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Spatial and Temporal Variations of Air Pollutants Around Multiple Generator Sites: A Case Study

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ABSTRACT

This study investigated the spatial and temporal variability of key air pollutants, namely carbon monoxide (CO), sulfur dioxide (SO_2), nitric oxide (NO), and fine particulate matter ($PM_{2.5}$) emitted from multiple kerosene-powered generators in the Al-Bonouk neighborhood of Baghdad, Iraq, was investigated. Field sampling was conducted monthly from June to August 2024 at nine fixed outdoor locations using a systematic, point-based sampling method. Locations were selected to reflect the generator proximity and wind direction. At each point, real-time readings were recorded monthly using a portable gas analyzer and PM detector. A total of 27 field samples were obtained, and each sample was analyzed for four pollutants, generating 108 analytical data points. Data were processed using bar plots, line graphs, box plots, and spatial heat maps to evaluate pollutant distribution, emission hotspots, and seasonal variation. The highest concentrations were recorded near Generator 2, CO (55.5 parts per million (ppm), NO (8.89 ppm), SO_2 (5.87 ppm), and $PM_{2.5}$ (0.46 µg/m³). Concentrations decreased with distance and wind dispersion. WHO guideline comparisons confirmed consistent exceedances, underscoring urgent health concerns and the need for regulatory action in urban areas.

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INTRODUCTION

In recent decades, air pollution has emerged as a major environmental issue because it causes direct harm to human health and diminishes the quality of life in urban areas. The increasing population, combined with ongoing energy demands, has led to the extensive use of electric generators throughout urban areas for backup power needs and permanent power supply in areas without adequate infrastructure(Murtadah et al. 2020). The generators provide essential energy services to communities, but they emit significant air pollutants, which include nitrogen oxides (NOx), carbon monoxide (CO), fine particulate matter ($PM_{2.5}$ and PM_{10}), volatile organic compounds (VOCs), and sulfur dioxide (SO_2).(Oriakpono et al. 2022)

The main issue arises because multiple generator sites across urban areas generate major differences in pollutant concentrations between different locations and periods. The unbalanced spread of pollution throughout the city creates challenges for air quality management and reduces the effectiveness of environmental policies(Geng et al., 2016). The examination of

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generator pollutant emissions throughout space and time enables researchers to detect pollution patterns, which leads to the creation of appropriate interventions at both local and national levels.Research indicates that generator emissions result from various factors, including the type of fuel used (diesel or gasoline), generator combustion efficiency, age of the generator, operational time, and environmental conditions such as building locations, traffic density, and wind patterns(Geng et al., 2016). The operational timing pattern affects both current pollution levels and the total amount of accumulated pollutants. The analysis of generator emissions in urban areas remains restricted because of limited monitoring capabilities, especially in cities with poor infrastructure and those that rely heavily on generators as their primary power source.(Mohammed et al. 2022; Shakya et al. 2022; Ohadugha et al. 2021)Air pollution heatmaps show the existence of "hotspots" because pollutants tend to accumulate around densely clustered generators or those located near vital facilities, markets and hospitals. The combined pollution from multiple generators operating in a small space results in long-lasting contaminated environments that endanger the health of local community members(Nakano et al., 2015). Studies indicate that pollution levels reach their highest points during specific daily periods, particularly during early morning and sunset hours, when generator usage reaches its peak due to power outages and rising electricity demand.(Xu et al., 2022)According to the World Health Organization (WHO), the ambient air quality guideline limits are 4 ppm for CO (24-hour mean), 0.005 ppm for SO_2 (24-hour mean), 0.053 ppm for NO_2 (annual mean), and 5 μg/m³ for $PM_{2.5}$ .Previous studies have analyzed generator-related emissions in different countries (A. Shakya et al. 2024; Ohadugha et al. 2021), showing localized hotspots near clustered generator zones. However, these studies often focus on single-point measurements or indoor exposure, with limited assessments of urban outdoor dispersion patterns in cities that are heavily dependent on generators. Additionally, few studies have addressed seasonal variations in emissions or provided high-resolution spatial mapping across multiple sampling sites. Therefore, this study fills a critical gap by examining the spatiotemporal variability of multiple air pollutants from kerosene-powered generators in a densely populated urban neighborhood. .Air quality management in cities requires complete knowledge of dynamic changes, which necessitates the creation of sophisticated monitoring systems that track pollutant variations across space and time(Gulia et al., 2015). The analysis of pollutant distribution and its interaction with environmental and meteorological factors was conducted using field-based measurements combined with statistical visualization techniques, including time-series graphs, box plots, and Gaussian-modeled pollution gradient maps, to capture spatial patterns and seasonal dynamics. The ability to forecast pollution levels in particular regions at specific times enables policymakers to create regulations regarding generator operating periods, fuel restrictions, and location planning for new generators to reduce urban pollution(Wang & Hao 2012). This problem affects multiple development challenges, especially in densely populated and low-to middle-income cities, where clean energy alternatives remain unavailable or unaffordable (Kakodia et al., 2025). The fast rate of urban growth demands an integrated strategy that links scientific monitoring with environmental analysis and urban planning to develop sustainable air quality management approaches.(Kumari et al. 2025; Beattie et al. 2025; Longhurst et al. 2025)This study integrated field measurements with statistical and visual analyses to identify emission hotspots, assess seasonal trends, and compare pollutant levels with WHO standards. The findings support more targeted environmental planning and public health risk reduction strategies in generator-reliant communities.

MATERIALS AND METHODS

The field investigation was conducted from June to August 2024. The research team collected 27 field samples from nine permanent outdoor sampling points (P1–P9) each month.

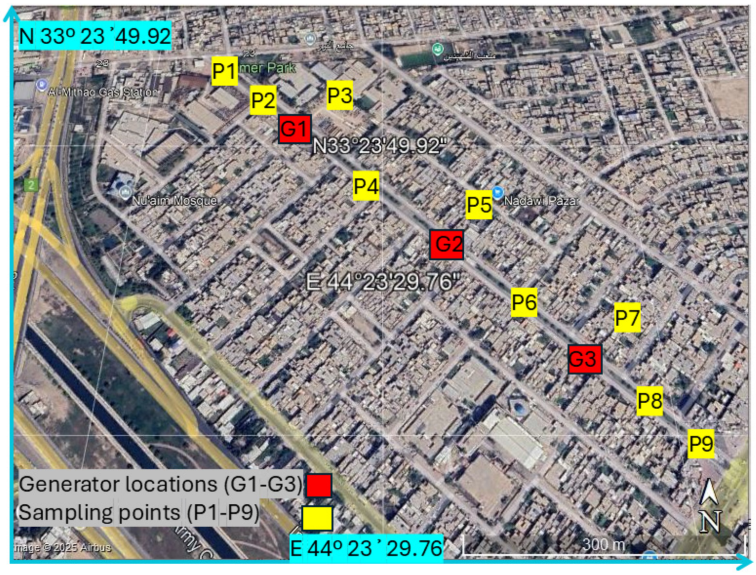

Fig. 1. Study area map showing generator locations.
Source: Adapted from Google Earth (retrieved June 24, 2025).

The research team collected 108 analytical observations through the analysis of four pollutants (CO, SO_2, NO, and $PM_{2.5}$) in each sample.

Study Area Description

The Al-Bonouk neighborhood in Baghdad Governorate, Iraq, was selected as the study area to investigate the impact of electric generators on the air quality and the surrounding environment. The residential area is densely populated and depends on electric generators because of frequent power outages. The mixed residential and commercial nature of the area makes it a suitable location for assessing the impact of these generators on air quality and public health. Data will be collected from various points within the neighborhood, focusing on areas with high generator usage, to ensure the reliability of the results and to analyze the environmental and health implications. Figure (1) presents the study area in the Al-Bonouk neighborhood of Baghdad, using satellite imagery adapted from Google Maps. Generator locations (G1, G2, and G3) are marked with red squares, and air quality sampling points (P1–P9) are highlighted with yellow labels. The map includes a scale bar (100 m) for distance reference and a north arrow for orientation (Google Earth, 2025)

The total distance measured along the street was 877.25 m. Three electric generators were located at different points along the street, contributing to localized air pollution. The presence of these generators indicates potential sources of air pollutants, such as particulate matter, nitrogen oxides, and sulfur dioxide. The dense residential area surrounding the generators raises concerns regarding residents’ exposure to these pollutants.

Meteorological Conditions During Sampling

Meteorological parameters were measured on-site using an Extech AN340 portable environmental meter. This handheld device recorded the ambient temperature, relative humidity, and wind speed during each sampling session. The AN340 is widely used in field-based air quality studies and provides reliable multi-variable environmental data.(Yong et al., 2022)

Sampling Design and Locations

Field sampling was conducted from June to August 2024, which aligned with the peak season of diesel generator use in Baghdad. Due to increased electricity demand, power outages

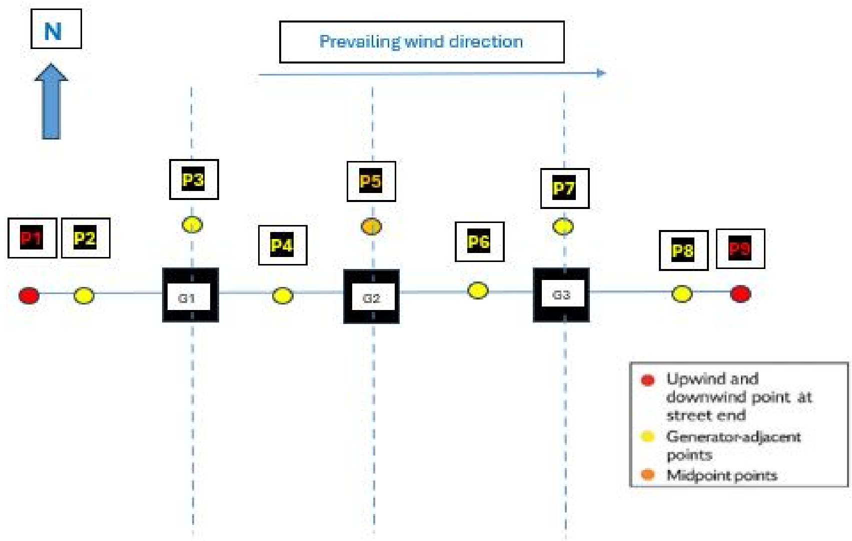

Fig. 2. Locations of the sampling

are frequent in summer, and generator runtimes are extended, especially in residential areas such as Al-Bonouk.

These months also experience extreme weather conditions. Temperatures often exceed 45°C. The humidity is low, and the wind speed is moderate. These conditions affect the dispersion and accumulation of pollutants in the air. Choosing this period allowed the study to capture the worst-case exposure scenarios. Additionally, the dry season ensured stable field access with minimal disruption from weather.

A total of nine sampling locations (P1–P9) were selected and classified based on their positions relative to the emission sources. The points were grouped into three categories: upwind/downwind points located at the street ends, generator-adjacent points located directly next to the three generator units, and midpoint locations positioned between successive generators. Each category was assigned a distinct color and symbol, as shown in Figure 2, and this classification was used to assess spatial patterns in pollutant concentrations.(Contardo et al. 2024; Clark et al. 2024; Shaddick et al. 2023)

Air Sampling Device (Sniffer)

The Sniffer operates as a compact portable sampling instrument that determines the total suspended particulates (TSP) in atmospheric air. The device draws a specific volume of air through a fiberglass filter paper at a set flow rate. The filter medium trapped particulate matter in this setup. The device contains a built-in vacuum pump, flow meter, and digital timer that work together to establish exact sampling conditions. The Sniffer operates in field environments to measure air quality at 1.5 m above ground level and near intermittent emission sources, including generators. Filter paper analysis after collection requires either weighing the paper before and after sampling or specialized laboratory equipment to determine particulate concentrations in micrograms per cubic meter ($\mu g/m^3$). The device functions as a vital instrument for environmental research because it delivers precise, real-time measurements of particulate matter.(Abeykoon et al., 2022; Zanetti et al., 2023)

The Gas Analyzer

The Gas Analyzer operates as a sophisticated instrument that delivers immediate measurements of ambient air pollutants, including sulfur dioxide (SO_2), carbon monoxide (CO), and nitrogen oxides (NO_x). The portable device depends on infrared absorption, electrochemical sensors, and chemiluminescence detection technologies to measure gas concentrations, which are typically reported in parts per million (ppm) or parts per billion (ppb). The Gas Analyzer is an essential tool for environmental generator emission studies to assess the impact of combustion on air quality. The device allows researchers to create comprehensive pollution profiles through simultaneous gas measurements, enabling them to verify regulatory standards. The modern Gas Analyzers feature built-in data logging capabilities and GPS integration, and wireless connectivity, which enables efficient field operations and immediate real-time data transmission for pollution level response.(Dhall et al., 2021; Petrov et al., 2022; Qi et al., 2024)

Data analysis methods

Data collected from the nine sampling sites were subjected to multiple analysis stages to assess both spatial and temporal variations in pollutant concentrations. The measured values of CO, SO_2, NO, and PM were subjected to descriptive statistical analysis for data summary across June, July, and August. Time-series plots, including line graphs and bar charts, were used to show monthly changes and detect peak values at each monitoring site. Boxplot analysis revealed dataset variability and interquartile ranges while detecting potential outliers to understand emission patterns over time(Sadeghkhani & Sadeghkhani 2025). Each pollutant and month received Gaussian-based pollution gradient maps to evaluate the spread of pollutants based on the source location and wind patterns. The spatial models simulated pollutant diffusion to reveal emission hotspots, which were most prominent around generator 2. Heatmaps were created using Python (Seaborn and Matplotlib libraries) to generate these maps. The plots visualized spatial and temporal variations in pollutant concentrations using a 2D matrix with sampling sites and pollutant values. The color intensity reflects the concentration magnitude. Although GIS-based spatial modeling was not used, this approach allowed for a visual and data-driven representation of Gaussian-like dispersion.The recorded concentrations were compared with the World Health Organization (WHO) ambient air quality standards to determine exceedances and health implications. The combined assessment method allowed both numerical and visual evaluations of pollutant behavior, which established a solid basis for evidence-based environmental policy recommendations.(Byun et al. 2021; Zhao et al. 2024; Sartelet et al. 2025)

RESULTS AND DISCUSSION

Influence of Meteorological Conditions on Pollutant Dispersion

Table 1 shows the meteorological data showing high temperatures and moderate wind speeds during the study period. In June, the average temperature was 43°C. It increased to 45°C in July and 46°C in August. The wind speed ranged from 3 to 4 m/s. The relative humidity varied between 22% and 26%.

These weather conditions affect pollutant behavior. The highest SO_2 levels were recorded in July when the wind speed peaked at 4 m/s. Faster winds and higher temperatures may have supported wider dispersion and sulfur oxidation. In contrast, the PM concentration peaked in June. High heat and low humidity likely allowed the fine particles to remain suspended in the air.

Table 1. Monthly Averages of Meteorological Parameters in Baghdad During the Sampling Period

Month	Temperature (cº)	humidity %	wind speed (m/s)
June	43	22	3
July	45	22	4
August	46	26	3

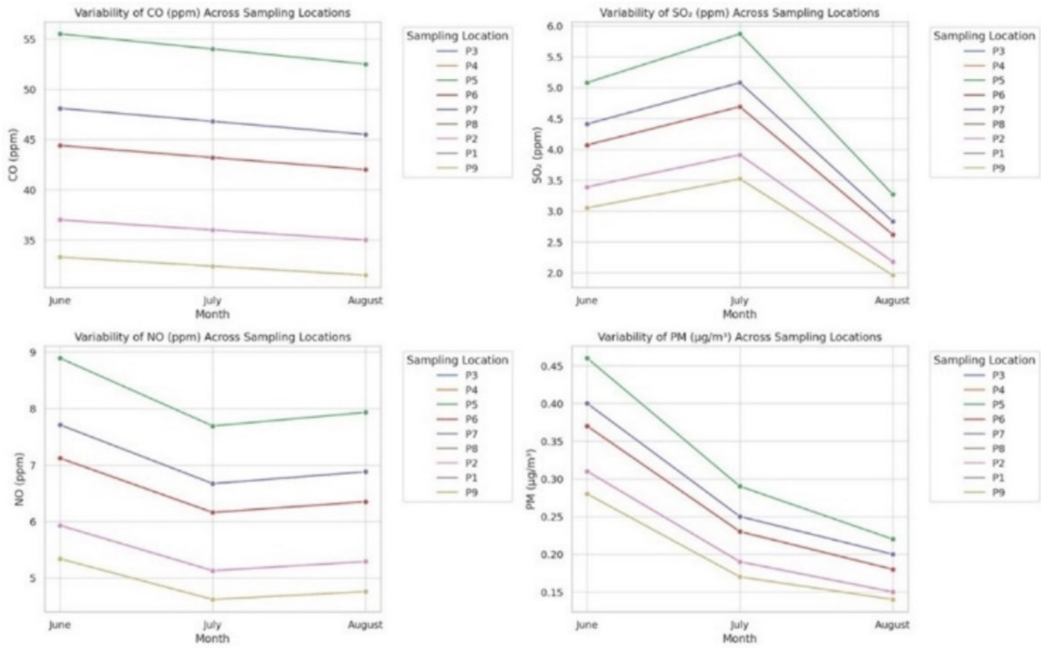

Fig. 3. Variability of Air Pollutants Across Sampling Locations

In August, the humidity rose to 26%, whereas the wind speed decreased slightly. These conditions may have encouraged more pollutant settlement and reduced airborne concentrations. Overall, the results highlight the seasonal impact of temperature, wind, and humidity on the spread and accumulation of airborne pollutants.

Temporal and Spatial Variability of Air Pollutants Across Sampling Locations

Figure (3) illustrates the analysis of air pollutant concentrations throughout the study area from June to August, demonstrating both spatial patterns and seasonal trends. The CO concentration reached its peak value of 55 ppm near Generator 2 in June. The location experienced both increased fuel combustion and extended generator operation periods. The expected diffusion effect was confirmed by the progressive decrease in CO concentrations from the midpoints to the downwind areas, especially at the far ends of the street. The fuel-based emission origin of SO_2 and NO was confirmed by their similar spatial distribution, which showed significant reductions at street edges and upwind/downwind sites. Peak SO_2 levels occurred in July, possibly because of elevated ambient temperatures that enhanced oxidation processes. The Particulate Matter (PM) levels showed a continuous decrease at all locations during the study period, with the highest readings in June, which matched the hotter weather conditions and dustier environments. The distant points experienced the most significant decrease in PM values because of the effective atmospheric dispersion. The results demonstrate that emission source proximity, together with seasonal weather patterns, strongly affects pollutant distribution, with Generator 2 being a major emission source that requires emission control measures.

Effect of Distance and Generator Proximity on Pollutant Levels

Figure 4 shows site-specific pollutant dominance more clearly when analyzing locations within a month. Generator 2 (P5) produces the highest emission intensity across all pollutants throughout every month, which establishes its position as the main emission source. The pollutant levels at the points adjacent to the generators (P2, P3, P4, P6, P7, and P8) were more similar to those near the generators than to those at distant background sites, indicating

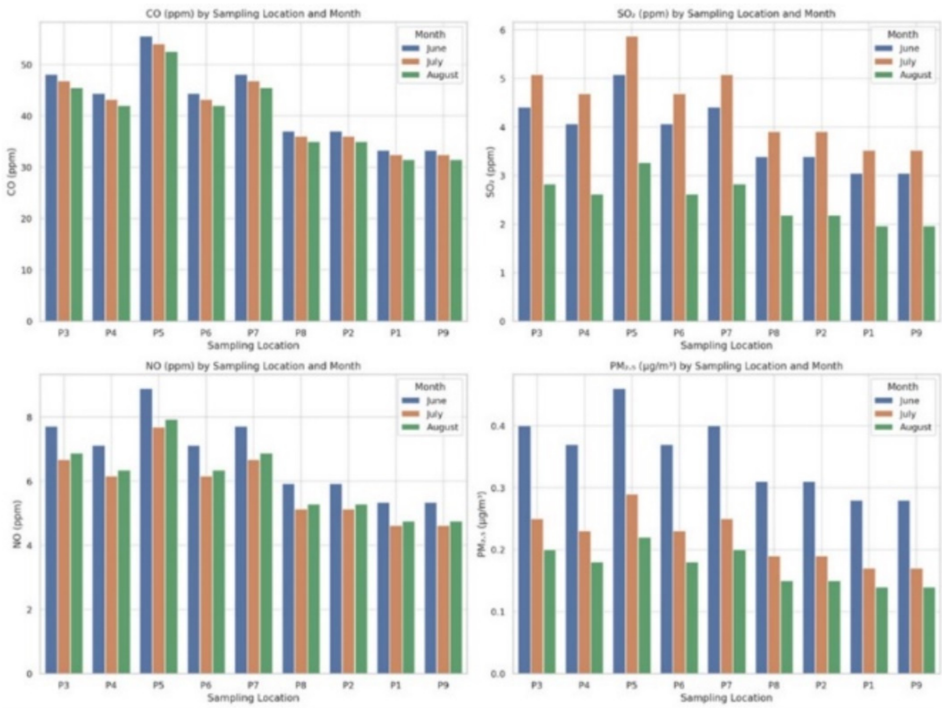

Fig. 4. Effect of Distance and Generator Proximity on Pollutant Levels

substantial spatial overlap or combined pollution from adjacent sources. The pollutant levels of CO and NO remained steady between June and August, but SO_2 and PM concentrations decreased substantially at both street ends and wind-exposed points. The dispersion mechanisms work better for heavier or more reactive pollutants, such as SO_2 and particulates, because these substances are affected by local weather patterns and possibly reduced generator operation or environmental dust amounts during later months. Figure 4 shows that the upwind and downwind areas (P1 and P9) always showed reduced emissions, which confirms the wind's impact on pollutant movement and supports the strategic placement of residential areas and sensitive land uses near prevailing wind directions.

Monthly Dispersion and Statistical Distribution of Air Pollutants

Figure 5 presents the box plots grouped by month for each pollutant. This revealed seasonal trends and variations in pollutant levels. CO and NO spread more in June, whereas SO_2 peaked in July. $PM_{2.5}$ values were relatively low but fluctuated more during the warmer months. This time-based visualization highlights the influence of seasonal factors on emission behavior.

The interquartile range (IQR) values for CO, NO, and PM were wider in June, indicating that the values were spread across different sampling locations. The results indicate that there were more uneven emissions, which could be attributed to higher generator loads or fluctuating operational durations during early summer. August showed reduced IQRs across most pollutants, particularly for PM, indicating a more uniform distribution and potential stabilization in environmental conditions or generator usage.

The SO_2 boxplots showed a clear peak in July, with a higher median and wider range than in other months. This could be due to increased sulfur oxidation at higher ambient temperatures or changes in the fuel combustion efficiency. The overall decrease in variability from June to August across all pollutants indicates the gradual dissipation of concentrated emissions and convergence towards background levels in the peripheral zones. It is also important to note that

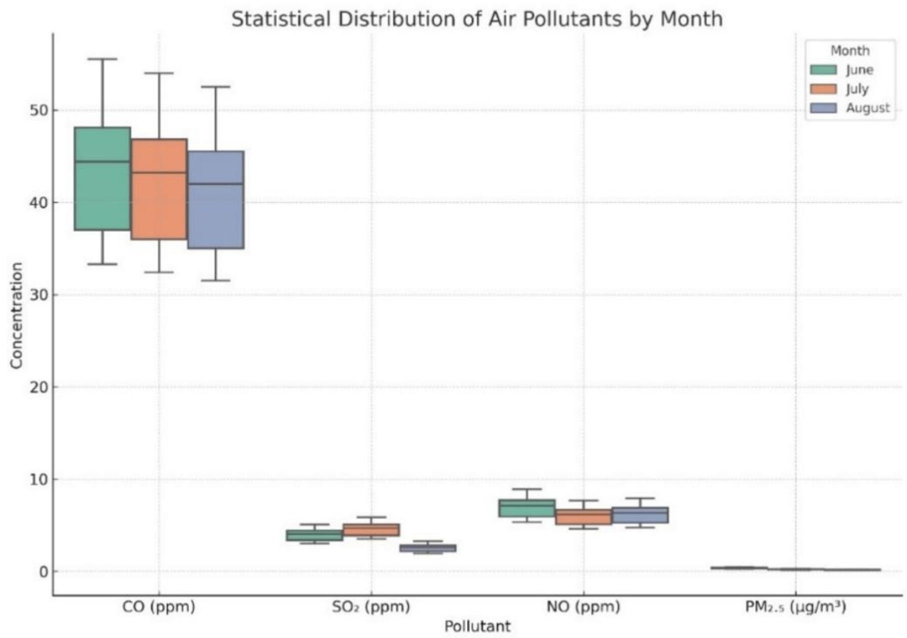

Fig. 5. Monthly Statistical Distribution of Air Pollutants

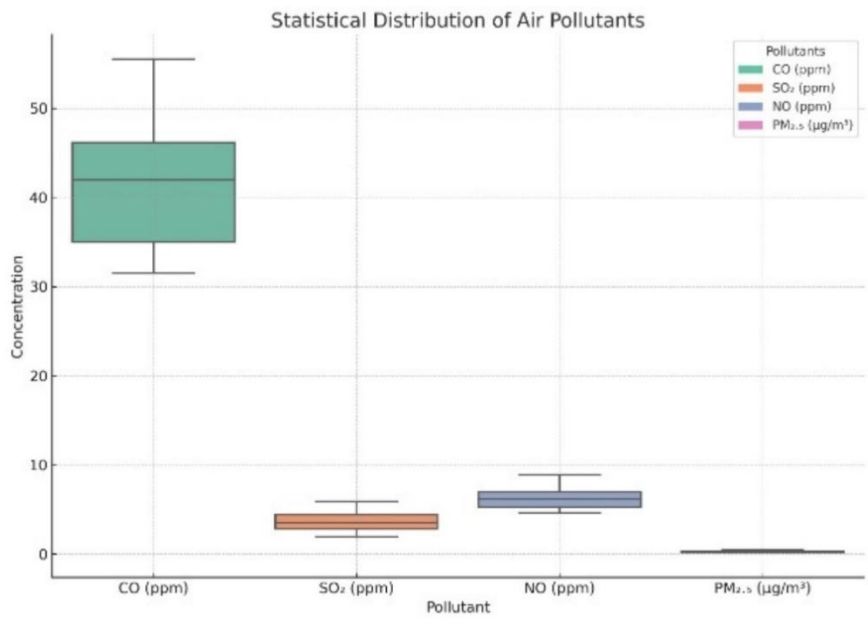

Fig. 6. Overall Statistical Distribution of Air Pollutant Concentrations

there were no statistical outliers for any of the pollutants across the months, which strengthens the consistency of the data and the validity of the sampling approach.

The box plots in Figure 6 show the complete distribution patterns of each pollutant. The visualization combined data from all sampling locations and months to show the median values, interquartile ranges, and outliers. The visualization helps researchers understand the overall spread and variability of pollutant concentrations in the study area.The interquartile range of carbon monoxide (CO) was the highest, indicating significant variability because of the

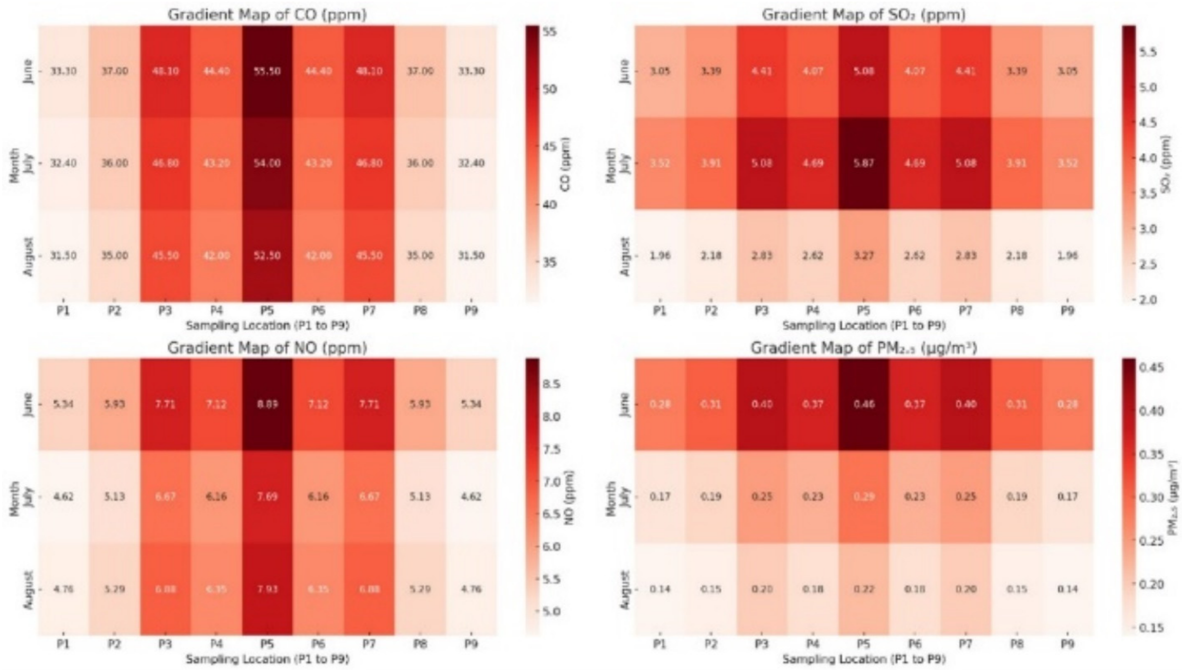

Fig. 7. Gradient Map of Air Pollutants

differences in generator location and operation intensity. The distribution of Nitric oxide (NO) values showed moderate variation while remaining steady throughout the entire dataset. The sulfur dioxide (SO_2) concentrations showed minimal variation, with some localized changes. Fine particulate matter ($PM_{2.5}$), expressed in µg/m^3, appeared to have the most stable distribution, with lower values and minimal dispersion. These statistical patterns imply that CO and NO are the most variable and dominant pollutants in the study area, whereas SO_2 and $PM_{2.5}$ occurred at lower and more consistent concentrations. This distribution enhances our understanding of emission behavior and pollutant exposure risks in generator-dense urban environments.

Spatio-Temporal Dispersion of Air Pollutants Based on Gradient Mapping

Figure (7) illustrates the multi-panel gradient maps that enable detailed spatial and temporal assessments of air pollutant dispersion using real concentration data collected from nine strategically located sampling points. The highest intensity zones of CO, SO_2, NO, and PM pollutants appeared consistently at the study area midpoint near Generator 2 at P5, which verified its position as the main emission source. The CO and NO maps displayed the most extensive concentration plumes in June and July, which exceeded 50 ppm and 8 ppm, respectively. The observed distribution matched the expected combustion dynamics because the generator proximity and operational frequency directly affected the concentration levels.

The SO_2 concentration reached its highest point in July, showing a wider spatial distribution because summer heat enhanced sulfur oxidation. The PM dispersion pattern showed limited spread, while June recorded peak concentrations because dry weather conditions allowed more particulate matter to remain suspended in the air. All sampling points (P1 and P9) located at the outer boundaries of the street network recorded minimal pollutant values, demonstrating how the distance from emission sources and wind direction patterns reduce pollutant concentrations. The spatial gradient mapping technique used in this study provides better interpretability than standard line and bar plots by showing emission hotspots and dispersion patterns across the street domain.

Effects of wind direction on pollutant dispersion

The study area experienced pollutant dispersion patterns that were heavily influenced by the wind direction. The main wind direction, which moved from northwest to southeast along the street axis, strongly affected the distribution of the generator emissions. The gradient maps of all pollutants demonstrated a regular decrease in concentration values that started at the central emission points, especially Generator 2 (P5), and continued toward the southeast street end. The locations situated in the downwind direction showed reduced pollutant concentrations compared to the surrounding emission sources because wind helped spread and reduce pollutant concentrations. The background pollutant levels at upwind locations remained slightly higher than those at distant peripheral areas because of restricted ventilation and localized stagnation. Wind-driven transport affects CO and PM dispersion the most because these pollutants are highly sensitive to wind movements. The analysis of wind effects improves the accuracy of exposure risk assessment and demonstrates why meteorological parameters must be included in future emission modeling and urban air quality planning.

Policy Implications

This study utilized pollution gradient mapping as a strong spatial diagnostic tool for environmental risk assessment and emission control planning. The visualization of pollutant concentration distributions across street corridors enables researchers to detect high-emission hotspots, transitional exposure zones, and low-risk peripheral areas. Detailed spatial information helps create environmental risk zones, which enable focused interventions instead of widespread control strategies. The repeated detection of Generator 2 peak emissions for different pollutants and months indicates that targeted regulatory measures or operational changes should be implemented in that area. The model improves its predictive accuracy for future dispersion patterns by analyzing the pollutant intensity with wind direction and spatial location. The method converts raw monitoring information into simple spatial knowledge, which provides a useful framework for developing evidence-based recommendations regarding receptor placement and generator positioning and fuel quality standards. Pollution gradient mapping provides substantial value for environmental policy development and public health defense through evidence-based zoning and emission reduction approaches. (Sigsgaard & Hoffmann 2024)

Comparison of regulatory standards

Figure 8 presents a comparative analysis of the measured concentrations of major air pollutants—CO, SO_2, NO, and $PM_{2.5}$, and the World Health Organization (WHO) air quality guidelines. The figure includes monthly values across all sampling points, with WHO limits indicated as red dashed lines for reference.The measured concentrations of carbon monoxide (CO) consistently exceeded the WHO limit of 4 ppm across all sites and months, with peak values observed near Generator 2 (P5). Similarly, the nitric oxide (NO) levels were considerably higher than the recommended maximum of 0.053 ppm, indicating significant emissions likely linked to diesel combustion.Sulfur dioxide (SO_2) showed fluctuating patterns but still exceeded the 0.005 ppm limit, particularly in June and July, suggesting increased generator activity during early summer. $PM_{2.5}$, converted and expressed in µg/m^3, remained below the WHO threshold of 5 µg/m^3; however, the data still reflect elevated particulate exposure during low-humidity months. This figure highlights the spatial and temporal patterns of air pollution and emphasizes the critical exceedances above regulatory thresholds, which pose substantial public health risks, particularly in densely populated urban areas. The major exceedance of all monitored pollutants demonstrates the immediate need for policies to reduce both immediate and future health dangers.(Irfan, 2024)

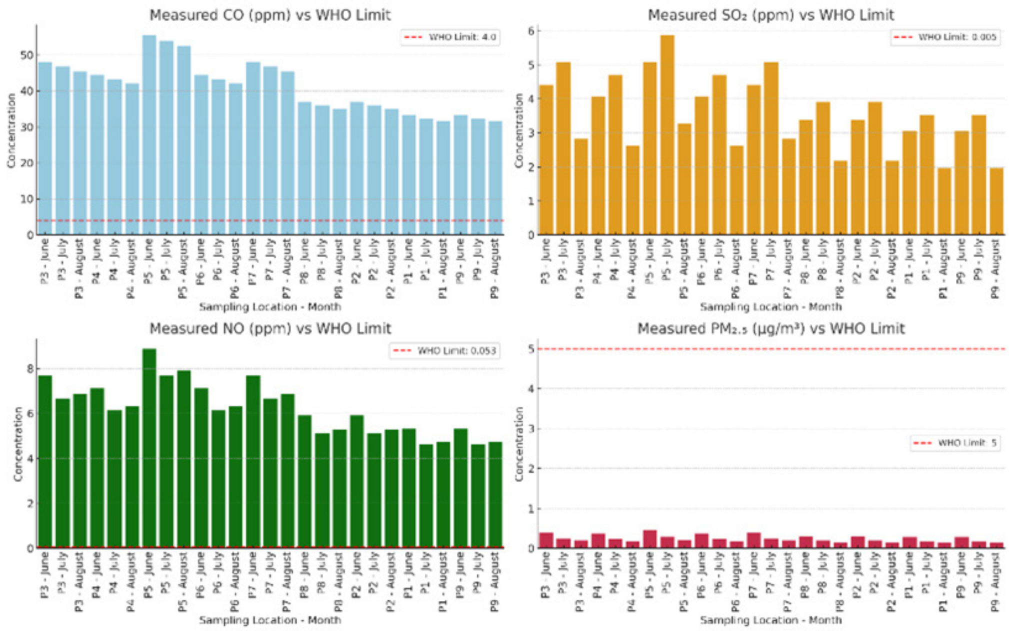

Fig. 8. Comparison with Regulatory Standards

Public health implications

The high levels of air pollutants detected in this study pose major health risks for people living in densely populated residential areas where generator emissions are present. Prolonged exposure to high CO concentrations reduces blood oxygen delivery, which creates cardiovascular dangers for children, elderly people, and those with existing respiratory problems. Excessive SO_2 concentrations trigger bronchoconstriction and cause more asthma attacks, even after brief exposure periods. The detection of NO as a NO_2 proxy indicates possible respiratory inflammation and worsening of chronic pulmonary diseases. Elevated PM levels represent $PM_{2.5}$ exposure, have been proven to lead to lung cancer, cardiovascular disease, and premature death in the long term. The spatial distribution of these pollutants, which accumulate near generator sites and are influenced by wind direction patterns, leads to uneven exposure and health disparities. This research demonstrates the immediate requirement for public health interventions, which should include better emission regulations, cleaner fuel selection, and generator placement outside sensitive locations such as schools and healthcare facilities(de Bont et al., 2024)**.** Recent studies have shown that Baghdad is one of the most polluted cities in the world. $PM_{2.5}$ levels reached 80.1 µg/m³, over 16 times higher than the WHO guideline of 5 µg/m³. This extreme pollution has been linked to an increase in respiratory and cardiovascular diseases among city residents. For example, measurements from the Al-Waziriya monitoring station recorded SO_2 levels as high as 0.067 g/m³ in October, exceeding the safe exposure limits. These findings highlight the urgent need for stricter emission controls and targeted public health actions in Baghdad(Rabie et al., 2024).

CONCLUSIONS

This study provides a complete evaluation of the distribution of generator-based air pollutants across space and time in densely populated urban areas. The results show that pollutant levels are not distributed evenly because they strongly depend on the generator location, wind direction, and seasonal weather patterns. Generator 2 was the main emission source for all pollutants during every month of the study. The street-end and wind-aligned sampling points showed lower pollutant concentrations than the other locations. Pollution intensity peaked during early summer before decreasing in August because generator usage decreased, and environmental conditions stabilized. The combination of pollution gradient mapping with statistical analysis improved spatial trend detection to provide essential information for urban planners and policymakers. The significant violation of WHO air quality standards for CO, SO_2, NO, and PM indicates an urgent requirement for regulatory enforcement, together with the use of clean energy alternatives. This study supports the implementation of specific emission control measures, urban risk zoning systems, and enhanced environmental monitoring to reduce public health risks and achieve sustainable air quality management.

GRANT SUPPORT DETAILS

This research did not receive any financial support.

CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, have been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

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