

**Leveraging Doppler Satellite Remote
Sensing to Assess Spatiotemporal Air
Qualit Dynamics inthe Baghdad-Karbala-
Najaf Urban Corridor**

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Abstract

This research examines the spatiotemporal dynamics of air pollutant concentrations across the Baghdad-Karbala-Najaf corridor, leveraging Doppler-based satellite remote sensing data. The analysis focuses on five critical atmospheric contaminants: sulfur dioxide (SO₂), nitrogen dioxide (NO₂), carbon monoxide (CO), ozone (O₃), and fine particulate matter (PM_{2.5}). Findings reveal pronounced variability in pollution levels, attributable to synergistic interactions between meteorological parameters and anthropogenic factors, with peak exacerbations observed during the Arbaeen pilgrimage a mass religious gathering. Urban centers in Baghdad exhibited the highest baseline pollution concentrations, driven by vehicular density and industrial emissions, while Karbala and Najaf demonstrated episodic spikes correlated with large-scale religious events. Precipitation emerged as a statistically significant mitigating factor, particularly in scavenging SO₂ and NO₂ from the atmospheric column. The study proposes evidence-based scientific and policy interventions, advocating for integrated sustainable urban planning, deployment of real-time air quality surveillance systems, and ecological mitigation protocols for managing high-density human congregations.

Keywords: Air Pollution Dynamics; Doppler Remote Sensing; Satellite Atmospheric Monitoring; Arbaeen Mass Gathering; Anthropogenic Emissions (SO₂, NO₂, CO, PM_{2.5}, O₃); Air quality.

Introduction

Air pollution, characterized by the presence of harmful atmospheric substances including gases (e.g., NO₂, SO₂, CO, O₃) and particulate matter (PM_{2.5}), poses significant threats to public health and environmental sustainability (1,3). Primary anthropogenic sources such as vehicular emissions, industrial activities, and fossil fuel combustion contribute to respiratory diseases, cardiovascular morbidity, and premature mortality, particularly when pollutant concentrations exceed critical thresholds (4,5). The complex interplay between suspended particulates and gaseous pollutants exacerbates these risks, with PM_{2.5} being especially hazardous due to its ability to penetrate deep into the respiratory system (6). Concurrently, gases like ground-level ozone (O₃) and sulfur dioxide (SO₂) not only impair human health but also contribute to environmental degradation through acid rain formation and climate feedback mechanisms (7,9).

Urbanization and population growth have intensified air pollution challenges globally, with developing regions like Iraq experiencing compounded effects due to industrial expansion, unregulated emissions, and episodic events such as the Arbaeen pilgrimage (10,11). Studies in Iraqi cities, including Baghdad, Mosul, and Erbil, highlight the role of meteorological factors (e.g., wind patterns, rainfall) and localized sources (e.g., diesel generators, brick kilns) in driving spatiotemporal pollution variability (12,14). For instance, Khalaf et al. (2009) documented substantial emissions from diesel generators in Kut, while Shihab (2021) identified PM₁₀ as the dominant pollutant in Mosul, with seasonal fluctuations linked to weather conditions (15,16).

This study leverages Doppler satellite data to systematically monitor air quality across Baghdad, Karbala, and Najaf—a region where pollution dynamics remain understudied despite acute exposure risks. Specif-

ic objectives include: (1) quantifying spatial-temporal variations in NO₂, SO₂, CO, O₃, and PM_{2.5}; (2) identifying dominant pollution sources (e.g., traffic, industry, religious gatherings); and (3) proposing evidence-based mitigation strategies tailored to Iraq's socio-environmental context. By integrating remote sensing with ground-truth data, this research aims to advance regional air quality management and inform policies targeting sustainable urban development and public health protection.

Air Pollution Theory in Iraq

Iraq faces significant air pollution challenges due to industrial activities, vehicular emissions, fossil fuel combustion, and widespread use of generators. Major pollutants include nitrogen dioxide (NO₂), sulfur dioxide (SO₂), carbon monoxide (CO), ozone (O₃), and particulate matter (PM_{2.5}), each posing severe health and environmental risks. NO₂ and SO₂, primarily from power plants and transportation, contribute to respiratory diseases and acid rain. CO, a byproduct of incomplete combustion, disrupts oxygen transport in blood. O₃ forms via photochemical reactions, exacerbating respiratory conditions. PM_{2.5}, emitted from industrial and vehicular sources, penetrates deep into lungs, increasing cardiovascular and respiratory mortality.

Weather conditions, including wind, temperature, and sandstorms, influence pollutant dispersion, while human activities—industrial operations, traffic congestion, and seasonal heating—further degrade air quality. The annual Arbaeen pilgrimage intensifies pollution through increased vehicular emissions, generator use, and waste burning, elevating NO₂, SO₂, CO, and PM_{2.5} levels. Regulatory measures and emission controls are urgently needed to mitigate health and ecological impacts, particularly in urban centers like Baghdad, Karbala, and Najaf.

Study area

The study area covers the region between Baghdad, Karbala, and Najaf, which is characterized by a mix of urban, industrial, and arid environments. Baghdad, as the capital and largest city of Iraq, experiences high levels of air pollution due to traffic emissions, industrial activities, and population density. Karbala and Najaf, both significant religious and cultural centers, witness periodic increases in air pollution, especially during large gatherings and seasonal weather changes. The region's climate is predominantly arid, with frequent dust storms and variable wind patterns that influence air quality shown in figure 1. By utilizing Doppler satellite data, this study aims to analyze spatial and temporal variations in air pollution across these areas, considering meteorological factors such as wind speed, direction, and atmospheric pressure.

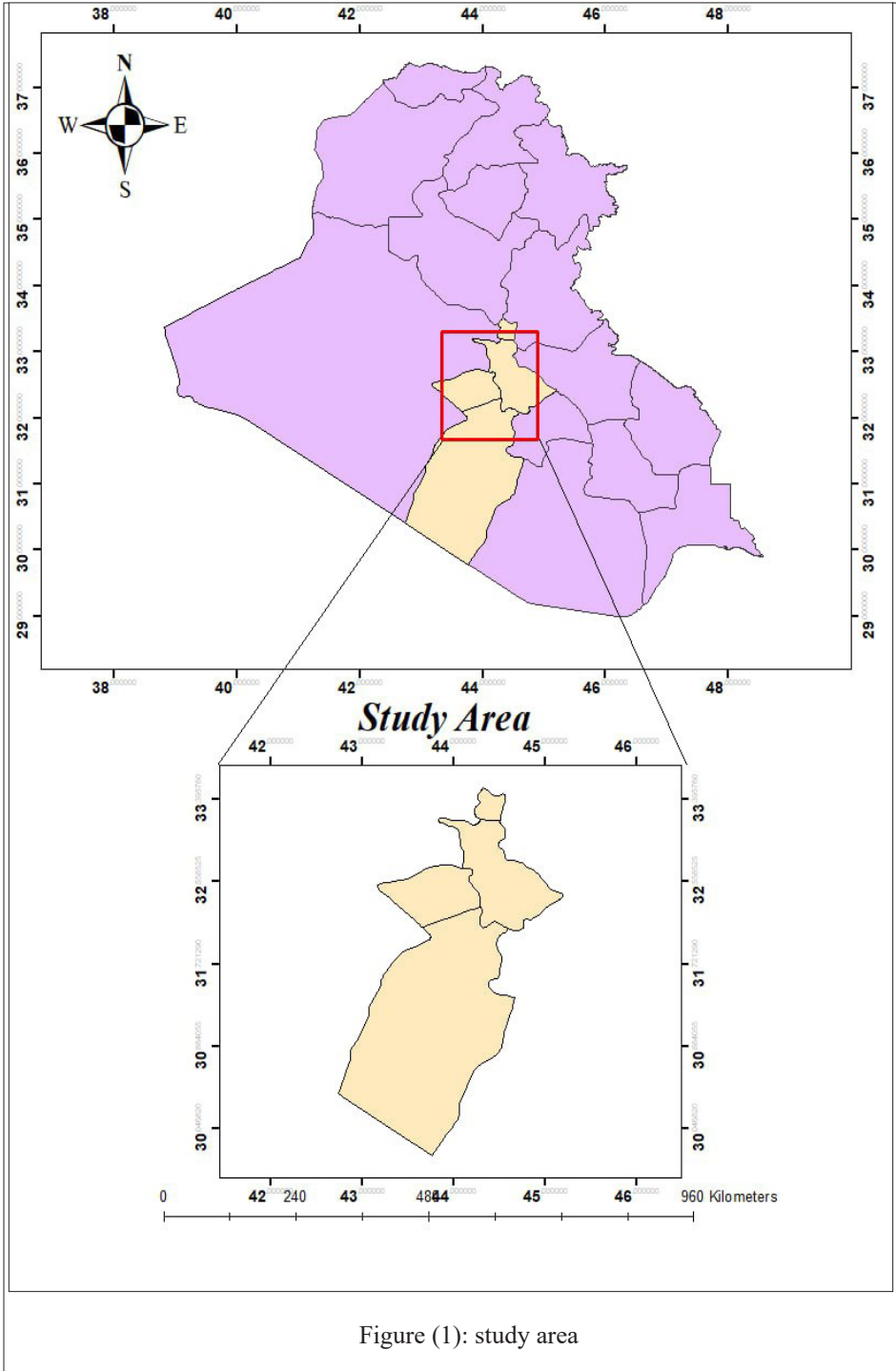


Figure (1): study area

Methodology

This study utilized Doppler satellite data to monitor air pollutants—SO₂, NO₂, CO, O₃, and PM_{2.5}—in Iraq, leveraging high-resolution remote sensing from platforms like Windy, Copernicus, and Sentinel Hub. The Doppler satellites (e.g., ESA missions) provided daily global coverage with a spatial resolution of 7 × 3.5 km², detecting pollutants via UV, visible, and infrared spectral bands. Complementary data from MODIS, OMI, and VIIRS enhanced aerosol and trace gas analysis.

Pollutant concentrations were extracted from Windy's interactive maps, which integrate real-time ECMWF and CAMS forecasts. SO₂ levels (2–10 Jan 2025) peaked at 63.02 µg/m³ (Sunday), while NO₂ (4–12 Feb 2025) reached 88.02 µg/m³ (Tuesday evening), reflecting traffic and industrial influences. PM_{2.5} (8–15 Mar 2025) varied from 13–39.77 µg/m³, with higher levels linked to dust storms. Rainfall's cleansing effect was quantified, showing SO₂ reduced by 81%, NO₂ by 79%, and CO by 65% post-rain due to atmospheric washing. Wind speed (17 km/h) further dispersed pollutants.

Statistical and graphical analyses (tables, line graphs) illustrated diurnal and seasonal trends, correlating pollution spikes with meteorological conditions (wind, rain, temperature) and human activities (traffic, industry). The methodology underscores satellite remote sensing's efficacy in urban air quality assessment and pollution mitigation strategies.

Results:

This study analyzed air pollutant concentrations (SO₂, NO₂, CO, PM_{2.5}) in Baghdad, Karbala, and Najaf, revealing significant variations driven by meteorological conditions and human activities, particularly during the Arbaeen pilgrimage.

1. Sulfur Dioxide (SO₂):

- Peak concentrations occurred in Baghdad due to industrial activity and traffic, while Karbala and Najaf showed elevated levels during Arbaeen from diesel generators, vehicular emissions, and open cooking.
- Rainfall reduced SO₂ by ~81%, demonstrating atmospheric cleansing. Industrial zones and temporary power demand during religious events were key contributors. Shown in figure (2 and 3).



Figure (2): Sulfur Dioxide (SO₂) distributions.

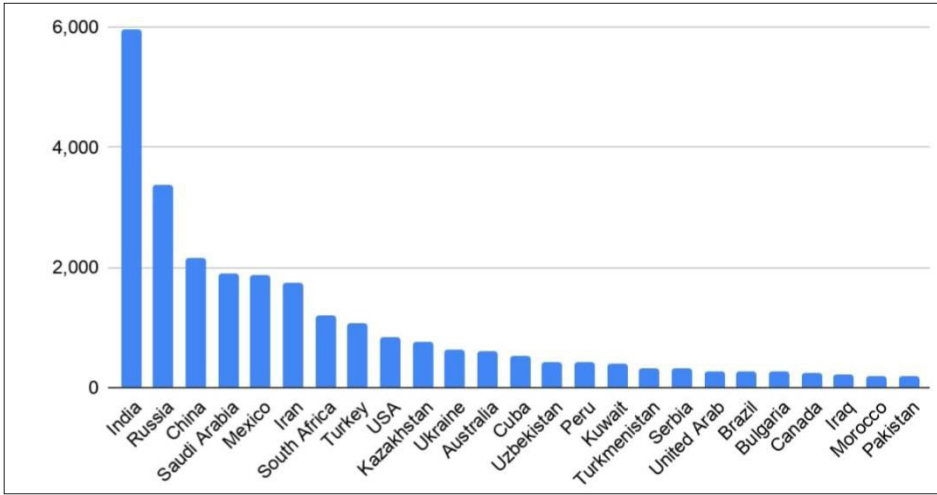


Figure (3): Statistics chart of the countries and cities that recorded the highest SO2 pollution rate for the year.

2. Nitrogen Dioxide (NO₂):

- Urban centers exhibited peak NO₂ during rush hours, with Arbaeen causing a sharp rise (e.g., 88.02 µg/m³ in Karbala/Najaf) due to traffic congestion and generator use.
- NO₂'s reactivity with atmospheric compounds worsened air quality, posing risks to respiratory health, especially for vulnerable groups shown in figure 4.

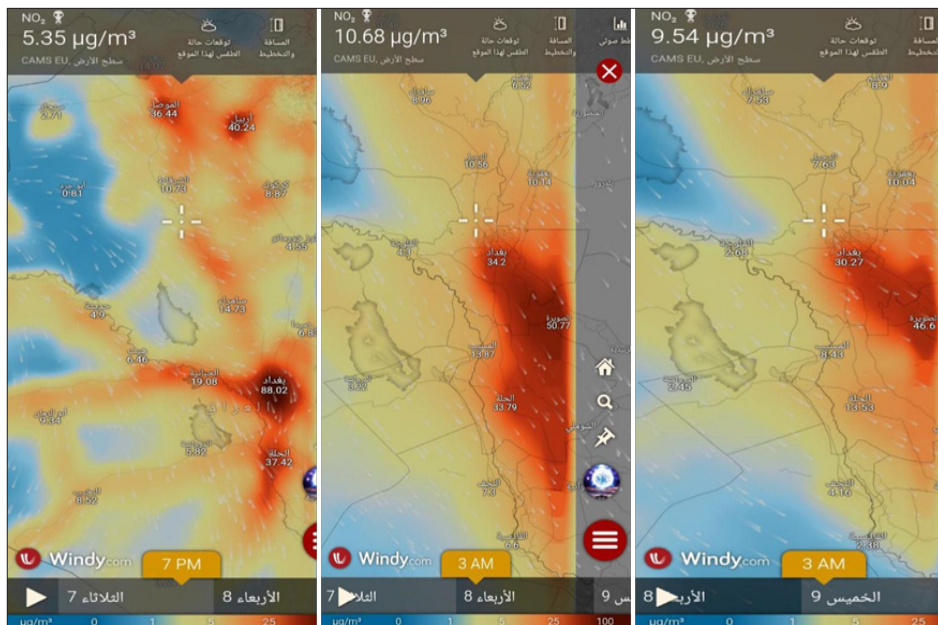


Figure (4): Nitrogen Dioxide (NO₂) distributions.

3. Carbon Monoxide (CO):

- Highest levels were linked to incomplete combustion from generators and vehicles during Arbaeen. Crowded roads and fossil fuel-based energy exacerbated emissions shown in figure 5.
- CO's odorless, invisible nature increased health risks, particularly in densely populated areas.

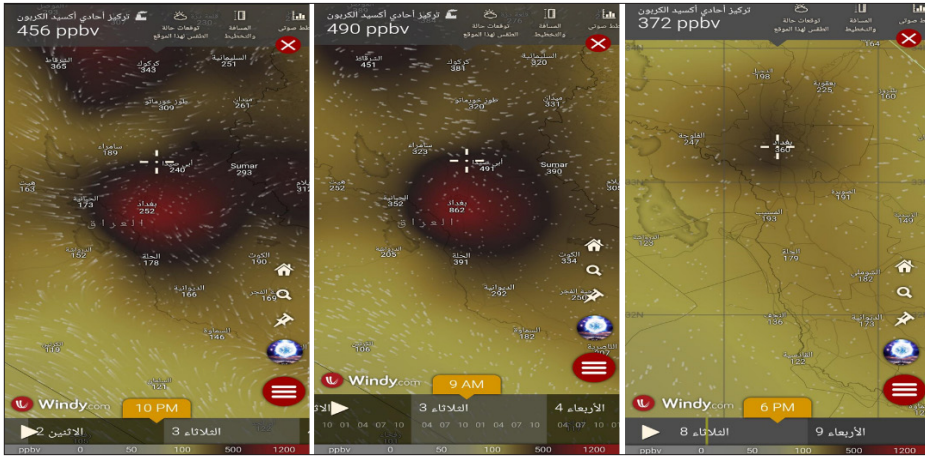


Figure (5): Carbon Monoxide (CO) distributions.

4.Particulate Matter (PM_{2.5}):

- Dust storms and human activities (e.g., waste burning, traffic) combined to elevate PM_{2.5}, with peaks reaching 39.77 $\mu\text{g}/\text{m}^3$.
- Arbaeen intensified emissions through open cooking and waste accumulation, compounding health risks from long-term exposure shown in figure 6.

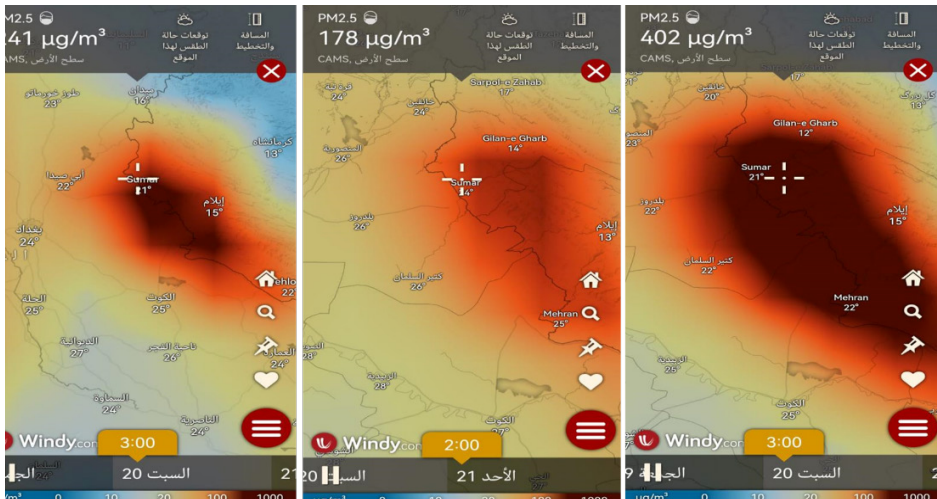


Figure (6): Particulate Matter (PM_{2.5}) distributions.

Key Findings:

- Religious events like Arbaeen amplified pollution via traffic, generators, and open burning.
- Meteorological factors (rain, wind) played a dual role: rain reduced pollutants (e.g., SO₂ by 81%), while calm winds trapped emissions in urban areas.
- Health impacts were severe for vulnerable populations, necessitating targeted mitigation strategies for industrial, transport, and energy sectors.

Meteorological Factors Influencing Gaseous Pollutant Concentrations:

- Wind and temperature are among the most influential meteorological factors affecting air pollution levels.
- Low wind speeds typically lead to pollutant accumulation near the surface, while higher wind speeds promote dispersion and improve air quality.
- Temperature fluctuations can either enhance chemical reactions that lead to pollutant formation or assist in vertical air movement that helps disperse pollutants. As a result, some pollutants may increase or decrease depending on the specific weather conditions. Shown in figures (7, 8, and 9).

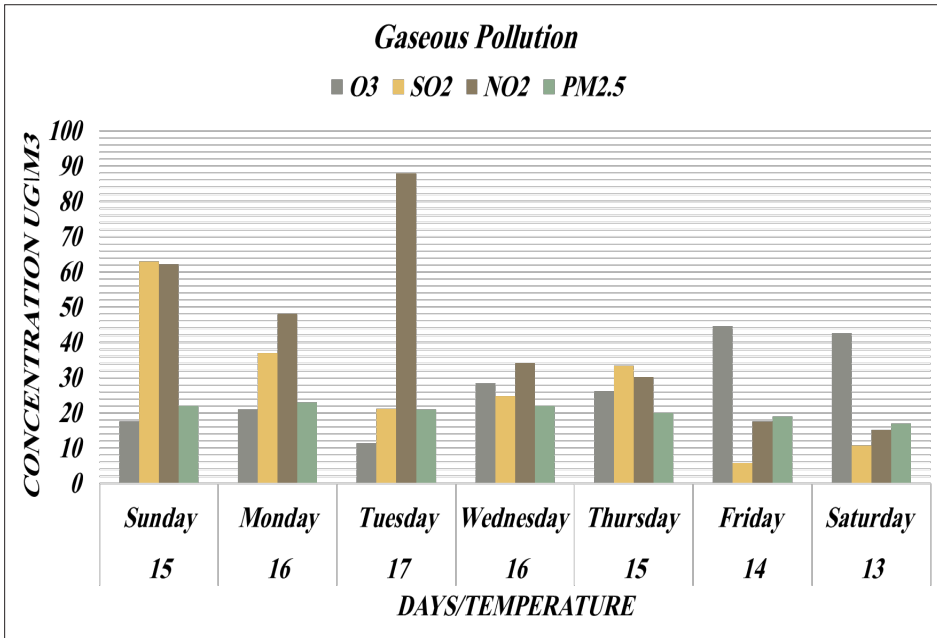


Figure (7): Pollution concentration in January with a wind speed of (12-15 km/h).

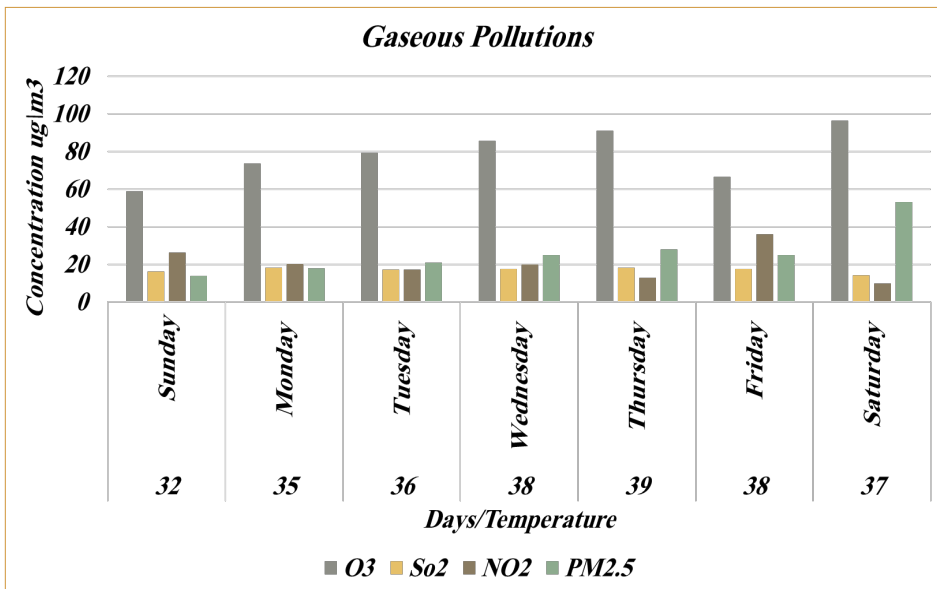


Figure (8): Pollution concentration in March with a wind speed of (22-26km/h).

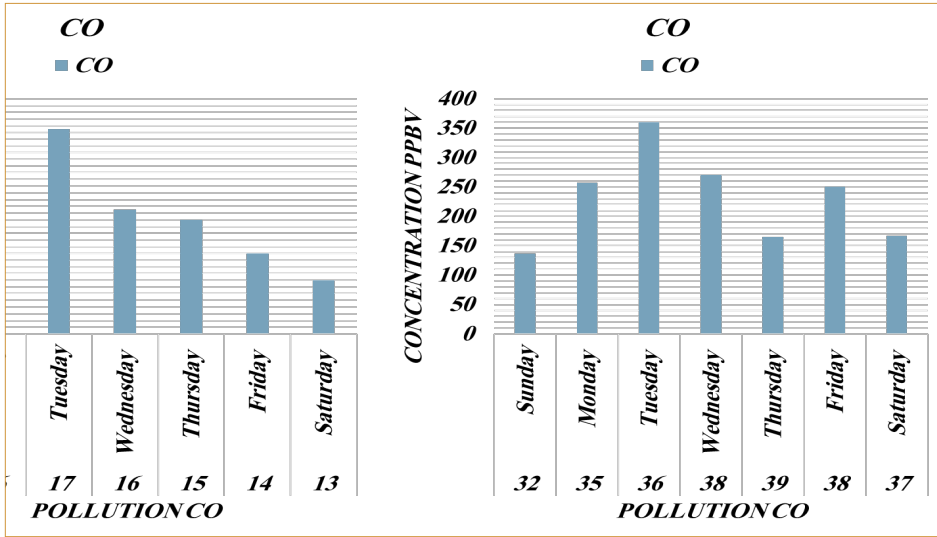


Figure (8): CO concentration in January with a wind speed of (12-15 km/h) and March with a wind speed of (22-26km/h).

Conclusion

This study highlights significant air pollution challenges in the Baghdad-Karbala-Najaf region, driven by industrial emissions, traffic congestion, and seasonal events like the Arbaeen pilgrimage. Baghdad exhibited the highest pollution levels due to dense urbanization and industrial activity, while Karbala and Najaf experienced spikes during religious gatherings from generator use, vehicular emissions, and open-air cooking. Key findings include:

- SO₂ correlated with industrial/fuel combustion and declined post-rain-fall.
- NO₂ peaked in traffic-heavy zones, exacerbated by diesel generators.
- CO rose during mass gatherings due to incomplete combustion.
- PM_{2.5} persisted from dust storms and anthropogenic sources (e.g., waste burning).
- O₃ increased during high-temperature photochemical reactions.

Meteorological factors—rain reduced pollutants (SO₂ by 81%), while calm winds worsened accumulation. Doppler satellite data (e.g., Windy platform) effectively tracked spatiotemporal pollution trends, underscoring its utility for policy and mitigation strategies. Urgent measures are needed to curb emissions from transport, industry, and energy sectors, especially during high-risk events.

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