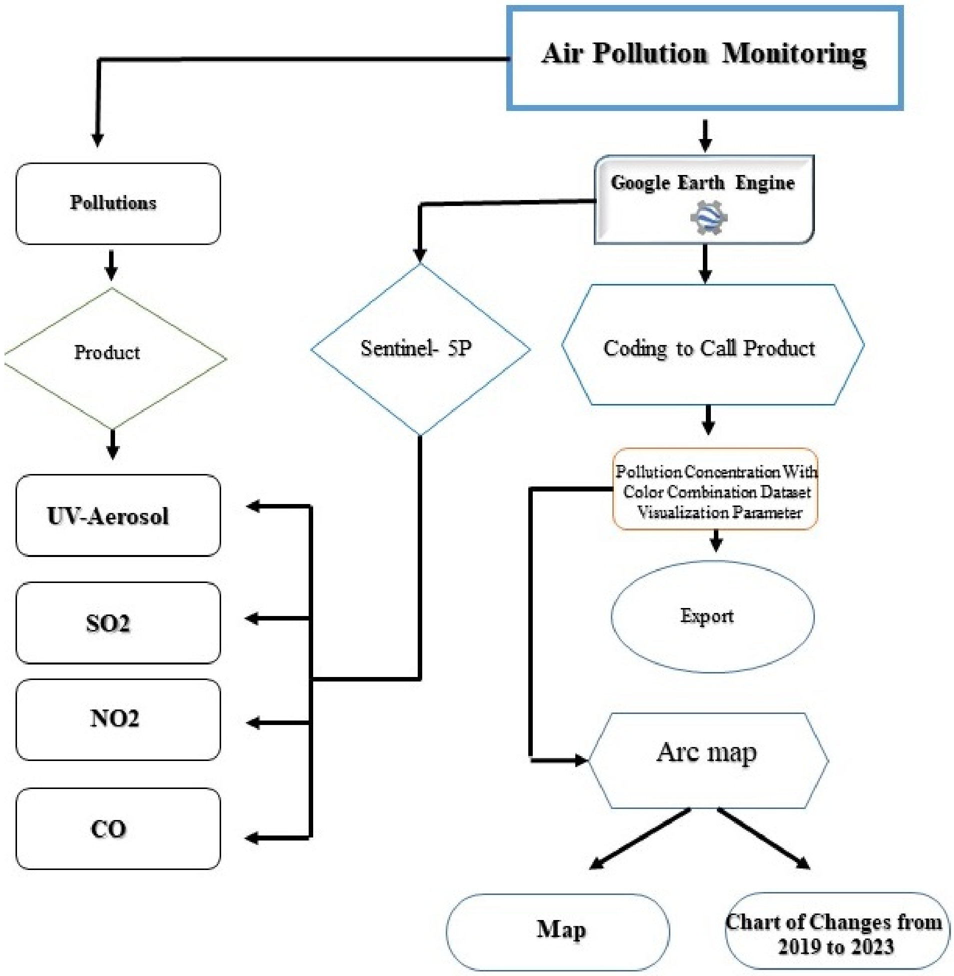

Figure 2. Research flowchart.

values indicate poor air quality and visibility. This parameter was mapped to evaluate the extent and severity of aerosol pollution.

2.4 Analysis of temporal and spatial trends

Temporal analysis

To assess the temporal trends of air pollutants, the study examined data spanning from 2019 to 2023. Monthly averages of NO_2, CO, SO_2, and AOD were computed to identify seasonal patterns and interannual variability. This analysis was essential for understanding the dynamics of pollution levels in response to meteorological conditions and industrial activities.

Spatial distribution mapping

Spatial distribution maps of the extracted pollutants were generated using GEE's visualization capabilities. These maps provided insights into the geographical extent and concentration of pollutants, highlighting pollution hotspots within Asalouyeh and surrounding areas. The spatial maps were created using the color combination method, which visually represented pollutant concentrations through color gradients.

2.5 Validation

To evaluate the accuracy of satellite-derived pollution data, this study incorporated ground-based air quality measurements from national and regional environmental monitoring stations in Asalouyeh. The validation process compared Sentinel-5P-derived pollutant concentrations with ground observations, using statistical metrics such as correlation coefficient (R), mean bias error (MBE), and root mean square error (RMSE).

Ground data specifications

The ground-based air quality data were obtained from the Iranian Department of Environment (DoE) and the Bushehr Environmental Protection Agency, which operate continuous monitoring stations in Asalouyeh. These stations measure atmospheric pollutants using high-precision instruments, ensuring reliable comparisons with Sentinel-5P data. The specifications of the ground-based monitoring system (Table 1) are as follows:

The validation involved a spatiotemporal correlation analysis between the satellite-derived pollutant concentrations and ground-based measurements over the study period (2019 – 2023). The Hanna (1993) statistical method was used to quantify the accuracy of Sentinel-5P data:

1. Correlation Coefficient (R): Measures the degree of linear correlation between ground-based and satellite-derived data. Higher values indicate stronger agreement.

2. Mean Bias Error (MBE): Assesses the average deviation of satellite estimates from ground measurements, helping to detect systematic over- or underestimation.

3. Root Mean Square Error (RMSE): Evaluates the overall accuracy of Sentinel-5P pollutant retrievals by calculating the standard deviation of errors.

3. Results

The analysis of Sentinel-5P satellite data from 2019 to 2023 revealed significant spatial and temporal variations in the concentrations of nitrogen dioxide (NO_2), carbon monoxide (CO), sulfur dioxide (SO_2), and aerosols over Asalouyeh. This study aims to provide a comprehensive overview of the findings, illustrating the impact of industrial activities on air quality in this region.

3.1 Nitrogen dioxide (NO_2)

NO_2 is a major component of urban air pollution and a precursor to surface ozone (O_3), particulate matter (PM), and acid rain. The data processing and analysis indicated a marked increase in NO_2 concentrations over the five-year study period.

- Spatial Distribution (2019 – 2023): As depicted in Fig. 3, the spatial distribution of NO_2 exhibited a notable increase in concentration from 2019 to 2023. In 2019, the NO_2 concentration ranged from 0.0022 to 0.0071 (μmol/m^2), while in 2023, it increased to a range of 0.0025 to 0.0099 (μmol/m^2). The southeastern regions and areas surrounding the Asalouyeh port showed the highest concentrations, correlating with industrial activity.

- Temporal Trends: Fig. 4 illustrates the temporal trends in NO_2 concentration, revealing a steady increase

Table 1. The specifications of the ground-based monitoring system.

Pollutant	Measurement instrument	Detection limit	Temporal resolution	Spatial coverage
NO_2	Chemiluminescence analyzer (API-200A)	0.1 ppb	Hourly	Urban and industrial zones
CO	Non-Dispersive infrared (NDIR) analyzer	0.05 ppm	Hourly	Traffic corridors, industrial areas
SO_2	UV Fluorescence spectroscopy (Thermo Fisher Model 43i)	0.1 ppb	Hourly	Industrial and coastal regions
Aerosols ($PM_{2.5}$ & PM^{10})	Beta attenuation monitor (BAM-1020)	1 μg/m^3	Hourly	City-wide network

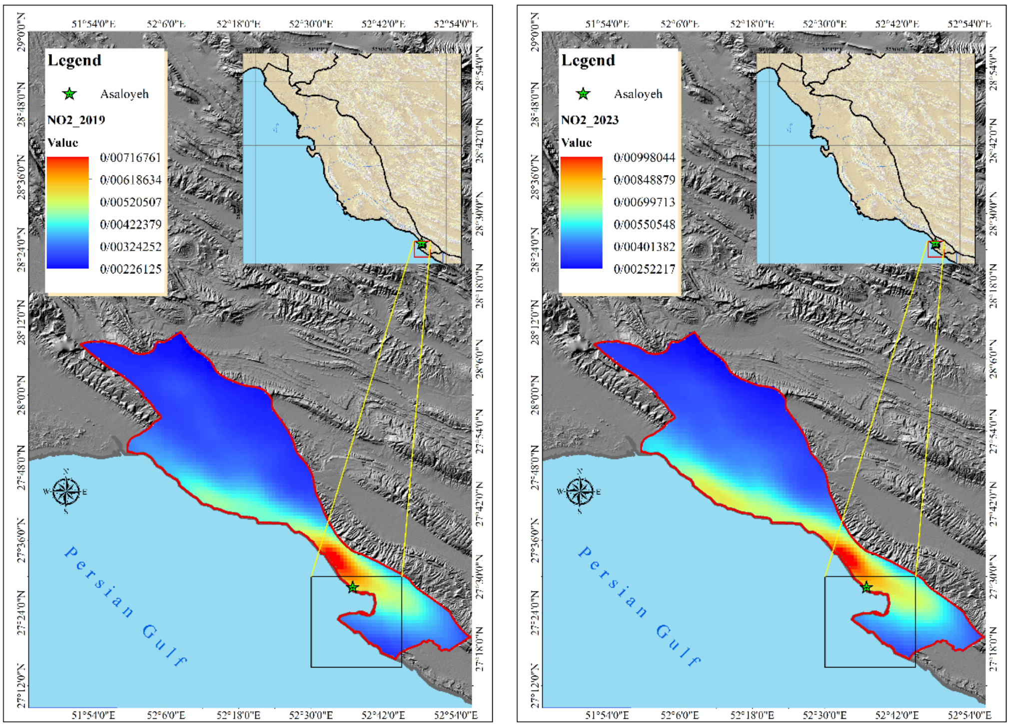

Figure 3. NO_2 2019 and 2023.

throughout the study period. This upward trend aligns with the expansion of industrial operations in Asalouyeh and the growth of transportation activities.

3.2 Carbon monoxide (CO)

CO is a colorless, odorless gas resulting from the incomplete combustion of carbon-containing fuels. Its toxicity and prevalence make it a critical pollutant to monitor.

- Spatial Distribution (2019 – 2023): The spatial distribution of CO, as shown in Fig. 5, indicates a significant increase in concentration, particularly in the southeastern part of Asalouyeh. In 2019, CO concentrations ranged from 0.63 to 0.88 ppm, whereas in 2023, the concentration escalated to a range of 0.58 to 0.86 ppm. This rise in concentration is most pronounced around industrial facilities, underscoring the impact of combustion-related emissions.
- Temporal Trends: The temporal trends depicted in Fig. 6 show an upward trajectory in CO levels from 2019 to 2023. This trend is consistent with increased vehicular emissions and industrial activities.

3.3 Sulfur dioxide (SO_2)

SO_2 is primarily emitted from industrial processes, including the combustion of fossil fuels. The analysis indicates a significant increase in SO_2 concentrations over the study period.

- Spatial Distribution (2019 – 2023): Fig. 7 illustrates the spatial distribution of $SO_2$2 in Asalouyeh. In 2019, SO_2 concentrations ranged from 0.00772734 to 0.037316 ppm. By 2023, these values had increased to a range of 0.0104357 to 0.0599827 ppm. Asalouyeh emerged as a significant hotspot for SO_2 emissions, particularly around petrochemical facilities.

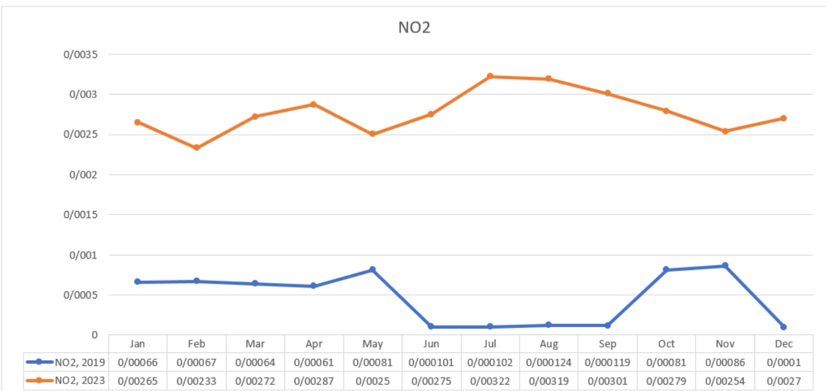

Figure 4. The concentration of NO_2 in 2019 and 2023.

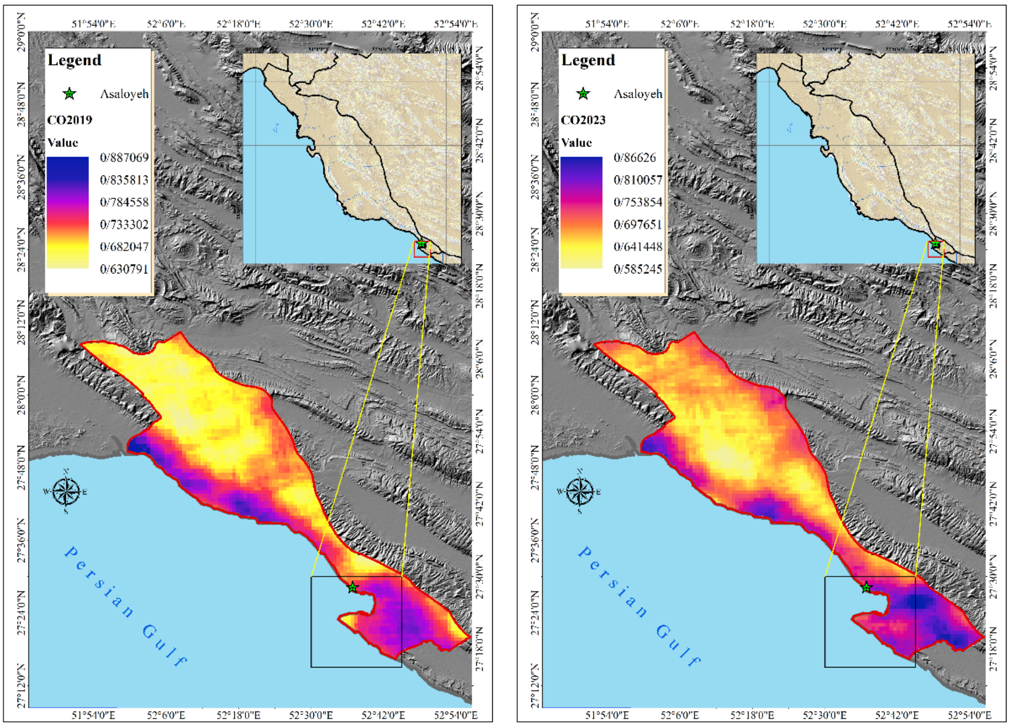

Figure 5. CO 2019 and 2023.

- Temporal Trends: The temporal analysis, shown in Fig. 8, demonstrates a notable increase in SO_2 levels from 2019 to 2023. This rise corresponds to the expansion of industrial activities and the lack of adequate pollution control measures.

3.4 Aerosols

Aerosols are small particles suspended in the atmosphere that can impact air quality and climate. They include particulate matter (PM) and are a significant component of urban air pollution.

- Spatial Distribution (2019 – 2023): The spatial distribution of aerosols, as presented in Fig. 9, reveals elevated concentrations in Asalouyeh. In 2019, aerosol levels ranged from −0.81 to 0.016 (AOD), while in 2023, they increased to a range of −0.034 to 0.8 (AOD). The highest concentrations were observed in industrial zones and urban centers.

- Temporal Trends: Fig. 10 illustrates the temporal trends in aerosol concentrations, showing an increase over the study period. This rise aligns with industrial emissions and the resuspension of particulate matter due to human activities.

3.5 Correlation with industrial activities

The data analysis demonstrates a clear correlation between industrial activities in Asalouyeh and the increased concentration of air pollutants. The rise in NO_2, CO, SO_2, and aerosols aligns with the growth of industrial operations, vehicular emissions, and inadequate pollution control measures in the region. Table 2 summarizes the average concentrations of pollutants and their annual changes.

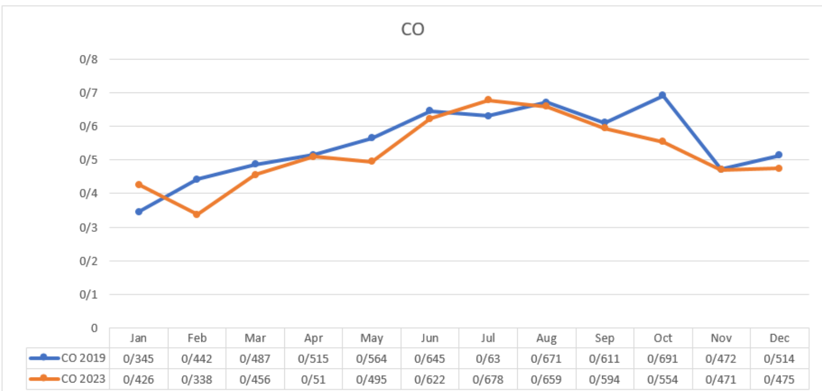

Figure 6. CO 2019 and 2023.

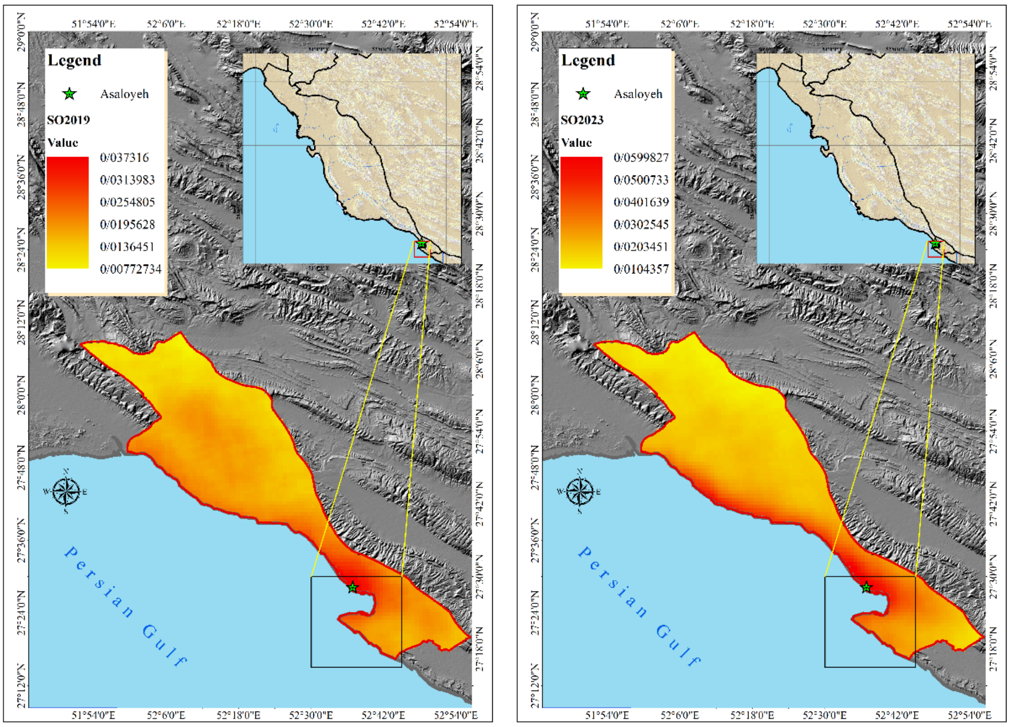

Figure 7. SO_2 2019 and 2023.

3.6 Statistical analysis and validation

The results of the Hanna (1993) method, which compared satellite-derived data with ground-based measurements, confirm the accuracy and reliability of the Sentinel-5P observations. The correlation coefficient (R), mean bias error (MBE), and root mean square error (RMSE) are presented in Table 3, demonstrating strong agreement between the datasets.

3.7 Implications for air quality management

The findings of this study underscore the urgent need for effective pollution control measures in Asalouyeh. The increasing concentrations of NO_2, CO, SO_2, and aerosols highlight the direct impact of industrial activities and inadequate environmental regulations. To address these issues, the following practical recommendations for pollution reduction are proposed:

Implementing stricter emission standards: The Iranian government should establish more stringent air quality regulations for industrial facilities, particularly in the petrochemical and transportation sectors. Adopting low-emission technologies and enforcing compliance with air pollution standards could significantly reduce pollutant levels.

Enhancing industrial waste management: Industrial sites in Asalouyeh should adopt advanced pollution control technologies, such as desulfurization systems and catalytic converters, to minimize emissions of SO_2 and NO_2. Regular maintenance of industrial equipment can further reduce fugitive emissions. Expanding air quality monitoring infrastructure: Increasing the number of ground-based monitoring stations will improve the accuracy of real-time pollution assessments and support better integration of satellite-derived data with local air quality networks.

Promoting cleaner transportation alternatives: Given the

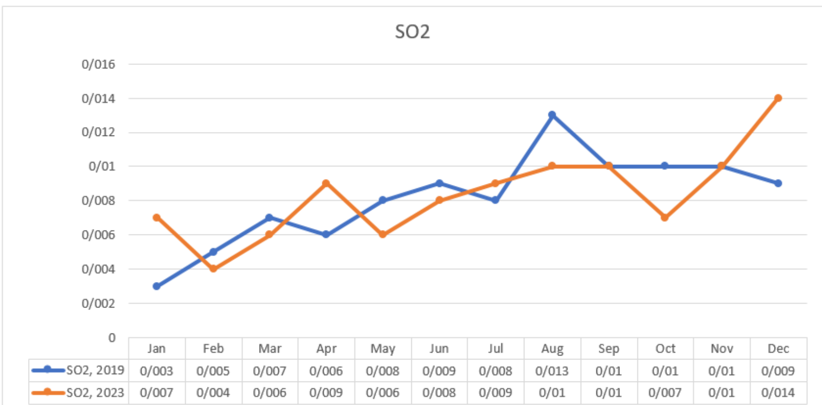

Figure 8. SO_2 2019 and 2023.

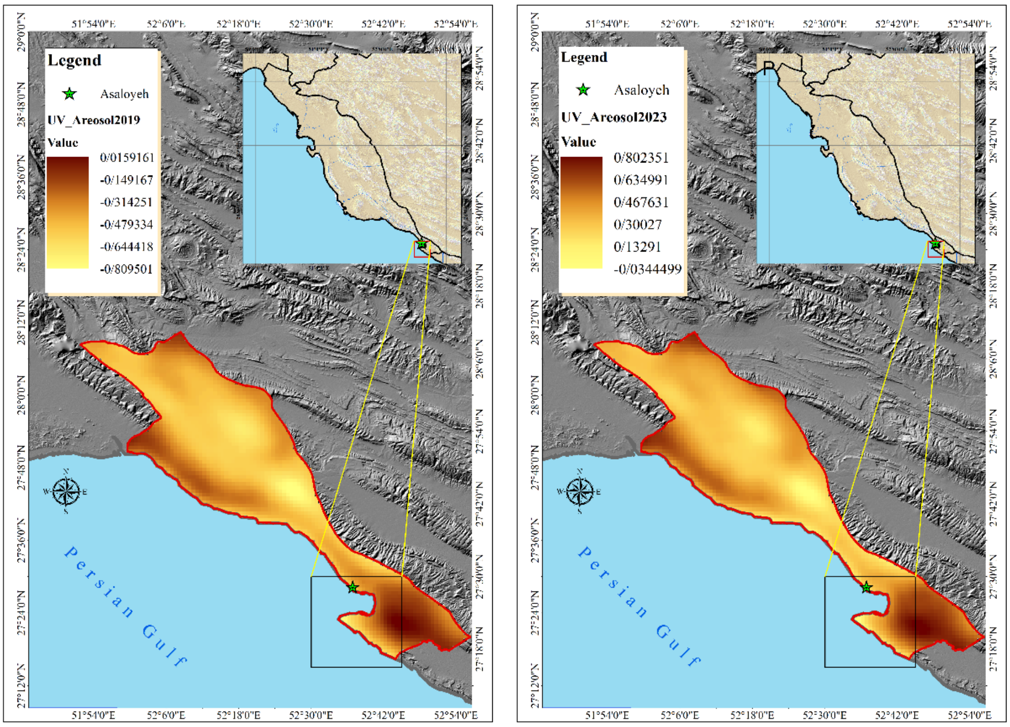

Figure 9. The biofertilizer pellets obtained.

contribution of vehicle emissions to NO_2 and CO pollution, investments in public transportation, electric vehicle infrastructure, and fuel efficiency improvements can significantly reduce air pollution levels.

Developing green buffers and urban planning strategies: Planting vegetation buffers and afforestation programs around industrial zones can help absorb pollutants and improve air quality. Urban planning regulations should also enforce the zoning of industrial sites away from residential areas to mitigate health risks.

Encouraging sustainable energy transition: Transitioning from fossil fuels to renewable energy sources, such as wind and solar power, can significantly reduce industrial emissions in the long term. Incentivizing carbon capture and storage (CCS) technologies for petrochemical industries should also be considered.

3.8 Uncertainty and sources of potential errors

Although the Sentinel-5P dataset and Google Earth Engine (GEE) provide high-resolution and large-scale atmospheric monitoring, certain uncertainties and limitations must be acknowledged:

Satellite data resolution limitations: The Sentinel-5P sensor provides atmospheric column measurements, meaning that pollutant concentrations are influenced by various altitude levels. Ground-level concentrations may deviate from satellite estimates, particularly in areas with high aerosol loads or cloud cover. Meteorological influences: Temperature, humidity, wind patterns, and seasonal variations affect pollutant dispersion and may introduce uncertainty in concentration estimates. Future studies should incorporate numerical weather models to improve interpretation.

Validation limitations: While we incorporated ground-based air quality data for validation, spatial and temporal mis-

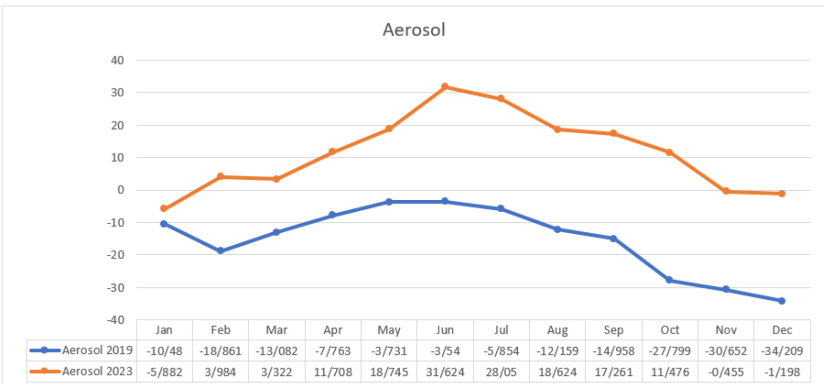

Figure 10. Aerosols 2019 and 2023.

Table 2. Summary of average pollutant concentrations (2019 – 2023).

Pollutant	2019 average concentration	2023 average concentration	Annual change (%)
NO_2	0.0019 – 0.0094 μmol/m^2	0.0019 – 0.0099 μmol/m^2	0 to −0.0005%
CO	0.11 – 0.02 ppm	0.07 – 0.88 ppm	57.1 to −97.7%
SO_2	−0.000446611 – 0.0395618 ppm	−0.4000520375 – 0.0602137 ppm	99.8 to −34.2%
Aerosols (AOD)	−1.24 – 1.12	−0.40 – 1.89	−210 to −40.7%

matches between satellite retrievals and monitoring stations may affect correlation results. A denser ground-monitoring network is needed to enhance validation accuracy. Anthropogenic vs. natural sources: The distinction between industrial emissions and naturally occurring pollutants (e.g., desert dust, and marine aerosols) remains a challenge. Advanced modeling techniques and chemical composition analysis can help separate these contributions.
Data processing limitations: Noise filtering, cloud masking, and radiometric calibration in satellite imagery introduce preprocessing uncertainties that may slightly alter concentration estimates. Using multiple satellite datasets (e.g., MODIS, OMI) for cross-validation can strengthen future assessments.

3.9 Future research directions

While this study provides critical insights into air pollution trends in Asalouyeh, several areas require further investigation:
Integration of ground-based and satellite data: Future research should combine Sentinel-5P observations with high-resolution ground sensors and mobile air quality monitoring to improve validation accuracy. Incorporation of additional pollutants: This study focused on NO_2, CO, SO_2, and aerosols. Future work should expand assessments to include $PM_{2.5}$, PM_{10}, volatile organic compounds (VOCs), and ozone (O_3) to capture the full spectrum of air pollution. Advanced modeling of pollution sources: Machine learning and data assimilation techniques should be used to differentiate industrial emissions from transportation, biomass burning, and natural dust events.
Public health impact assessments: Future studies should analyze the correlation between pollutant levels and hospital admissions for respiratory and cardiovascular diseases, providing quantifiable health risk assessments.
Climate change and pollution interactions: Investigating how climate change influences pollution trends in Asalouyeh will be essential for understanding long-term air quality projections and mitigation strategies.
Economic and policy evaluations: Assessing the economic burden of air pollution, its impact on productivity, and cost-benefit analyses of mitigation strategies can help design effective policy interventions.

4. Discussion

The industrial activities in Asalouyeh, particularly within the petrochemical sector, have led to significant environmental challenges, as evidenced by the substantial increases in atmospheric pollutants like nitrogen dioxide (NO_2), carbon monoxide (CO), sulfur dioxide (SO_2), and aerosols from 2019 to 2023. Our findings indicate that NO_2 concentrations increased from 0.0019 – 0.0094 μmol/m^2 in 2019 to 0.0019 – 0.0099 μmol/m^2 in 2023, while CO levels exhibited significant spatial variability, with concentrations rising from 0.11 – 0.02 ppm in 2019 to 0.07 – 0.88 ppm in 2023. SO_2 concentrations also showed an upward trend, increasing from −0.000446611 – 0.0395618 ppm in 2019 to −0.0000520375 – 0.0602137 ppm in 2023, further emphasizing the link between industrial emissions and deteriorating air quality. These findings align with prior studies that identified Asalouyeh as a pollution hotspot due to its proximity to the South Pars Gas Field (Abbasi et al., 2019; Keshmiri et al., 2018).
The observed trends in air pollution are consistent with other studies conducted in industrialized regions. For example, Shikwambana et al. (2020) used Sentinel-5P data to assess industrial pollution in South Africa, finding that NO_2 and SO_2 concentrations significantly correlated with industrial expansion. Similarly, Weng et al. (2022) reported that meteorological conditions play a crucial role in pollutant dispersion, which is also evident in Asalouyeh, where restricted airflow due to the surrounding Zagros mountain range exacerbates pollution accumulation. Recent research on air quality monitoring methodologies has highlighted

Table 3. Statistical comparison of satellite and ground-based measurements.

Pollutant	Correlation coefficient (R)	Mean bias error (MBE)	Root mean square error (RMSE)
NO_2	0.85	0.1 μg/m^3	0.5 μg/m^3
CO	0.75	0.15 μg/m^3	0.7 μg/m^3
SO_2	0.80	0.12 μg/m^3	0.6 μg/m^3
Aerosols (AOD)	0.70	0.18 μg/m^3	0.8 μg/m^3

the effectiveness of integrating satellite data with numerical models to enhance pollution assessments (Weng et al., 2022). Our study builds on these findings by demonstrating that Sentinel-5P and Google Earth Engine (GEE) provide a robust framework for real-time monitoring of industrial emissions.

Our results also corroborate findings from Iranian studies. For instance, Ghaderi et al. (2024) used Sentinel-5P to analyze air pollution in Khuzestan, another highly industrialized region in Iran and reported similar increases in NO_2 and CO concentrations. However, our study extends these insights by analyzing air pollution trends over a longer period (2019 – 2023) and integrating geospatial tools to identify pollution hotspots. Compared to other industrial regions worldwide, Asalouyeh exhibits higher SO_2 concentrations, which can be attributed to its extensive petrochemical activities and fossil fuel combustion.

The findings of this study have serious implications for public health and environmental management. NO_2 exposure is linked to respiratory diseases, cardiovascular conditions, and increased mortality rates (Bechle et al. (2013); World Health Organization [WHO (2024)]). Similarly, elevated CO levels can cause oxygen deprivation, affecting vulnerable populations such as children and the elderly (Alvim et al., 2021). The increasing concentration of SO_2 poses risks of acid rain formation, which can damage vegetation, soil, and water bodies (Stocker et al., 2013). Our study highlights the urgent need for policy interventions, such as stricter emission regulations and improved pollution control technologies, to mitigate the health and environmental risks associated with air pollution in Asalouyeh.

The spatial distribution maps generated in this study can assist policymakers in identifying critical pollution hotspots and prioritizing mitigation efforts. Implementing low-emission industrial technologies, enhancing air quality monitoring networks, and enforcing stricter environmental regulations are essential steps in reducing pollution levels. These strategies align with recent recommendations for sustainable industrial development (Nacef et al., 2016).

Despite the strengths of this study, certain limitations must be acknowledged. First, while Sentinel-5P data provide high-resolution atmospheric measurements, they do not capture micro-scale variations in pollutant concentrations. Future studies should integrate ground-based air quality monitoring data with satellite observations to improve accuracy. Second, our analysis focused on NO_2, CO, SO_2, and aerosols, but additional pollutants, such as volatile organic compounds (VOCs) and fine particulate matter ($PM_{2.5}$), should be included in future assessments to obtain a more comprehensive understanding of industrial emissions.

Furthermore, meteorological factors such as wind speed, temperature inversions, and humidity levels influence pollutant dispersion. Incorporating numerical weather prediction models could enhance the interpretation of pollution trends. Additionally, future research should explore the socioeconomic impacts of air pollution, including its effects on public health costs and economic productivity. Recent studies have emphasized the importance of integrating economic and environmental data to develop more effective pollution control strategies (Soleimani et al., 2021; Ashrafi et al., 2012).

5. Conclusion

This study provides a comprehensive analysis of air pollution trends in Asalouyeh from 2019 to 2023, revealing a significant increase in NO_2, CO, and SO_2 concentrations. The findings highlight the impact of industrial activities on air quality and emphasize the urgent need for enhanced environmental policies. By leveraging Sentinel-5P and GEE, this study demonstrates the effectiveness of remote sensing technologies for large-scale air quality monitoring, offering a scalable approach that can be applied to other industrial regions worldwide. Future research should focus on integrating satellite and ground-based measurements, incorporating additional pollutants, and analyzing the socioeconomic effects of air pollution to develop holistic mitigation strategies.

Authors contributions
H. Torabi and Z. Abedi wrote the original draft, Software, Methodology, Investigation, and Data curation. Z. Azizi and B. Mojaradi revised and edited the main text.

Availability of data and materials
The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Conflict of interests
The author declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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