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ORIGINAL PAPER

Assessment of criteria air pollutants near crude oil operations using AQI modeling and GIS tools*

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Abstract

Air pollution remains one of the most pressing environmental challenges of the 21st century, with profound implications for human health, climate stability, and ecological integrity. The rapid pace of urbanization and industrialization has led to elevated concentrations of airborne pollutants such as particulate matter ($PM_{2.5}$ and PM_{10}), nitrogen oxides (NO_x), sulfur dioxide (SO_2), carbon monoxide (CO), and ground-level ozone (O_3) in many regions around the world. These pollutants are primarily derived from anthropogenic sources including vehicular emissions, fossil fuel combustion, industrial discharges, and biomass burning. Chronic exposure to ambient air pollution has been strongly linked to increased incidence of cardiovascular diseases, respiratory disorders, cancer, and neurodegenerative conditions. This study presents a comprehensive review and assessment of regional air quality indicators, focusing on the spatial and temporal distribution of major pollutants and their potential sources. Emphasis is placed on the use of the Air Quality Index (AQI) as a tool for evaluating public health risks and guiding policy interventions. PM_{10} ranged 13.22-30.0 µg m^{-3}, CO reached 16.25 mg dm^{-3}, O_3 increased from 0.062 to 0.077 mg dm^{-3}. The analysis includes examination of long-term trends in pollutant concentrations, correlation with meteorological parameters, and identification of pollution hotspots. Additionally, mitigation strategies and regulatory frameworks aimed at improving air quality are discussed, with particular attention to their efficacy and implementation barriers. The findings underscore the urgent need for integrated environmental management policies, enhanced pollution monitoring infrastructure, and public awareness campaigns to curb the adverse effects of air pollution. The study advocates for the adoption of evidence-based, interdisciplinary approaches to air quality management, integrating technological innovation, regulatory action, and community participation.

Keywords: air quality ındex (AQI), oil-based industrial pollution, GIS-based spatial analysis, environmental health risk

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INTRODUCTION

Air pollution is a critical global issue that poses profound risks to both human health and ecological systems. The primary anthropogenic sources of air pollution include industrial processes, vehicular emissions, power generation, and fossil fuel combustion. Natural phenomena such as dust storms, volcanic activity, and wildfires also contribute significantly to ambient air contamination in various regions (Cohen et al. 2017). According to the World Health Organization (WHO), 99% of the global population is exposed to air that exceeds recommended pollutant limits, resulting in approximately seven million premature deaths annually due to respiratory and cardiovascular conditions (WHO 2021).

The burden of air pollution is especially severe in low- and middle-income countries, where rapid urbanization, industrial expansion, and insufficient environmental regulations exacerbate the problem (Gurjar et al. 2010). Economic growth in these regions is often accompanied by increased energy consumption, expansion of transportation networks, and uncontrolled construction activities, all of which elevate the emissions of criteria pollutants such as particulate matter (PM_{10} and $PM_{2.5}$), nitrogen dioxide (NO_3), sulfur dioxide (SO_2), carbon monoxide (CO), and ozone (O_3) – Rakib et al. (2014), Abdulaziz et al. (2022).

In Iraq, the deterioration of air quality has become increasingly apparent in recent years. Contributing factors include the expansion of crude-oil-fired power plants, widespread use of private and institutional diesel generators due to frequent electricity shortages, rising vehicle density, and continued reliance on fossil fuels for residential heating (Al-Kasser 2021). These sources not only emit primary pollutants but also precursors to secondary pollutants like ground-level ozone and secondary particulate matter.

The Khurmala oil field, located in the Erbil Governorate in northern Iraq, is one of the country's key hydrocarbon production zones. It hosts multiple energy infrastructure components, including crude separation units, gas treatment plants, and a large-scale power station operating primarily on fossil fuels. As energy production in the region increases to meet rising demand, so too does the potential for localized air pollution and its associated health risks.

Given these dynamics, this study was designed to provide a comprehensive evaluation of ambient air quality in the Khurmala region. Specifically, it aims to:

- monitor the concentration of six major pollutants (PM_{10}, $PM_{2.5}$, NO_3, SO_2, CO, and O_3) across five locations;
- calculate the aqı according to the us epa framework;
- analyze spatial and temporal variation in pollutant levels using geostatistical techniques;

– identify pollution hotspots and their proximity to emission sources such as flaring towers and generator clusters.

This research contributes to the growing body of literature on air pollution in oil-producing regions and provides critical data to inform environmental policy, urban planning, and public health interventions in Iraq.

MATERIALS AND METHODS

Study design and objectives

This study employed a longitudinal and spatially distributed sampling methodology to assess air quality variations in the Khurmala oil-producing region of the Kurdistan Region of Iraq (KRI). The objective was to quantify and analyze the concentrations of major air pollutants across five strategic locations impacted by oil-based energy infrastructure, using standardized measurement techniques and geospatial analysis. Key pollutants included particulate matter ($PM_{2.5}$ and PM_{10}), NO_3, SO_2, CO, and ground-level ozone (O_3), following guidelines established by the United States Environmental Protection Agency (USEPA 2008).

Description of study area

The Khurmala Field is located approximately 45 km south of Erbil, within a semi-arid, low-vegetation zone characterized by intense hydrocarbon extraction and processing. The study focused on five sites: S1: the main power plant, S2: the central pipeline station (CPS), S3: the Amin gas treatment unit, S4: the southern crude oil station, S5: the Alla separation unit.

These locations were chosen due to their proximity to flaring operations, gas processing units, and crude oil transmission facilities. Each station reflects a distinct type of emission profile, enabling source-specific analysis (Figure 1).

Sampling procedures and equipment

Air pollutant concentrations were recorded using calibrated field-grade portable instruments conforming to EPA and WHO standards (Chow 1995, WHO 2006, Gao et al. 2012, Spinelle et al. 2017):

– Dustmate Environment dust dedector for gravimetric samplers and optical particle counters for $PM_{2.5}$ and PM_{10},
– Drager X-am 5000 gas measurement device with electrochemical sensors for NO_3, SO_2, and CO,
– Drager X-am 5000 gas measurement device for ground-level ozone.

Data were collected during the months of October and November for two years (2020 and 2023), chosen to represent the transition period between dry

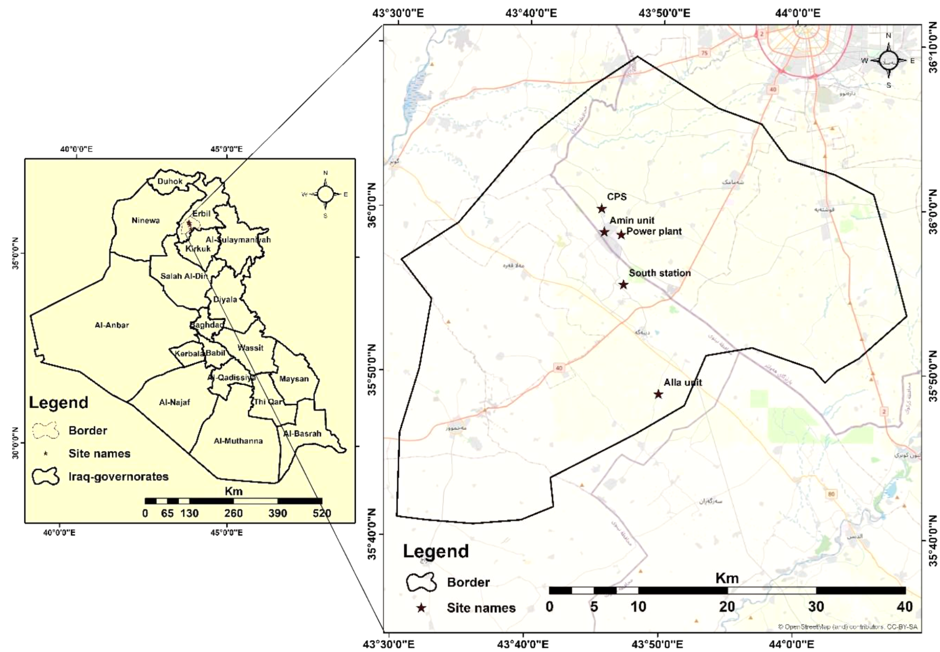

Fig. 1. Study area and sampling points

summer conditions and early winter meteorological inversion, both of which critically influence pollution dispersion.

AQI calculation

The AQI for each pollutant was calculated using the standardized method developed by the USEPA (2014), which involves the linear interpolation of observed concentrations within breakpoint concentration ranges defined for each pollutant. The formula applied is:

$$AQI_p = \frac{I_{Hi} - I_{Lo}}{BP_{Hi} - BP_{Lo}} \times \left(C_p - BP_{Lo}\right) + I_{Lo} \tag{1}$$

where: C_p – Measured concentration of pollutant p,
BP_{Hi}, BP_{Lo} – Upper and lower breakpoint concentrations that bracket C_p,
I_{Hi}, I_{Lo} – AQI values corresponding to those breakpoints.

This method is used to convert pollutant concentrations (e.g., in μg m^{-3} or ppm) into AQI values on a scale from 0 to 500, which are then classified into health categories as shown Table 1 (USEPA 2014).

Geospatial and statistical analysis

Spatial interpolation of pollutant concentrations was conducted using the inverse distance weighting (IDW) method in ArcGIS 10.8. This technique

Table 1

Air quality index (AQI) categories

Air quality index	Levels of health concern	Health Concern
0-50	good	Air quality is considered satisfactory, and air pollution poses little or no risk.
51-100	moderate	Air quality is acceptable; however, for some pollutants, there may be a moderate health concern for a very small number of people who are unusually sensitive to air pollution.
101-150	unhealthy for sensitive groups	Members of sensitive groups (e.g., individuals with respiratory or heart conditions, older adults, and children) may experience health effects. The general public is less likely to be affected.
151-200	unhealthy	Everyone may begin to experience health effects; members of sensitive groups may experience more serious health effects.
201-300	very unhealthy	Health alert: everyone may experience more serious health effects.
301-500	hazardous	Health warnings of emergency conditions. The entire population is more likely to be affected.

was selected for its robustness in environmental datasets with moderate station density. Geographic layers included topography, emission sources, and population density overlays to identify spatial correlations between pollution and exposure. Statistical analysis was performed using IBM SPSS Statistics v26. Descriptive statistics (mean, SD, min, max) were calculated for each site and year. One-way ANOVA and Pearson correlation coefficients were applied to assess temporal and spatial variability in pollutant concentrations and their relationship with meteorological parameters such as wind speed and direction, which were also recorded using onsite meteorological stations.

RESULTS AND DISCUSSION

Air quality monitoring was conducted at five industrially impacted sites near the Khurmala oil field during October–November in 2020 and again in 2023. The six key air pollutants assessed included PM_{10} $PM_{2.5}$, NO_3, SO_2, CO, and O_3. The data revealed spatiotemporal differences in pollutant levels, with some notable improvements in certain parameters by 2023, while others worsened, particularly in high-emission zones near oil processing infrastructure (Table 2).

Particulate matter (PM_{10} and $PM_{2.5}$)

PM_{10} concentrations ranged from 14.48 to 30.00 μg m^{-3} in 2020 and 13.22 to 30.00 μg m^{-3} in 2023. $PM_{2.5}$ levels ranged from 7.92 to 14.88 μg m^{-3} in 2020

Table 2

Measured air quality parameters fot 2020 and 2023 years

Parameters	S1				S2				S3				S4				S5			
	2020		2023		2020		2023		2020		2023		2020		2023		2020		2023	
	Oct.	Nov.	Oct.	Nov.	Oct.	Nov.	Oct.	Nov.	Oct.	Nov.	Oct.	Nov.	Oct.	Nov.	Oct.	Nov.	Oct.	Nov.	Oct.	Nov.
PM_{10}(μg m^{-3})	21.5	22.3	19.1	27.3	15.3	20.6	13.2	30.0	18.5	26.7	17.5	22.7	24.7	26.2	14.5	18.4	14.5	27.2	20.5	21.4
$PM_{2.5}$(μg m^{-3})	10.6	11.2	11.1	15.9	7.92	11.5	9.38	14.7	9.30	13.4	11.0	12.7	11.1	14.9	9.23	13.2	8.89	13.7	10.9	11.7
O_3 (mg dm^{-3})	0.049	0.045	0.05	0.068	0.037	0.062	0.055	0.071	0.041	0.054	0.063	0.061	0.049	0.026	0.057	0.077	0.040	0.042	0.048	0.067
NO_2 (mg dm^{-3})	0.135	0.083	0.213	0.140	0.212	0.115	0.212	0.033	0.285	0.153	0.300	0.118	0.297	0.245	0.305	0.248	0.300	0.043	0.224	0.225
CO (mg dm^{-3})	11.9	6.90	10.5	7.03	11.0	7.60	6.25	8.03	16.3	8.05	12.3	9.25	13.6	11.5	14.8	13.4	10.6	5.80	6.30	5.28
SO_2 (mg dm^{-3})	0.029	0.009	0.010	0.005	0.021	0.025	0.005	0.005	0.008	0.006	0.008	0.005	0.006	0.006	0.010	0.005	0.006	0.007	0.010	0.008

and increased slightly to 9.23-15.91 μg m^{-3} in 2023. Despite the minor increases, values for both fractions remained below the World Health Organization's 24-hour limits of 45 μg m^{-3} (PM_{10}) and 15 μg m^{-3} ($PM_{2.5}$) – WHO (2021). Spatially, higher concentrations were recorded at the South Station and Amin Unit, both located downwind of flaring and combustion sources. The slight increase in $PM_{2.5}$ in 2023 may reflect the rising use of small-scale diesel generators amid power shortages (Hama-Aziz 2022).

Gaseous pollutants (NO_3, CO, SO_2, O_3)

NO_2 levels showed an increase in mean and peak values. In 2020, values peaked at 0.300 mg $dm^{-3}$and reached 0.305 mg dm^{-3} in 2023 at the south station, exceeding the WHO guideline of 0.105 mg dm^{-3} for 1-hour exposure. NO_3 is a strong indicator of fuel combustion, particularly from mobile engines and flaring operations (Mead et al. 2013).

CO concentrations ranged from 5.80 to 16.25 mg dm^{-3} in 2020 and slightly decreased to 5.28-14.75 mg dm^{-3} in 2023. Although this reduction is encouraging, several readings still approached or exceeded AQI thresholds of very unhealthy (AQI > 200), particularly at the amin unit. This reflects incomplete combustion from diesel and crude-based generators (Raub et al. 2000).

SO_2 concentrations showed a notable decrease, ranging from 0.006--0.029 mg dm^{-3} in 2020 and dropping to 0.005-0.010 mg dm^{-3} in 2023. The improvement is likely due to partial fuel upgrades and better filtering of flares (USEPA 2025).

O_3 levels increased in 2023, peaking at 0.077 mg dm^{-3} compared to 0.062 mg dm^{-3} in 2020. This is likely due to elevated precursor emissions (NO_x and VOCs) and increased solar radiation, facilitating photochemical ozone formation near the power plant and south station (Atkinson 2000, Jerrett et al. 2009).

In 2020, AQI values for PM and SO_2 were classified as good to moderate, while CO and NO_2 occasionally entered the unhealthy for sensitive groups and very unhealthy ranges.

In 2023, overall AQI values slightly increased, with ozone AQI rising into the Unhealthy category in multiple locations.

Maps of gaseos polltant for 2020 and 2023 illustrated in Figure 2 and Figure 3 respectively.

The most polluted locations were consistently the power plant and south station, which are downwind of major flaring units and operate multiple generators.

Spatial patterns and environmental ımplications

Using ArcGIS 10.8 and IDW interpolation, pollutant dispersion maps revealed localized pollution hotspots centered around the flaring units and oil transmission hubs. Prevailing wind directions (135°–270°) transported pollutants northeastward, affecting downwind residential and agricultural

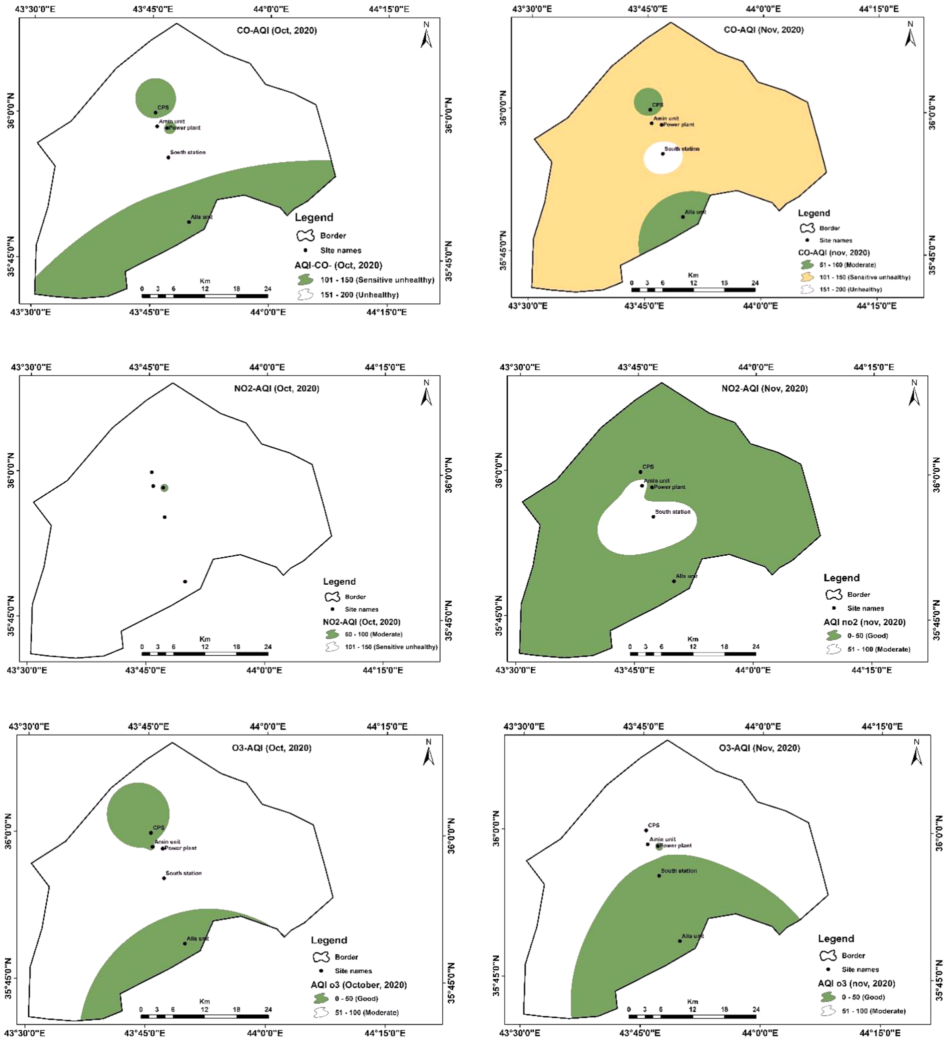

Fig. 2. AQI maps for CO, NO_2 and O_3 in 2020

zones. These patterns suggest that meteorology, in addition to emission intensity, plays a critical role in shaping local air quality (Byun, Schere 2006).

The decline in SO_2 and partial reduction in CO may indicate early success in fuel-type adjustments or flare controls. However, the increase in ozone and sustained high NO_2 levels reflect ongoing challenges in managing secondary pollutant formation and combustion – related emissions. Without a comprehensive flaring management system and transition to cleaner fuel technologies, the region remains vulnerable to air quality deterioration and its associated health risks (Landrigan et al. 2018).

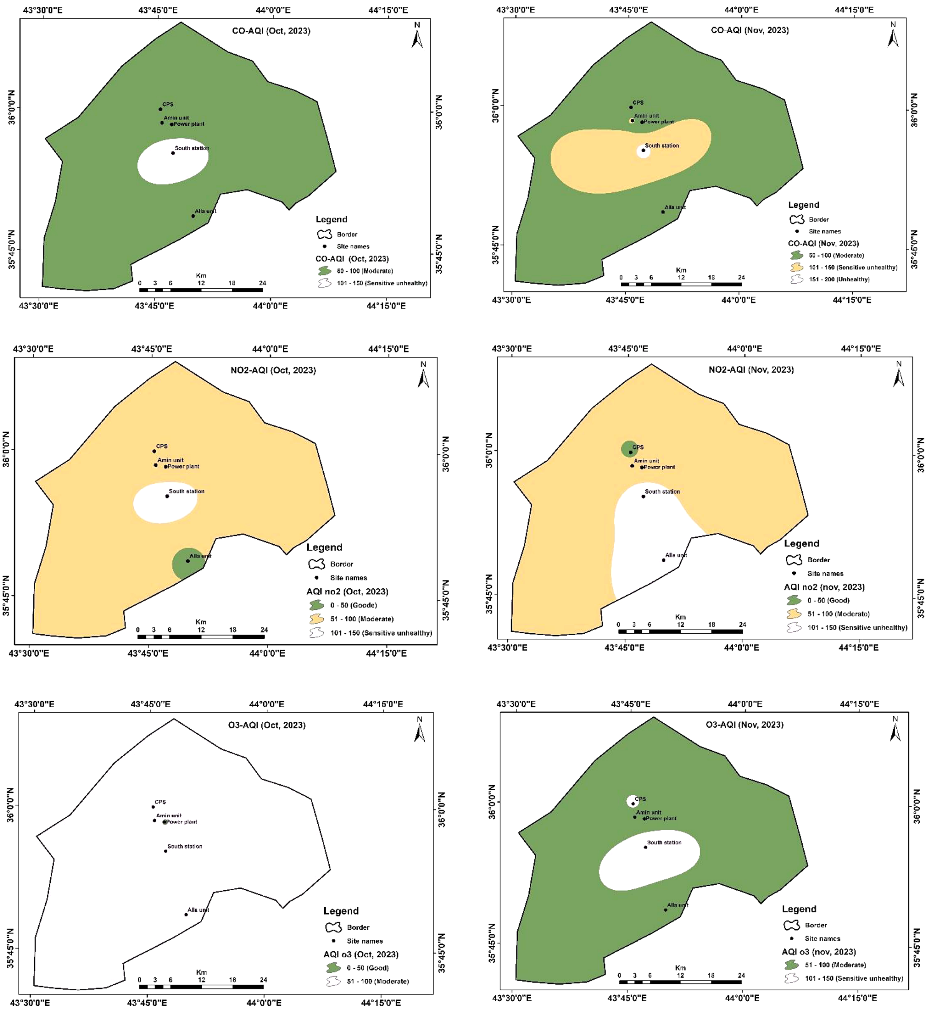

Fig. 3. AQI maps for CO, NO_2 and O_3 in 2023

CONCLUSIONS

This study provides a systematic evaluation of ambient air pollution in the Khurmala oil-producing region over two years. The key conclusions are:

1. The primary contributors to elevated AQI are industrial flaring and diesel combustion from power generation units and pipelines.
2. While particulate and SO_2 concentrations remained below health thresholds, NO_2, CO, and O_3 levels often exceeded recommended limits.
3. Temporal comparison shows moderate improvement in PM and SO_2

concentrations by 2023, but ozone and nitrogen dioxide levels remained problematic.

4. Spatial analysis identified the Power Plant and South Station as consistent pollution hotspots, requiring targeted emission mitigation.

The findings highlight the urgent need for stricter emission controls, flaring minimization, and expanded monitoring in energy-rich regions.

Author contributions

M.F.D.- supervision, writing – review & editing, conceptualization, methodology, M.M.A.K. – writing – original draft preparation, conceptualization, data curation, formal analysis, M.H.H. – supervision, methodology, S.J. – software, visualization. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

The authors ensure that they have neither professional nor financial connections related to the manuscript sent to the Editorial Board) should be provided.

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