Health Innovation Reports 2025,1(3):14-26
DOI: 10.64048/hir.v1n3.003

Original Research

Long-Term Air Pollution and Health Risks in Erbil, Kurdistan-Iraq: A Satellite-Based Assessment

Muzhda Q. Qader [1*]

Received: 3 May 2025 Revised: 9 September 2025 Accepted: 3 October 2025 Published: 15 October 2025

Abstract

Background and Aim Air pollution is a leading global cause of premature mortality, yet evidence from conflict-affected and rapidly developing Middle Eastern cities remains scarce. This study assessed long-term air quality trends and related health risks in Erbil, Iraq.

Methods A six-year observational study was performed using Sentinel-5P satellite data from five fixed sites representing urban, industrial, and mixed zones. Seventy-two monthly datasets (12 per year × 6 years) were analyzed for carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), ozone (O_3), methane (CH_4), and formaldehyde (HCHO). Pollutant concentrations (μg/m³) were used to compute the Air Quality Index (AQI), Air Quality Health Index (AQHI), and WHO exceedance ratios. Statistical analyses included ANOVA and correlation tests ($p \leq 0.05$).

Results Pollutant levels showed distinct seasonal and interannual variations. CO and SO_2 peaked in winter, while O_3 and HCHO were highest in summer. COVID-19 lockdowns (2020–2021) temporarily reduced CO and NO_2. Mean annual AQI ranged from 168.8 to 190.6 (Unhealthy), and AQHI values remained elevated (7.9–9.4). Exceedances above WHO limits were substantial for NO_2 (260.7%), SO_2 (188.4%), and O_3 (271.6%) whereas HCHO stayed below threshold (79–92%). These concentrations, two to three times higher than international safety levels, indicated increased risks of respiratory, cardiovascular, and oxidative stress-related conditions. Strong positive correlations were observed among combustion-related pollutants ($r = 0.64$–0.72, $p < 0.05$).

Conclusion Air quality in Erbil remains critically degraded due to vehicle emissions, industrial activities, and dust storms. Temporary improvements during lockdowns were un sustained. Urgent measures including emission inspections, a continuous monitoring network, and transition to cleaner fuels are required to reduce public-health risks and promote sustainable air-quality management.

Keywords Air Pollution · Sentinel-5P Satellite · Remote Sensing · Air Quality Health Index (AQHI) · Public Health Risk Assessment

✉ Muzhda Qasim Qader
muzhda.qadir@hmu.edu.krd

[1] Department of Public Health, Hawler Medical University, Erbil, Kurdistan Region, Iraq

* Corresponding author: Muzhda Qasim Qader, Department of Public Health, Hawler Medical University, Erbil, Kurdistan Region, Iraq, muzhda.qadir@hmu.edu.krd, Tel number: + +9647503734319

Introduction

Air pollution is one of the leading environmental threats to human health worldwide. It contributes to respiratory and cardiovascular diseases, premature mortality, and ecosystem degradation (Manisalidis et al., 2020). In developing regions, rapid urbanization and industrial growth have intensified these risks. Erbil, the capital of the Kurdistan Region of Iraq, has undergone rapid economic and population growth during the past two decades, increasing energy consumption, vehicle numbers, and industrial activity (Muzhda, 2025, Qader et al., 2025, Hamajan and Mohammed, 2024a). These developments have likely worsened the city's air quality (Nishan, 2019, Hamajan and Mohammed, 2024b). Air pollution is composed of a complex mixture of gases and aerosols, including sulfur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), ozone (O_3), and volatile organic compounds such as formaldehyde (HCHO). High concentrations of these pollutants cause inflammation of the respiratory tract, oxidative stress, and long-term cancer risks (Almetwally et al., 2020, Manisalidis et al., 2020). More than 40% of Iraq's land is desert, and frequent dust storms exacerbate air pollution across the Middle East, including Erbil (Awadh, 2023).

Following years of conflict, the Kurdistan Region has entered a post-war reconstruction period marked by rapid industrialization, unplanned urban expansion, and increased traffic emissions (Manisalidis et al., 2020, Mohammed et al., 2025, Qader, 2025). Drought and land-use change have reduced vegetation cover by over 50 %, while the urban population grew from 4.66 million in 2013 to 6.56 million in 2023 (Nasir et al., 2022). Previous studies reported that SO_2, NO_2, and CO are the main air pollutants in Iraqi cities (Alallawi et al., 2023). The rise in these pollutants parallels growing cancer and respiratory-disease incidence in Iraq and the Kurdistan Region (Al-Fouadi and Parkin, 1984, Karwan et al., 2022, Hussain and Lafta, 2021). The Air Quality Index (AQI) developed by the United States Environmental Protection Agency converts pollutant concentrations (µg/m^3) into a single value from 0–500, where higher scores indicate poorer air quality (Index, 2009, Veal, 2021).

Similarly, the Air Quality Health Index (AQHI) integrates multiple pollutants to represent short-term health risk (Stieb et al., 2008, WHO, 2021). The World Health Organization also provides guideline limits for each pollutant, which allow comparison of measured values with safe exposure thresholds (WHO, 2021). Despite these global frameworks, long-term, multi-pollutant studies are lacking in Erbil. Existing research is fragmented, limited in spatial coverage, or based solely on short-term ground measurements. Integrating satellite-derived data with ground validation can provide continuous, city-wide information necessary for evidence-based policy.

Therefore, the present study aims to: (i) Evaluate six-year (2018–2023) temporal and seasonal variations of major atmospheric pollutants in Erbil using Sentinel-5P satellite data validated by ground measurements. (ii) Compare pollutant levels with WHO and Iraqi standards using the AQI and AQHI frameworks. (iii) Identify key pollution sources and discuss their public-health implications to guide sustainable air-quality management in northern Iraq. This study provides the first integrated analysis of long-term air quality and health risk in Erbil and establishes a replicable model for other Middle Eastern cities facing similar environmental challenges.

Materials and Methods

Study area

The study was conducted in Erbil, the capital of the Kurdistan Region of Iraq, located in the northern part of the country between 36°08′–36°42′ N and 43°58′–44°29′ E, at an elevation of approximately 420 meters above sea level. Erbil experiences a semi-arid continental climate characterized by hot, dry summers and cool winters, with an average annual rainfall of about 375 mm, most of which occurs between November and April. Over the past decade, the city has undergone rapid urbanization and industrial growth, with its population increasing from 4.7 million in 2013 to 6.6 million in 2023, leading to intensified energy consumption, vehicular emissions, and construction activities. To assess the spatial variability of air pollutants across different land-use types, five fixed monitoring sites were established throughout the city. These included an urban-traffic site in the city center with dense vehicular movement and commercial activities; an industrial site in southern Erbil dominated by factories and oil depots; a residential site in northern Erbil representing a low-traffic background area; a university district characterized by mixed residential and academic land use with moderate traffic; and a suburban-peri-urban site in eastern Erbil influenced by agricultural and open-land emissions. Together, these sites represented the diversity of microenvironments and pollution sources across the metropolitan area, providing a comprehensive framework for evaluating air quality variations in Erbil (*Figure 1*).

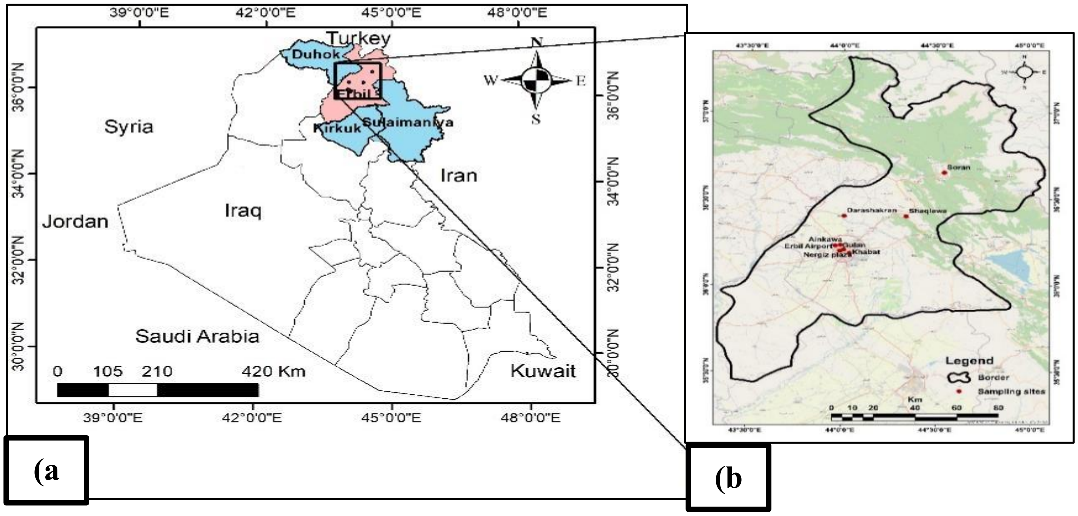

Figure 1: (a) Map showing the location of Erbil Governorate within Iraq and the Kurdistan Region, along with neighboring governorates including Duhok, Sulaimaniyah, and Kirkuk. (b) Detailed map of Erbil, Kurdistan Region of Iraq (36°08′–36°42′ N, 43°58′–44°29′ E).

Data Collection

This study was a six-year observational analysis (2018–2023) integrating Sentinel-5P satellite data with ground-based monitoring. Satellite data for CO, NO_2, SO_2, O_3, CH_4, and HCHO were obtained from the Copernicus Open Access Hub and processed using Google Earth Engine (GEE). Monthly averages were produced for each pollutant, with Cloudy or missing Sentinel-5P pixels were masked before compositing, and months with <70% valid data were excluded from analysis. No interpolation was performed to avoid bias. Ground validation was conducted concurrently using calibrated instruments: Aeroqual Series 500 (NO_2, SO_2, O_3), Testo 350 Flue Gas Analyzer (CO, CH_4), PPM Technology Formaldehyde Meter htV-M (HCHO), and UV Radiometer UV-340 (UV index proxy). Instruments were verified before deployment with certified calibration gases and maintained under ISO 9001 standards. Sentinel-5P provides columnar or tropospheric measurements of atmospheric gases, which represent integrated concentrations through the vertical column rather than surface-level values. To derive near-surface equivalent concentrations (µg/m³), satellite retrievals were collocated spatially and temporally with ground-based measurements obtained at five fixed monitoring sites. Monthly mean concentrations from both datasets were compared, and site-specific linear regression models were developed to generate conversion factors for each pollutant. The strength of these relationships (R^2 = 0.68–0.84; RMSE = 7.5–12.3 µg/m³) confirmed that the satellite-derived values adequately reflected surface variability within the study area. Where the correlation was weaker (e.g., for O_3), Sentinel-5P data were treated as qualitative indicators of spatial and temporal trends rather than exact surface concentrations. All concentrations were standardized to µg/m³ following WHO (2021) conventions using temperature- and pressure-adjusted molecular conversion factors at standard atmospheric conditions (25 °C, 1 atm).

Index Calculation Methods

To evaluate air quality and related health risks, three indicators were calculated: Air Quality Index (AQI), WHO Health Risk Score, and Air Quality Health Index (AQHI).

Air Quality Index (AQI)

The AQI is widely used to represent the severity of air pollution and its potential health impact (Act et al., 2006, Veal, 2021, Index, 2009). In this study, AQI values were calculated for CO, NO_2, and SO_2 using monthly average concentrations expressed in µg/m³. A modified version of the U.S. EPA breakpoint-based formula was applied, adapted to the available monthly mean data. The calculation followed the same framework, with pollutant concentrations converted to µg/m³ equivalents before applying breakpoints

$$\mathbf{I}= \frac{(I_{hi}-I_{lo})}{(C_{hi}-C_{lo})} \text{ x } (C - C_{lo}) + I_{lo} \qquad \textbf{(1)}$$

where I = AQI index value, C is the measured pollutant concentration (µg/m³), C_{hi} and C_{lo} are concentration breakpoints, and I_{hi}, I_{lo} are the corresponding index limits (0–

50, 51–100, etc.). Units were standardized to µg/m³ for all pollutants.

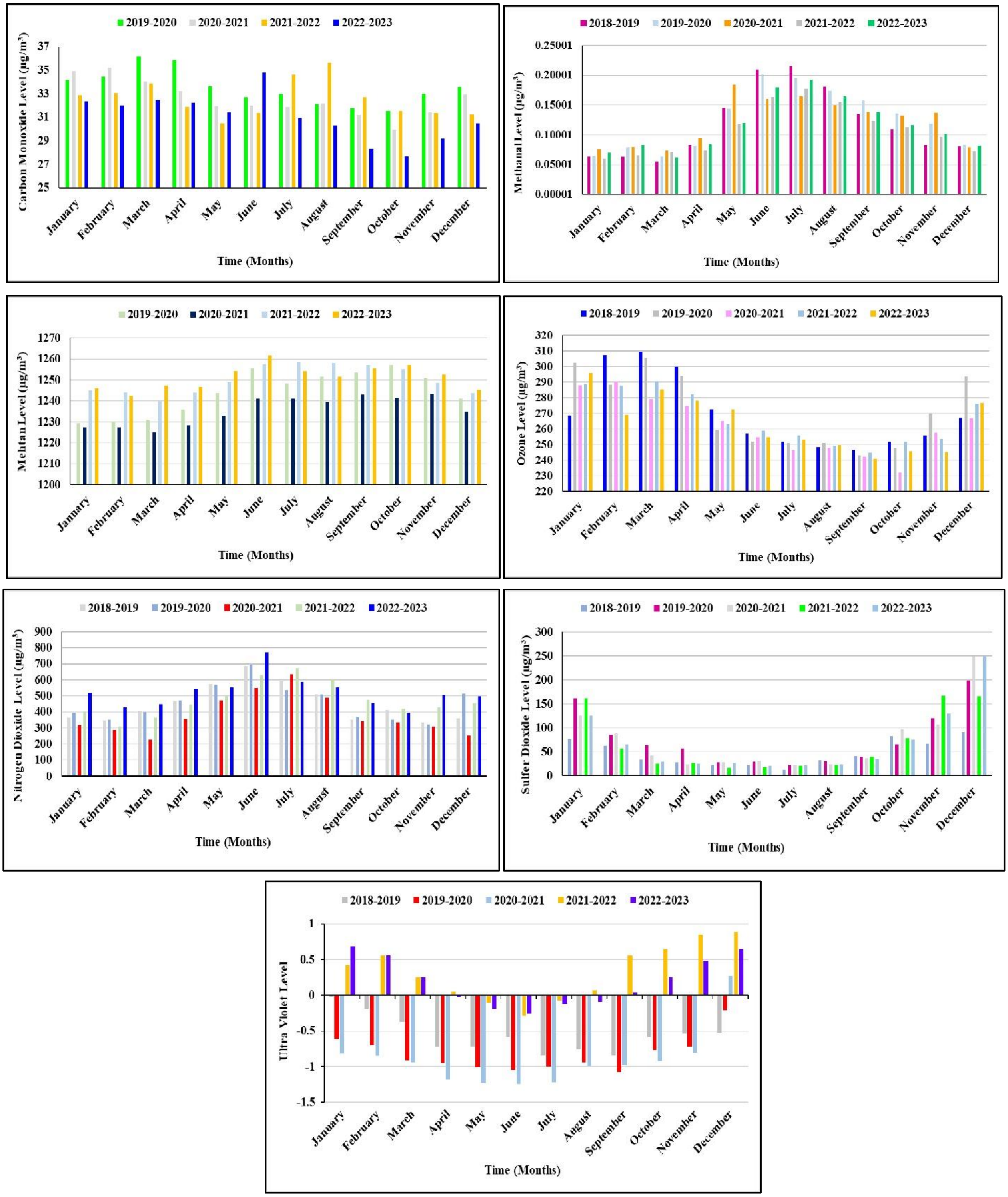

Figure 2: Monthly variation of major atmospheric pollutants in Erbil from Sentinel-5P satellite data (2018–2023). Trends for carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), ozone (O_3), methane (CH_4), formaldehyde (HCHO), and the UV Aerosol Index (UVAI) are presented as six-year time series. Concentrations are expressed in µg/m³.

Air Quality Health Index (AQHI)

The AQHI is designed to represent health risk from combined exposure to multiple pollutants (Stieb et al., 2008, Goshua et al., 2022, Nazarenko et al., 2020, WHO, 2021).

The AQHI was calculated using NO_2 and O_3 data. The relative contribution of each pollutant is shown by its β coefficient (*Table 1-3*). This approach ensures consistency with WHO guideline units

$$\mathbf{AQHI} = \frac{1000}{10.4} \times \left(e^{(0.000871 \times NO_2 \times 1000)} + e^{(0.000537 \times O_3 \times 1000)} - 2\right) \quad \mathbf{(2)}$$

Where: β O3=0.000871 and β NO2=0.000537. The AQHI ranges from 1 (low) to 10+ (very high) risk.

WHO Health Risk

Health risk was assessed by comparing measured pollutant concentrations with WHO guidelines. All concentrations were standardized to μg/m³. For pollutants where WHO values are reported in ppm, conversions were made using standard temperature and pressure (25 °C, 1 atm; 1 ppm NO_2 = 1125 μg/m³, 1 ppm SO_2 = 1569 μg/m³, 1 ppm CO = 685 μg/m³, 1 ppm O_3 = 1174 μg/m³, 1 ppm HCHO = 735 μg/m³, 1 ppm CH_4 = 392 μg/m³) (Goshua et al., 2022, WHO, 2021). A simple risk indicator was calculated as a ratio of the measured value to the WHO guideline value, expressed as a percentage:

$$\textbf{Risk \%} = \frac{\textbf{Measured Value}}{\textbf{WHO Limit}} \times 100 \quad \mathbf{(3)}$$

where $C_{(WHO)}$ is the (WHO, 2021), air-quality guideline. Values above 100 % indicate concentrations exceeding safe exposure limits.

Comparison with Regulatory Standards

To put the observed concentrations into context, they were compared with Iraqi national standards and WHO guidelines. These reference limits are summarized in *Table 4* (WHO, 2021, Nazarenko et al., 2020, Veal, 2021, Almetwally et al., 2020, Faridi et al., 2023).

Statistical analysis

Air quality data were analyzed using SPSS IBM v 27.0. Descriptive statistics (mean, median, standard deviation, standard error, range) summarized pollutant distributions. Temporal patterns were examined via time series analysis, linear regression, and seasonal decomposition. Relationships between pollutants and time were modeled using linear and multiple regression, with significance set at $p \leq 0.05$ and explanatory power evaluated by R^2. Seasonal differences were assessed with ANOVA, and inter-pollutant associations were explored through a correlation matrix. Prior to statistical modeling, the data were examined for normality, homoscedasticity, and multicollinearity. Shapiro–Wilk and Levene's tests confirmed that normality and variance assumptions were not violated ($p > 0.05$), ensuring the validity of ANOVA and regression analyses.

Results and Discussion

Monthly Variability of Air Quality Parameters

Seasonal and interannual variations in urban pollutants reflected the combined influence of emissions, meteorology, and photochemistry (*Figure 3a*). Descriptive analysis presented in *Table 5*, along with ANOVA results, confirmed significant interannual differences for CO, NO_2, and SO_2 ($p < 0.05$). The regression models were statistically significant ($p < 0.05$) with coefficients of determination (R^2) ranging from 0.63 to 0.79. CO demonstrated the highest concentrations during winter and the lowest during summer, reflecting increased heating demand and limited atmospheric dispersion in winter compared with enhanced photochemical activity and mixing during summer. A gradual decline post-2020, from 33.5 μg/m³ in 2019–2020 to 31.0 μg/m³ in 2022–2023, reflects traffic reductions and cleaner fuel use (Barzegar et al., 2024). Methanal peaked in summer (June–August) each year, confirming strong biogenic and photochemical sources, while winter concentrations remained low. Slightly higher levels in 2022–2023 indicated increased biomass burning, consistent with prior reports of methanal as a dominant summer VOC (Sahu et al., 2017). CH_4 remained stable with modest summer–autumn increased from soil and local waste/agricultural sources, showing a small upward trend from 1235.4 μg/m³ (2020–2021) to 1251.3 μg/m³ (2022–2023), in line with global methane growth trends (Feng et al., 2023). O_3 reported spring–summer maxima and winter minima, with the lowest mean in 2020–2021, partly reflecting reduced precursor emissions during COVID-19 restrictions, though meteorological influences may also have contributed (*Figure 3b*). NO_2 mirrored seasonal patterns, declining sharply in 2020–2021 (380.5 μg/m³) and rebounding in 2022–2023 (521.4 μg/m³), consistent with mobility reductions (Gong et al., 2025).

SO_2 peaked in winter, revealed contributions from heating and industrial fuel use, and declined after 2020 with cleaner fuel adoption (Alam et al., 2025). The UV Aerosol Index (UVAI) from Sentinel-5P was used as a qualitative proxy for aerosol and dust loading. However, it does not directly represent ground-level particulate matter concentrations relevant for health. Negative UVAI anomalies from 2018–2021 shifted to positive values after 2021, indicated reduced aerosol/cloud suppression (Fania et al., 2024). Descriptive statistics demonstrated that SO_2 as the most variable pollutant (SD > 60 μg/m³; ranges > 200 μg/m³). ANOVA and Kruskal–Wallis tests (*Table 6*) confirmed significant interannual differences for CO, NO_2, and SO_2 ($p < 0.05$), whereas O_3 and HCHO were stable ($p > 0.05$). NO_2 showed the strongest interannual effect (ANOVA $F = 5.41$, $p = 0.007$), reflecting both emission reductions in 2020–2021 and subsequent rebounds. These results validated that seasonal meteorology, photochemistry, and anthropogenic emissions collectively drive pollutant dynamics, with exceptional events, such as COVID-19 mobility restrictions, exerting measurable short-term impacts on urban air quality.

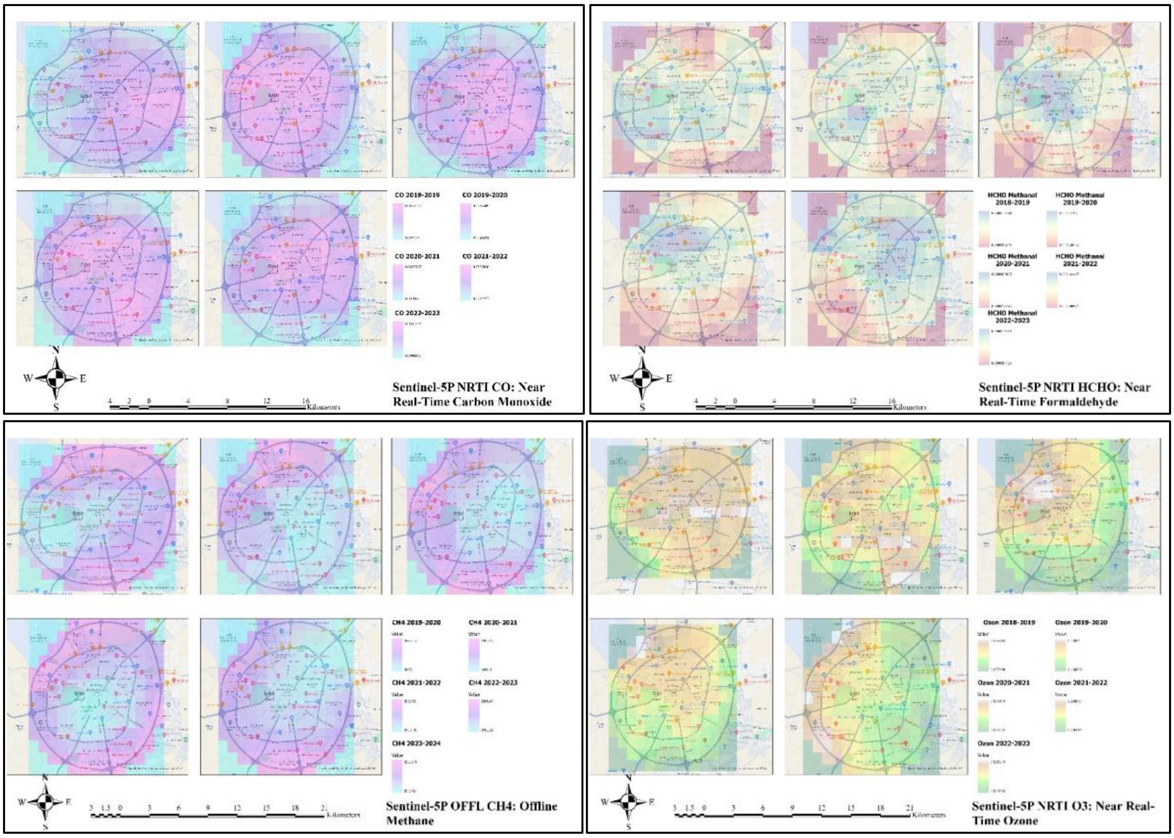

Figure 3a: Spatiotemporal distribution of CO, HCHO, CH_4, and O_3 over Erbil (2018–2023) from Sentinel-5P TROPOMI. Color scales indicate mean concentrations (µg/m³); warmer tones show higher levels. Hotspots align with traffic, industrial, and dense residential areas

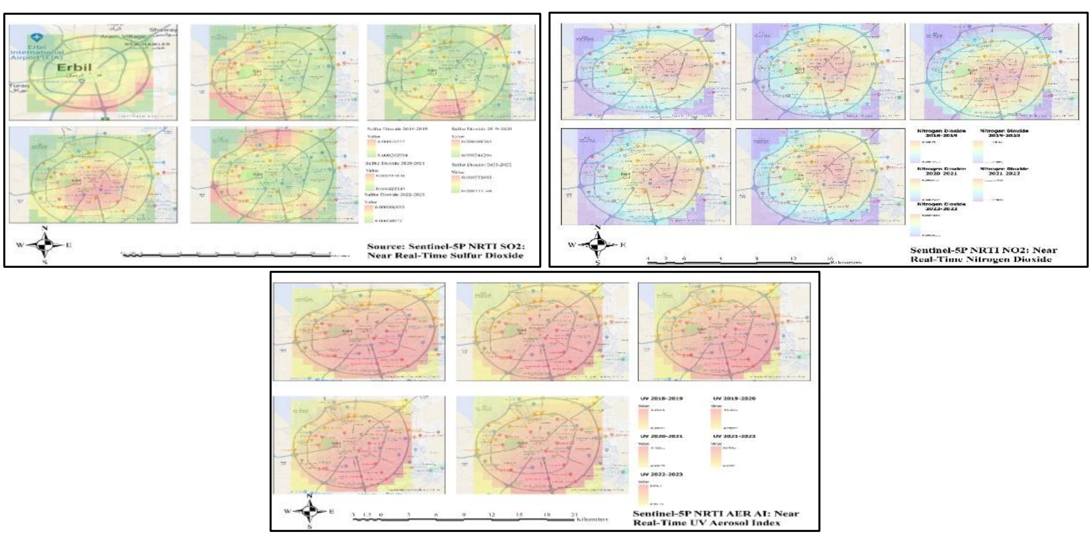

Figure 3b: Spatiotemporal distribution of SO_2, NO_2, and UV Aerosol Index (UVAI) across Erbil (2018–2023) from Sentinel-5P TROPOMI. Color scales indicate mean concentrations (µg/m³); warmer tones show higher levels. Hotspots align with traffic, industrial, and dense residential areas

Table 1: Categories of Air Based on Air Quality Index (AQI) (Index, 2009)

AQI Range	Air Quality Condition
0–50	Good
51–100	Moderate
101–150	Unhealthy for Sensitive Groups
151–200	Unhealthy
201–300	Very Unhealthy
>300	Hazardous

Note: Air quality categories are defined according to Air Quality Index (AQI) ranges to indicate potential health impacts.

Table 2: β Coefficients for AQHI Calculation

Pollutant	β coefficient (per ppb)
NO_2	0.000537
O_3	0.000871
SO_2	0.000394
CO	2.96E-05

Note: β coefficients represent pollutant-specific risk weights used in the calculation of the Air Quality Health Index (AQHI).

Table 3: β Coefficients for AQHI Calculation

Pollutant	WHO Guideline Limit	Averaging Period
CO (Carbon Monoxide)	≤ 10,305 µg/m³	8-hour
NO_2 (Nitrogen Dioxide)	≤ 200 µg/m³	1-hour
O_3 (Ozone)	≤ 100 µg/m³	8-hour
SO_2 (Sulfur Dioxide)	≤ 40 µg/m³	24-hour
HCHO (Formaldehyde)	≤ 100 µg/m³	30-minute

Note: WHO guideline limits were used as international reference standards for assessing ambient air pollutant concentrations.

The Pearson correlation analysis (*Table 7*) revealed statistically significant positive associations among several primary combustion-related pollutants. Nitrogen dioxide (NO_2) demonstrated a strong correlation with sulfur dioxide (SO_2; $r = 0.72$, $p < 0.05$) and a moderate correlation with carbon monoxide (CO; $r = 0.64$, $p < 0.05$), suggesting common emission sources, primarily vehicular traffic and industrial fuel combustion. A moderate correlation was also observed between NO_2 and formaldehyde (HCHO; $r = 0.55$, $p < 0.05$), indicating the mixed origin of HCHO from both direct emissions and secondary photochemical processes. Carbon monoxide showed a weaker but still significant correlation with HCHO ($r = 0.40$, $p < 0.05$). In contrast, ozone (O_3) displayed low and non-significant correlations with other pollutants ($r \leq 0.36$, $p > 0.05$), reflecting its secondary photochemical nature rather than direct emission sources.

Table 4: Iraqi National Standards &. WHO Guidelines for Ambient Air Quality (µg/m³)

Parameter	Av. Period	Iraqi Standards (µg/m³)	WHO Guidelines (µg/m³)
Carbon monoxide	1-hour	40,250 µg/m³ (35 ppm)	30,000 µg/m³ (26.2 ppm)
	8-hour	14,900 µg/m³ (13 ppm)	10,305 µg/m³ (9 ppm)
Nitrogen dioxide	1-hour	188 µg/m³ (0.1 ppm)	200 µg/m³ (0.106 ppm)
	Annual	94 µg/m³ (0.05 ppm)	40 µg/m³
Sulfur dioxide	1-hour	262 µg/m³ (0.1 ppm)	500 µg/m³
	24-hour	105 µg/m³ (0.04 ppm)	40 µg/m³

Note: Iraqi national ambient air quality standards are presented alongside WHO guideline values for comparative assessment.

Table 5: Descriptive statistics summarize annual variability and distribution patterns of atmospheric pollutant anomalies from 2018 to 2023

Pollutant	Year	Mean	Median	SD	SE	Min	Max	Range
CO	2019-2020	33.500	33.297	1.482	0.428	31.491	36.150	4.658
	2020-2021	32.573	32.078	1.561	0.451	29.937	35.207	5.270
	2021-2022	32.540	32.252	1.549	0.447	30.471	35.635	5.164
	2022-2023	31.003	31.172	1.987	0.574	27.657	34.764	7.107
HCHO	2018-2019	0.119	0.097	0.058	0.017	0.055	0.215	0.160
	2019-2020	0.125	0.127	0.050	0.015	0.064	0.202	0.138
	2020-2021	0.122	0.135	0.040	0.011	0.073	0.183	0.110
	2021-2022	0.108	0.105	0.041	0.012	0.059	0.178	0.118
	2022-2023	0.116	0.109	0.044	0.013	0.062	0.192	0.130
NO2	2018-2019	450.49	409.29	115.69	33.395	333.47	683.67	350.20
	2019-2020	456.85	435.07	112.83	32.572	320.27	696.06	375.79
	2020-2021	380.52	338.59	126.30	36.459	226.38	633.68	407.30
	2021-2022	474.84	450.39	109.40	31.581	309.94	675.12	365.18
	2022-2023	521.36	511.10	97.88	28.256	393.99	772.52	378.53
O3	2018-2019	269.66	261.96	23.11	6.672	246.37	309.21	62.840
	2019-2020	271.55	264.84	23.54	6.796	243.16	305.48	62.320
	2020-2021	262.05	261.30	18.47	5.332	232.02	289.97	57.950
	2021-2022	266.83	261.12	17.03	4.916	244.56	290.36	45.800
	2022-2023	263.88	261.92	18.02	5.202	240.66	295.78	55.120
SO2	2018-2019	47.567	37.092	26.72	7.714	12.49	91.05	78.563
	2019-2020	75.350	60.185	57.31	16.544	22.89	199.40	176.508
	2020-2021	72.596	39.153	66.96	19.328	22.73	249.02	226.285
	2021-2022	66.391	32.742	61.79	17.838	17.11	166.63	149.523
	2022-2023	68.711	31.907	68.99	19.915	20.73	248.71	227.979
CH_4	2019-2020	1243.95	1245.8	10.34	2.980	1229.5	1257.34	27.820
	2020-2021	1235.38	1237.1	7.040	2.030	1224.7	1243.35	18.620
	2021-2022	1250.04	1248.9	6.850	1.980	1239.8	1258.37	18.540
	2022-2023	1251.25	1252.2	5.750	1.660	1242.3	1261.71	19.390
UV	2018-2019	-0.558	-0.587	0.254	0.073	-0.842	-0.028	0.815
	2019-2020	-0.832	-0.931	0.248	0.071	-1.082	-0.209	0.872
	2020-2021	-0.911	-0.960	0.407	0.117	-1.249	0.273	1.522
	2021-2022	0.320	0.345	0.392	0.113	-0.290	0.890	1.180
	2022-2023	0.185	0.144	0.340	0.098	-0.260	0.685	0.945

Note: Descriptive statistics summarize annual variability and distribution patterns of atmospheric pollutant anomalies from 2018 to 2023.

Air Quality Trends and Health Implications

Annual Air Quality Index (AQI) data for Erbil (2018–2023; *Table 8*) showed fluctuating pollutant specific and overall air quality. All pollutant concentrations were standardized to µg/m³ before AQI and AQHI computation to ensure consistency with WHO guidelines and EPA breakpoint categories. AQI categories: Good (0–50), Moderate (51–100), Unhealthy (151–200), Very Unhealthy (201–300). CO-related AQI peaked in 2019–2020 (185.2) and declined to 155.7 by 2022–2023, reflecting reduced emissions and cleaner fuel adoption. NO_2 AQI varied sharply, decreased in 2020–2021 (120.3) likely due to COVID-19 restrictions, then increased to 165.9 in 2022–

2023. SO_2 AQI peaked in 2021–2022 (135.4) following winter emissions but declined after 2020, consistent with improved fuel use. AQI mirrored these trends, with the highest value in 2019–2020 (190.6) and gradual reduction to 168.8 by 2022–2023, reflecting both seasonal effects and emission controls. Annual mean Air Quality Health Index (AQHI) remained elevated throughout the study, ranging from 7.9 in 2019–2020 to 9.4 in 2021–2022, indicated sustained health risks from ambient air pollution. The slight decline to 8.8 in 2022–2023 revealed moderate decrease in exposure, but still above safe thresholds (Tang et al., 2024, Adebayo-Ojo et al., 2023).

Table 6: ANOVA and Kruskal–Wallis Tests Across Years

Pollutant	ANOVA F	ANOVA p	Kruskal–Wallis H	KW p
CO	4.62	0.012	9.34	0.025
NO_2	5.41	0.007	10.2	0.017
SO_2	3.22	0.041	7.15	0.049
O_3	1.25	0.293	2.8	0.425
HCHO	2.98	0.052	5.3	0.071

Note: ANOVA and Kruskal–Wallis tests were applied to evaluate statistically significant differences in pollutant levels across years.

Table 7: Pearson Correlation Matrix Between Pollutants (2018–2023, µg/m³)

Pollutant	CO	NO_2	SO_2	O_3	HCHO
CO	1	0.64*	0.58*	0.12	0.40*
NO_2	0.64*	1	0.72*	0.36	0.55*
SO_2	0.58*	0.72*	1	0.29	0.48
O_3	0.12	0.36	0.29	1	0.3
HCHO	0.40*	0.55*	0.48	0.3	1

Note: Pearson correlation coefficients describe the strength and direction of associations between major air pollutants.

Table 8: Annual Air Quality Index (AQI) and Air Quality Health Index (AQHI) for major pollutants in Erbil (2018–2023)

Year	CO (AQI)	NO_2 (AQI)	SO_2 (AQI)	Overall AQI	AQHI
2018–2019	N/A	132.5	118.7	140.3	8.3
2019–2020	185.2	142.8	126.1	190.6	7.9
2020–2021	178.6	120.3	101.7	182.9	8.7
2021–2022	160.9	156.2	135.4	170.2	9.4
2022–2023	155.7	165.9	121.6	168.8	8.8

Note: Annual AQI and AQHI values were calculated to evaluate overall air quality status and associated health risks in Erbil.

Table 9: Percentage exceedance of WHO guideline values for major pollutants in Erbil (2018–2023, µg/m³ basis at 25 °C, 1 atm)

Year	CO (%)	NO_2 (%)	SO_2 (%)	O_3 (%)	HCHO (%)
2018–2019	N/A	225.2	118.9	269.7	87.5
2019–2020	0.3	228.4	188.4	271.6	91.9
2020–2021	0.3	190.3	181.5	262	89.7
2021–2022	0.3	237.4	166	266.8	79.4
2022–2023	0.3	260.7	171.8	263.9	85.3

Note: Percentage exceedance values indicate the proportion by which annual pollutant concentrations surpassed WHO guideline limits.

The percentage exceedance of WHO guideline values for major pollutants in Erbil (*Table 9*) demonstrated a persistent air quality concern. NO_2 remained high throughout (190.3–260.7%), peaked in 2022–2023, while SO_2 ranged from 118.9–188.4% and O_3 stayed consistently elevated (262–271.6%). HCHO exceeded guidelines moderately (79.4–91.9%), whereas CO exceedance was negligible (0.3%), with no data for 2018–2019.These sustained exceedances correspond with elevated AQI and AQHI values, reflecting strong contributions from seasonal emissions, traffic, and industrial sources. The rising NO_2 levels highlight intensifying anthropogenic impacts, while stable O_3 levels proposed persistent photochemical formation. According to the United States Environmental Protection Agency (EPA)(Veal, 2021), AQI values are classified into six categories representing different health concern levels: Good (0–50), Moderate (51–100), Unhealthy for Sensitive Groups (101–150), Unhealthy (151–200), Very Unhealthy (201–300), and Hazardous (>300). The annual mean AQI values observed in Erbil (168.8–190.6) fall within the Unhealthy category, indicating that exposure to ambient air pollutants may cause adverse health effects across the general population. Comparable exceedances have also been reported in other Iraqi cities, underscoring the regional scale of urban air pollution. For instance, Basra recorded mean annual NO_2 levels of 480–510 µg/m³ and SO_2 of 130–160 µg/m³ during 2020–2022 (Alallawi et al., 2023), while Mosul had mean NO_2 concentrations near 495 µg/m³ (Awadh, 2023). These values similar with the current results for Erbil (NO_2 = 521 µg/m³; SO_2 = 142 µg/m³), reflecting similar sources of vehicular and industrial emissions across Iraq's major urban centers. Such parallels indicate the need for coordinated national emission reduction strategies rather than isolated city-level interventions.

Spatiotemporal Variations of Atmospheric Pollutants

Satellite-based observations using Sentinel-5P between 2018 and 2023 revealed pronounced spatiotemporal variability in atmospheric pollutants over Erbil, with patterns consistent with those reported in other rapidly urbanizing Middle Eastern cities. Carbon monoxide (CO) remained elevated in traffic corridors, decreasing only during the COVID-19 lockdowns before rebounding, a trend also observed in Tehran and Indonesia where mobility restrictions temporarily reduced combustion-related pollutants (Barzegar et al., 2024, Alharbi et al., 2022, Suhardono et al., 2023). Formaldehyde (HCHO) displayed seasonal peaks in industrial and densely populated districts, resembling findings from Cairo where photochemical activity and VOC emissions drive secondary pollution. Methane (CH_4) was persistently high across the study period, particularly near waste and agricultural zones, paralleling observations in Baghdad and Amman where uncontrolled landfill emissions contribute to long-term CH_4 accumulation. Ozone (O_3) revealed higher concentrations in downwind suburban regions, with peaks during 2020–2021, reflecting secondary formation processes similar to those reported in Dubai and Kuwait City, where NO_2 reduction during lockdowns enhanced ozone accumulation. Sulfur dioxide (SO_2) was concentrated near industrial facilities and power plants, highest in 2018–2020 but declining afterward, consistent with regional shifts toward improved fuel quality in Turkey and Jordan, additionally Nitrogen dioxide (NO_2) strongly mirrored vehicular activity, dropping during lockdown years but rebounding in 2022–2023, similar with global studies that documented NO_2 reductions of 20–40% in major cities during pandemic restrictions (El Kenawy et al., 2021, Abbas et al., 2023, Adam et al., 2021, Cooper et al., 2022). Finally, the UV Aerosol Index (UVAI) reflected dust storm seasonality, with peaks in spring and summer, similar to regional satellite-based studies that attribute high aerosol burdens to transboundary dust from Syria and the Arabian Peninsula. Quantitatively, the mean annual NO_2 concentration in Erbil (521 µg/m³) was slightly higher than reported for Tehran (Karami et al., 2025) and Amman (Omari), but comparable to Baghdad (510 µg/m³) (Hashim et al., 2021). Similarly, Erbil's SO_2 levels (142 µg/m³) were within the same range as values observed in Cairo (150 µg/m³). These similarities reinforce that northern Iraqi air quality challenges parallel those of other densely urbanized Middle Eastern environments affected by vehicular and industrial emissions. The elevated concentrations of NO_2 and SO_2 observed in this study are strongly associated with respiratory illnesses such as asthma, chronic obstructive pulmonary disease (COPD), and bronchitis, while prolonged exposure to O_3 and HCHO contributes to oxidative stress, cardiovascular disorders, and increased hospitalization rates. These findings emphasize the substantial public health burden posed by ambient air pollution in Erbil and underline the need for preventive policy interventions targeting emission reduction and population health protection. Although the integration of Sentinel-5P satellite data with ground-based observations provided a comprehensive view of long-term air quality dynamics in Erbil, certain methodological considerations must be recognized. Sentinel-5P primarily measures tropospheric column densities rather than direct ground-level concentrations; therefore, the surface values presented here are derived through statistical calibration with local measurements. This conversion introduces inherent uncertainty related to atmospheric mixing and meteorological variability. Furthermore, the use of monthly averages, necessitated by the temporal resolution of satellite observations, captures persistent exposure trends but may underestimate short-term pollution peaks that have immediate health impacts. Despite these limitations, the strong correlation between satellite and ground data and the agreement with regional findings support the validity of the observed temporal patterns and pollution sources. The study therefore provides a reliable basis for understanding long-term air quality behavior in the Kurdistan Region and for guiding targeted emission-control strategies.

Limitations and Future Work

This study represents the first long-term integration of Sentinel-5P satellite data with ground-based validation for air quality assessment in Erbil; however, several limitations should be acknowledged. First, Sentinel-5P retrievals reflect total column densities, and although calibration with local ground data improved surface-level estimation, residual uncertainty remains due to vertical profile variation and meteorological influences. Conversion of volumetric mixing ratios (ppm) to mass concentrations (μg/m³) was performed under standard conditions (25 °C, 1 atm). Variations in ambient temperature and pressure across seasons can alter these conversions by approximately ±10–15 %, introducing a modest uncertainty range in the reported values. Second, monthly mean concentrations were used for AQI and AQHI computation because satellite temporal resolution did not permit consistent daily retrievals. This approach provides robust long-term exposure assessment but may underestimate short-term peak pollution episodes. Consequently, the AQI categories presented here reflect sustained monthly exposure rather than acute daily exceedances. Third, particulate matter ($PM_{2.5}$ and PM_{10}) data were unavailable during the study period, and their omission limits a complete evaluation of population exposure, as particulate matter often represents the dominant health risk factor in urban atmospheres. Finally, meteorological factors such as wind speed, temperature inversions, and boundary layer height were not directly incorporated into the regression models, and their influence on pollutant dispersion could partly explain some seasonal fluctuations observed. Despite these constraints, the overall consistency between satellite and ground data, the strong statistical significance of temporal trends ($p \leq 0.05$), and the alignment of results with regional studies indicate that the findings reliably characterize long-term air quality patterns and associated health implications in Erbil. Future research should integrate high-resolution sensors, particulate-matter data, and meteorological modeling to further refine exposure assessments and enhance predictive air-quality management for northern Iraq.

Conclusion

This six-year study provides the first comprehensive spatiotemporal assessment of air quality in Erbil, integrating Sentinel-5P remote sensing with ground-based calibration. Results show that annual mean concentrations of NO_2, SO_2, and O_3 exceeded WHO guideline values by 188–272%, while CO exceeded only marginally (0.3%). Formaldehyde remained consistently below WHO thresholds. Although temporary improvements occurred during the COVID-19 lockdown period, pollutant levels quickly rebounded in 2022–2023. Annual AQI values ranged from 168.8 to 190.6, placing Erbil air quality in the “unhealthy” category, while the AQHI remained persistently high (7.9–9.4), indicating sustained exposure risks for the entire population. These findings confirm that air quality in Erbil is shaped by the combined influence of rapid urbanization, post-war industrial activity, fossil-fuel dependence, and recurrent dust events. The consistent exceedance of international standards underscores the urgent need for evidence-based mitigation strategies, including stricter emission controls, cleaner energy adoption, and urban planning interventions. The AQI–AQHI–WHO exceedance framework presented here establishes a robust reference for public health policy in Iraq and offers a transferable model for other under-monitored Middle Eastern cities.

Statements and Declarations

Funding None.

Competing Interests The authors declare no conflict of interest.

Ethics Statement This study was reviewed and approved by the Medical Ethics Committee of Hawler Medical University, Erbil, Iraq, during their eighth meeting (Paper Code: 8A) on 27/6/2024. All procedures were conducted in accordance with the ethical standards of the Declaration of Helsinki.

Data Availability Statement The data that support the findings of this study are available from the corresponding author upon reasonable request.

Clinical trial registration This study did not constitute a clinical trial and therefore did not require registration.

Transparency Statement The lead author Muzhda Q. Qader affirms that this manuscript is an honest, accurate, and transparent account of the study being reported; that no important aspects of the study have been omitted; and that any discrepancies from the study as planned (and, if relevant, registered) have been explained.

Acknowledgements Thanks to all the peer reviewers and editors for their opinions and suggestions and for their support of this research.

Permission to reproduce material from other sources There are no reproduced materials in the current study.

Author Contributions Muzhda Q. Qader: Writing original draft, Analysis interpretation of data and Visualization, Conceptualization and Editing & final approval of the version submitted.

References

ABBAS, I. I., KHAN, I., GINIGE, T. A. & ABDELKADER, A. 2023. Air Quality Transformation in Twelve Major Cities during Covid-19 Lockdowns: A Global Assessment. *International Journal of Data Science and Advanced Analytics,* 5, 264-271. http://dx.doi.org/10.69511/ijdsaa.v5i5.211.

ACT, C. A., ACT, R. & ACT, R. 2006. Environmental protection agency (EPA). *Report on Carcinogens,* 168.

ADAM, M. G., TRAN, P. T. & BALASUBRAMANIAN, R. 2021. Air quality changes in cities during the COVID-19 lockdown: A critical review. *Atmospheric Research,* 264, 105823. https://doi.org/10.1016/j.atmosres.2021.105823.

ADEBAYO-OJO, T. C., WICHMANN, J., AROWOSEGBE, O. O., PROBST-HENSCH, N., SCHINDLER, C. & KÜNZLI, N. 2023. A new global air quality health index based on the WHO air quality guideline values with application in Cape Town. *International Journal of Public Health,* 68, 1606349. https://doi.org/10.3389/ijph.2023.1606349.

AL-FOUADI, A. & PARKIN, D. 1984. Cancer in Iraq: seven years' data from the Baghdad Tumour Registry. *International journal of cancer,* 34, 207-213. https://doi.org/10.1002/ijc.2910340211.

ALALLAWI, A. I., HAMEED-AMEEN, A. M. & KHALF AL-JUBOURI, K. I. 2023. The effect of seasonal temperatures on the levels of air pollutants in rural and urban areas in Iraq. *Nativa,* 11, 1-7. https://doi.org/10.31413/nativa.v11i2.15801.

ALAM, M. J., KARIM, I. & ZAMAN, S. U. 2025. Seasonal dynamics and trends in air pollutants: A comprehensive analysis of PM2. 5, NO2, CO, SO2 and O3 in Houston, USA. *Air Quality, Atmosphere & Health*, 1-18. https://doi.org/10.1007/s11869-025-01790-9.

ALHARBI, B. H., ALHAZMI, H. A. & ALDHAFEERI, Z. M. 2022. Air quality of work, residential, and traffic areas during the COVID-19 lockdown with insights to improve air quality. *International Journal of Environmental Research and Public Health,* 19, 727. https://doi.org/10.3390/ijerph19020727.

ALMETWALLY, A. A., BIN-JUMAH, M. & ALLAM, A. A. 2020. Ambient air pollution and its influence on human health and welfare: an overview. *Environmental Science and Pollution Research,* 27, 24815-24830. https://doi.org/10.1007/s11356-020-08362-4

AWADH, S. M. 2023. Impact of North African sand and dust storms on the Middle East using Iraq as an example: Causes, sources, and mitigation. *Atmosphere,* 14, 180. https://doi.org/10.3390/atmos14010180.

BARZEGAR, V., SARBAKHSH, P., VALIZADEH, R. & GHOLAMPOUR, A. 2024. Air Quality Variations and Influence of COVID-19 Lockdown Restrictions on it in Tabriz, Iran. *International Journal of Environmental Research,* 18, 109. http://dx.doi.org/10.1007/s41742-024-00660-z.

COOPER, M. J., MARTIN, R. V., HAMMER, M. S., LEVELT, P. F., VEEFKIND, P., LAMSAL, L. N., KROTKOV, N. A., BROOK, J. R. & MCLINDEN, C. A. 2022. Global fine-scale changes in ambient NO2 during COVID-19 lockdowns. *Nature,* 601, 380-387. https://doi.org/10.1038/s41586-021-04229-0.

EL KENAWY, A. M., LOPEZ-MORENO, J. I., MCCABE, M. F., DOMÍNGUEZ-CASTRO, F., PEÑA-ANGULO, D., GABER, I. M., ALQASEMI, A. S., AL KINDI, K. M., AL-AWADHI, T. & HEREHER, M. E. 2021. The impact of COVID-19 lockdowns on surface urban heat island changes and air-quality improvements across 21 major cities in the Middle East. *Environmental Pollution,* 288, 117802. https://doi.org/10.1016/j.envpol.2021.117802.

FANIA, A., MONACO, A., PANTALEO, E., MAGGIPINTO, T., BELLANTUONO, L., CILLI, R., LACALAMITA, A., LA ROCCA, M., TANGARO, S. & AMOROSO, N. 2024. Estimation of Daily Ground Level Air Pollution in Italian Municipalities with Machine Learning Models Using Sentinel-5P and ERA5 Data. *Remote Sensing,* 16, 1206. https://doi.org/10.3390/rs16071206.

FARIDI, S., KRZYZANOWSKI, M., COHEN, A. J., MALKAWI, M., MOH'D SAFI, H. A., YOUSEFIAN, F., AZIMI, F., NADDAFI, K., MOMENIHA, F. & NIAZI, S. 2023. Ambient air quality standards and policies in eastern mediterranean countries: a review. *International Journal of Public Health,* 68, 1605352. https://doi.org/10.3389/ijph.2023.1605352.

FENG, H., GUO, J., PENG, C., MA, X., KNEESHAW, D., CHEN, H., LIU, Q., LIU, M., HU, C. & WANG, W. 2023. Global estimates of forest soil methane flux identify a temperate and tropical forest methane sink. *Geoderma,* 429, 116239. https://doi.org/10.1016/j.geoderma.2022.116239.

GONG, D., DU, N., WANG, L., DENG, X., ZHANG, X. & YANG, L. 2025. Impacts of meteorological and precursor emission factors on PM2. 5 and O3 from 2019 to 2022: Insights from multiple perspectives. *Atmospheric Research,* 315, 107933. https://doi.org/10.1016/j.atmosres.2025.107933.

GOSHUA, A., AKDIS, C. A. & NADEAU, K. C. 2022. World Health Organization global air quality guideline recommendations: executive summary. *Allergy,* 77, 1955-1960.

HAMAJAN, D. K. & MOHAMMED, H. D. 2024a. Analysis of Urban Sprawl Using Geographical Information System (GIS) Techniques; A Case Study in Erbil City-Kurdistan of Iraq. *Bilad Alrafidain Journal for Engineering Science and Technology,* 3, 59-71.

HAMAJAN, D. K. & MOHAMMED, H. D. 2024b. Analysis of Urban Sprawl Using Geographical Information System (GIS) Techniques; A Case Study in Erbil City-Kurdistan of Iraq. *Bilad Alrafidain Journal for Engineering Science and Technology,* 3, 59-71. https://dx.doi.org/10.56990/bajest/2024.030105.

HASHIM, B. M., AL-NASERI, S. K., AL-MALIKI, A. & AL-ANSARI, N. 2021. Impact of COVID-19 lockdown on NO2, O3, PM2. 5 and PM10 concentrations and assessing air quality changes in Baghdad, Iraq. *Science of the Total Environment,* 754, 141978.

HUSSAIN, A. M. & LAFTA, R. K. 2021. Cancer trends in Iraq 2000–2016. *Oman medical journal,* 36, e219. https://doi.org/10.5001/omj.2021.18.

INDEX, A. Q. 2009. A guide to air quality and your health. *USA: EPA*.

KARAMI, S., GHASSABI, Z., KHODDAM, N. & HABIBI, M. 2025. Investigating Meteorological Factors Influencing Pollutant Concentrations and Copernicus Atmosphere Monitoring Service (CAMS) Model Forecasts in the Tehran Metropolis. *Atmosphere,* 16, https://doi.org/10.3390/atmos16030264.

KARWAN, M., ABDULLAH, O. S., AMIN, A. M., MOHAMED, Z. A., BESTOON, B., SHEKHA, M., NAJMULDEEN, H. H., RAHMAN, F. M., HOUSEIN, Z. & SALIH, A. M. 2022.

Cancer incidence in the Kurdistan region of Iraq: Results of a seven-year cancer registration in Erbil and Duhok Governorates. *Asian Pacific Journal of Cancer Prevention: APJCP,* 23**,** 601. https://doi.org/10.31557/APJCP.2022.23.2.601.

MANISALIDIS, I., STAVROPOULOU, E., STAVROPOULOS, A. & BEZIRTZOGLOU, E. 2020. Environmental and health impacts of air pollution: a review. *Frontiers in public health,* 8**,** 14. https://doi.org/10.3389/fpubh.2020.00014.

MOHAMMED, S. J., AHMED, S. M., QADR, M. Q., BLBAS, H., ALI, A. N. & SABER, A. F. 2025. Climate Change Anxiety Symptoms in the Kurdistan Region of Iraq. *Journal of Pioneering Medical Sciences,* 14**,** 23-30. http://dx.doi.org/10.47310/jpms2025140104.

MUZHDA, Q. Q. 2025. Multi-Microbial consortia incorporating microalgae, bacteria, and fungi for effective heavy metal removal. *Bioremediation Journal,* 29**,** 1-12. https://doi.org/10.1080/10889868.2025.2552770.

NASIR, S. M., KAMRAN, K. V., BLASCHKE, T. & KARIMZADEH, S. 2022. Change of land use/land cover in kurdistan region of Iraq: A semi-automated object-based approach. *Remote Sensing Applications: Society and Environment,* 26**,** 100713. https://doi.org/10.1016/j.rsase.2022.100713.

NAZARENKO, Y., PAL, D. & ARIYA, P. A. 2020. Air quality standards for the concentration of particulate matter 2.5, global descriptive analysis. *Bulletin of the World Health Organization,* 99**,** 125.

NISHAN, M. 2019. Urban Expansion of Erbil and The Effects of Environmental During the Period 1947–2017 (A Study in The Geography of Cities. *Journal of Duhok University,* 22**,** 452-468. https://doi.org/10.26682/hjuod.2019.22.1.26.

OMARI, H. J. Assessment of Air Pollutants Levels in Major Jordanian Cities Before and After the COVID-19 Lockdown.

QADER, M. Q. 2025. Urbanization and Water Insecurity in Semi-Arid Regions: A Multi-Index Assessment of Water Quality, Ecological Risk, and Public Health Impacts. *Journal of Applied Toxicology,* 45**,** 1-14. https://doi.org/10.1002/jat.4949.

QADER, M. Q., ANWER, S. S., SHEKHA, Y. A. & ISMAEL, H. M. 2025. Comparative Evaluation of Microbial Strains for the Remediation of Heavy Metals from Synthetic Media. *Water, Air, & Soil Pollution,* 236**,** 1-11. https://doi.org/10.1007/s11270-025-08371-7

SAHU, L., TRIPATHI, N. & YADAV, R. 2017. Contribution of biogenic and photochemical sources to ambient VOCs during winter to summer transition at a semi-arid urban site in India. *Environmental Pollution,* 229**,** 595-606. https://doi.org/10.1016/j.envpol.2017.06.091.

STIEB, D. M., BURNETT, R. T., SMITH-DOIRON, M., BRION, O., SHIN, H. H. & ECONOMOU, V. 2008. A new multipollutant, no-threshold air quality health index based on short-term associations observed in daily time-series analyses. *Journal of the Air & Waste Management Association,* 58**,** 435-450.

SUHARDONO, S., SEPTIARIVA, I. Y., RACHMAWATI, S., MATIN, H. H. A., QONA'AH, N., NIRWANA, B., SURYAWAN, I., SARI, M. M. & PRAYOGO, W. 2023. Changes in the distribution of air pollutants (Carbon Monoxide) during the control of the COVID-19 pandemic in Jakarta, Surabaya, and Yogyakarta, Indonesia. *Journal of Ecological Engineering,* 24**,** https://doi.org/10.12911/22998993/159508.

TANG, K. T. J., LIN, C., WANG, Z., PANG, S. W., WONG, T.-W., YU, I. T. S., FUNG, W. W. Y., HOSSAIN, M. S. & LAU, A. K. 2024. Update of Air Quality Health Index (AQHI) and harmonization of health protection and climate mitigation. *Atmospheric Environment,* 326**,** 120473. https://doi.org/10.1016/j.atmosenv.2024.120473.

VEAL, L. 2021. United States environmental protection agency. *US Environmental Protection Agency (EPA)(2005) National Management Measures to Control Non-Point Source Pollution for Urban Areas*.

WHO 2021. WHO global air quality guidelines. World Health Organization Geneva, Switzerland