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Multidisciplinary environmental assessment of oil refinery activities in Erbil, Iraq: Implications for water, soil, air, and human health

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Abstract: This study presents an extensive environmental impact assessment of the Erbil Oil Refinery, located in the Kurdistan Region of Iraq. The evaluation included surface water, groundwater, soil, and air quality analyses to identify the ecological and public health implications of refinery operations. Surface water samples from the Greater Zab River revealed elevated biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), and copper concentrations downstream from the refinery, suggesting localized organic and heavy metal contamination. Groundwater analysis from six wells detected widespread exceedance of Total Petroleum Hydrocarbons (TPH), arsenic, and lead beyond Iraqi permissible limits, indicating serious risks to potable water safety. Air quality monitoring showed high concentrations of $PM_{2.5}$ exceeding USEPA standards, particularly near the refinery, while PM_{10} remained within safe limits in most seasons. Soil samples collected from eight sites demonstrated significant petroleum hydrocarbon presence and elevated levels of trace metals such as lead and copper near the refinery. Using the Canadian Council of Ministers of the Environment (CCME) indices, surface water and groundwater were classified as "fair" to "good", while soil quality ranged from "medium" to "low". The findings underscore the urgent need for regulatory enforcement, remediation strategies, and long-term monitoring to protect environmental and human health in Erbil.

Introduction

The expansion of industrial activities in the 20th and 21st centuries has significantly exacerbated environmental pollution worldwide. Among the industries contributing most to environmental degradation, the petroleum sector, particularly oil refining, has had a profound impact on air, water, soil, and human health (Siddiqua *et al.* 2022). The discharge of pollutants such as hydrocarbons, heavy metals, sulfur compounds, and particulate matter from oil refinery operations is a critical concern in both developed and developing nations (Afaj and Al-Khashab 2008). These contaminants can infiltrate ecosystems, contaminate water bodies, degrade soil quality, and compromise air purity, resulting in a broad spectrum of ecological and health challenges.

In Iraq, the oil industry plays a central role in economic development, with Erbil serving as one of the country's major industrial centers. The Erbil Oil Refinery, located in the Kurdistan Region of Iraq, has significantly contributed to energy production and employment. However, concerns have been raised regarding the environmental consequences of its operations. Previous studies on industrial pollution in Iraq have primarily focused on air and water quality, often neglecting comprehensive assessments that integrate geological and ecological factors (Stevens 2018).

The current study aims to fill this gap by conducting a multidisciplinary environmental impact assessment (EIA) of the Erbil Oil Refinery. It systematically evaluates the quality of surface water, groundwater, soil, and ambient air in the surrounding area. The study also quantifies potential health risks associated with exposure to contaminated media. A suite of physical, chemical, and biological parameters was measured, and geostatistical tools were used to analyze spatial variability. The Canadian Council of Ministers of the Environment (CCME) Water Quality Index (WQI), Soil Quality Index (SoQI), and Air Quality Index (AQI) were employed to interpret the results and provide actionable insights.

By integrating environmental chemistry, public health risk assessment, and geospatial analysis, this research contributes to the scientific understanding of refinery-related pollution and supports the development of evidence-based environmental policies in Iraq.

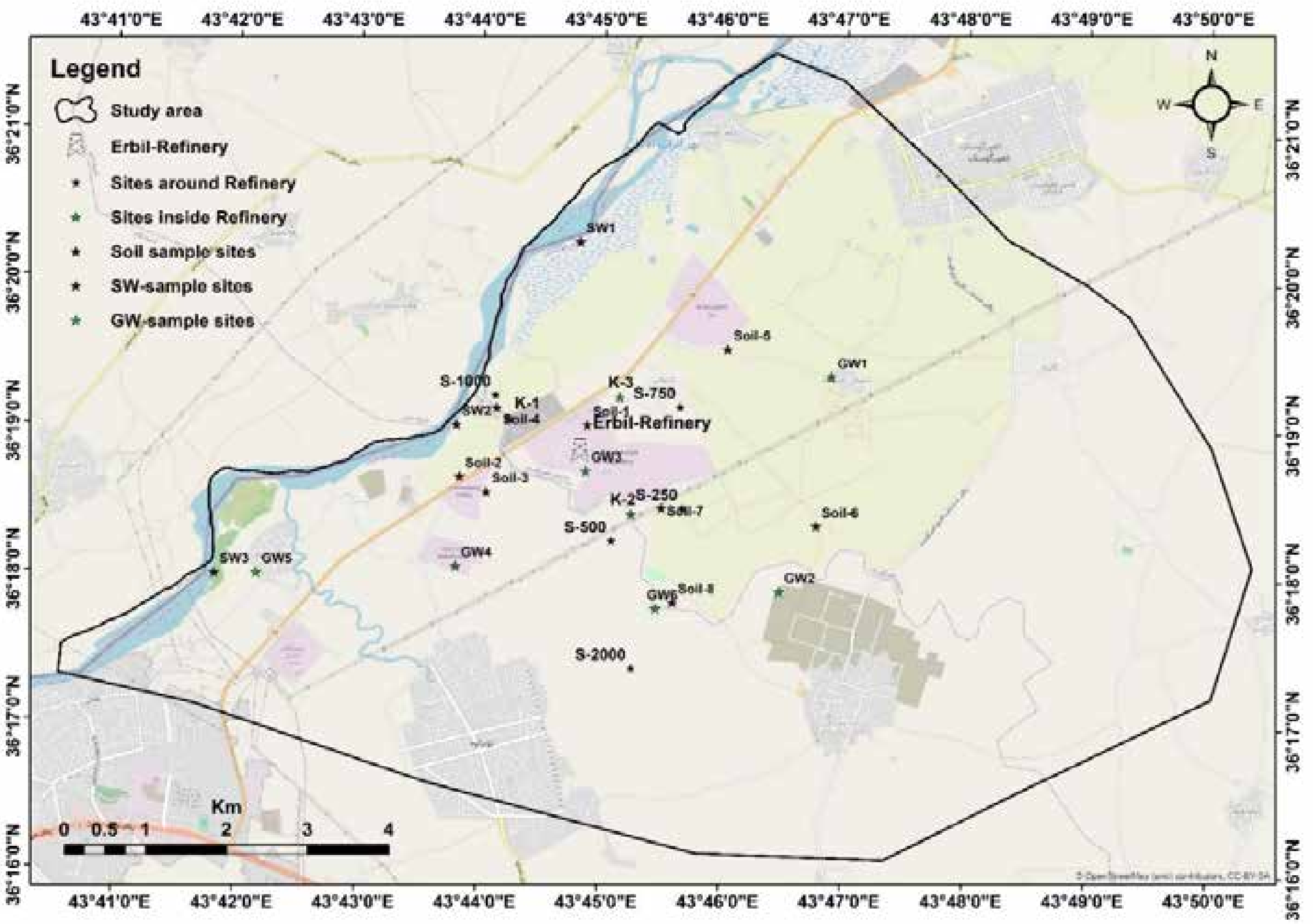

Figure 1. Study area and sampling points

Materials and Methods

Study Area

The Erbil Oil Refinery is located in the northwestern sector of Erbil, Iraq (latitude 36.3179°N, longitude 43.7573°E). The region is geographically bounded by the Greater Zab River to the northwest and the Lesser Zab River to the southeast. Covering an area of approximately 18,170 km², Erbil's geology is characterized by sedimentary rock formations that influence groundwater flow and the migration of pollutants. The refinery consists of five processing units responsible for producing petroleum derivatives such as naphtha, kerosene, gasoil, fuel oil, gasoline, and liquefied petroleum gas (LPG). Figure 1 illustrates the study area and sample locations.

Sampling Design and Field Methods

A comprehensive field campaign was conducted to assess the environmental impact of the refinery. Detection limits and analytical precision for key analytes are illustrated in Table 1.

Surface Water Sampling

Three sampling points were established along the Greater Zab River: upstream (SW-1), midstream (SW-2, adjacent to the refinery), and downstream (SW-3). Samples were collected during the summer of 2024 and analyzed for physicochemical parameters, nutrients, and trace metals. The parameters measured included pH, electrical conductivity (EC), total dissolved solids (TDS), nitrate (NO_3^-), chloride (Cl^-), sulfate (SO_4^{2-}), and heavy metals such as Cu, Pb, Zn, Cr, and Cd.

Table 1. Detection limits and analytical precision for key analytes

Parameter	Method	LOD	LOQ	Reference
Lead (Pb)	EPA 200.8	0.001 mg/L	0.005 mg/L	J. Trujillo-González *et al.* (2017)
Arsenic (As)	EPA 200.8	0.002 mg/L	0.01 mg/L	Ite *et al.* (2018)
Copper (Cu)	EPA 200.8	0.002 mg/L	0.01 mg/L	Al-Tameemi *et al.* (2020)
TPH (water)	EPA 8015	0.01 mg/L	0.05 mg/L	Anyanwu *et al.* (2023)
TPH (soil)	EPA 8015	1.0 mg/kg	5.0 mg/kg	Gao *et al.* (2022)

Biological indicators, including dissolved oxygen (DO), biochemical oxygen demand (BOD_5), and chemical oxygen demand (COD), were also assessed (Said *et al.* 2004).

Groundwater Sampling

Six groundwater wells (GW-1 to GW-6) were sampled across the region. Prior to sampling, each well was purhed to ensure representative aquifer conditions. Parameters analyzed included TDS, EC, pH, turbidity, major ions, heavy metals, and Total Petroleum Hydrocarbons (TPH).

Soil Sampling

Eight soil samples (S-1 to S-8) were collected from depths of 0–15 cm using a stainless-steel auger. The samples were air-dried, sieved to 2 mm, and analyzed for pH, EC, TPH, and trace metals including arsenic, copper, lead, chromium, and cadmium.

Air Quality Monitoring

Ambient air samples were collected at eight locations, including three within the refinery (K-1, K-2, K-3) and five at increasing distances (250–2000 m) away from the facility. Parameters monitored included $PM_{2.5}$, PM_{10}, SO_2, NO_2, CO, VOCs, O_3, and H_2S. Measurements were conducted during different seasons in 2024 using calibrated instruments such as the Dräger X-am 5000 and DustMate aerosol monitor.

Analytical Procedures

Water and soil samples were analyzed using standard methods, including spectrophotometry, titration, and inductively coupled plasma optical emission spectrometry (ICP-OES) (Trujillo-González et al. 2017). Acid digestion was performed for heavy metal extraction in soil samples (Güven and Akıncı 2011). TPH levels were determined using EPA-approved methods. Air quality indices were calculated following USEPA guidelines.

Geostatistical and Index Analysis

Spatial interpolation using Inverse Distance Weighting (IDW) in ArcGIS was applied to visualize pollutant distribution. Environmental quality was assessed using the Canadian Council of Ministers of the Environment (CCME) indices: Water Quality Index (WQI), Soil Quality Index (SoQI), and Air Quality Index (AQI). The indices incorporated scope (F1), frequency (F2), and amplitude (F3) of exceedances to classify environmental quality into five categories: excellent, good, fair, marginal, and poor (Lumb *et al.* 2006).

Results and Discussions

Surface Water Quality

Physicochemical Characteristics

Surface water samples were collected at three points along the Greater Zab River to assess the influence of the Erbil Oil Refinery on water quality. The parameters measured included pH, electrical conductivity (EC), total dissolved solids (TDS), alkalinity, hardness, major ions, and nutrients.

The pH values across the sampling sites ranged from 7.9 to 8.2, indicating slightly alkaline conditions typical of rivers influenced by carbonate geology and industrial discharges (Trajani 2006). Electrical conductivity ranged between 943 and 1027 µS/cm, with the highest values recorded at the upstream location (SW-1), likely reflecting baseline mineral content prior to refinery influence (Association 1926). TDS values were also highest at SW-1 (667.55 mg/L), with a mean of 639.38 mg/L across sites. These concentrations fall within the permissible limits for irrigation but necessitate caution for drinking purposes (Otokunefor and Obiukwu 2005).

Nitrate concentrations ranged from 25 to 34 mg/L, with an average of 28.66 mg/L. These values were below the Iraqi guideline for irrigation (45 mg/L), but their presence indicates potential inputs from agricultural runoff and industrial effluents. Sulfate (SO_4^{2-}) concentrations ranged from 67 to 105 mg/L, while chloride (Cl^-) levels ranged from 24 to 31 mg/L, reflecting moderate mineralization.

Total hardness ranged from 288 to 310 mg $CaCO_3$/L, with calcium and magnesium contributing between 94–105 mg/L and 54–89 mg/L, respectively. Alkalinity levels (278–312 mg $CaCO_3$/L) were moderately high, suggesting good buffering capacity against acidification, though this may also facilitate heavy metal mobility under certain conditions.

Organic Pollution Indicators

Dissolved oxygen (DO) concentrations ranged from 4.0 to 6.1 mg/L, with an average of 4.80 mg/L, indicating moderate oxygenation (Leggett *et al.* 2001). In contrast, BOD_5 levels ranged from 15 to 19.3 mg/L, significantly exceeding the typical range for unpolluted rivers (≤5 mg/L). Similarly, COD levels were recorded between 42 and 56 mg/L. These elevated values suggest a considerable organic load, likely from refinery discharges and nearby urban sources.

The elevated BOD_5 and COD levels indicate the presence of biodegradable and non-biodegradable organic matter, which can lead to oxygen depletion, adversely affecting aquatic life (Al-Naqishbandi 2002; Aziz 2004; Goran 2010).

Heavy Metals and TPH

Trace metal analysis revealed detectable levels of several metals. Copper concentrations were notably elevated at SW-3 (0.6269 mg/L), surpassing the Iraqi irrigation guideline of 0.2 mg/L and suggesting localized contamination near the refinery discharge point. Chromium (0.001–0.00192 mg/L), nickel (<0.002 mg/L), and cadmium (<0.0004 mg/L) remained below threshold levels. Lead concentrations ranged from 0.0267 to 0.0658 mg/L, approaching guideline values and raising concerns over cumulative exposure through irrigation and potential food chain transfer (Strickland *et al.* 1972; Genther and Beede 2013).

Total Petroleum Hydrocarbons (TPH) concentrations ranged from 0.0574 to 0.291 mg/L, with the highest levels recorded at the midstream point (SW-2), adjacent to the refinery. These values exceed the Iraqi standard of 0.01 mg/L for drinking water, confirming hydrocarbon pollution.

Comparable studies in the Niger Delta reported similar patterns of pollution. Anyanwu *et al.* (2023) and Ite *et al.* (2018) documented TPH/HM levels in surface water exceeding WHO standards by 200–400%, mainly due to unregulated effluent discharge from refineries and oil spills. Physicochemical and heavy metal analyses in surface water are illustrated in table 2.

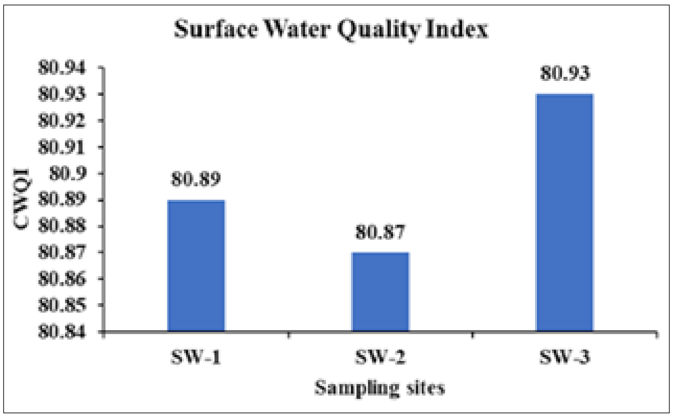

Figure 2. Surface water quality index

Surface Water Quality Index (WQI)

Using the CCME WQI method, surface water was classified as "Good" at all three sampling sites: SW-1 (80.89), SW-2 (80.87), and SW-3 (80.93) (Figure 2). Although these ratings suggest that the water is generally suitable for irrigation, the elevated BOD_5, COD, copper, and TPH values indicate that the water is unsuitable for direct human consumption without prior treatment. The classification reflects average conditions and may underrepresent localized pollution peaks.

Implications and Comparison

Compared to global studies of refinery-influenced surface waters, the present findings align with patterns observed in other industrial regions, where organic pollutants and trace metals accumulate downstream of discharge points. The current results emphasize the need for pre-treatment of industrial effluents prior to discharge and implementing routine monitoring of river health.

Groundwater Quality

Physicochemical Characteristics

Groundwater samples were collected from six wells (GW-1 to GW-6) located at varying distances and elevations around the Erbil Oil Refinery. These samples were analyzed to determine their suitability for drinking and irrigation purposes, focusing on parameters such as pH, turbidity, electrical conductivity (EC), total dissolved solids (TDS), major ions, and nutrients.

The pH of groundwater samples ranged from 7.0 to 8.1, indicating slightly alkaline to neutral conditions consistent with the regional carbonate lithology (Al-Shammary and Al-Mayyahi 2021). Turbidity values were relatively low (0.54–4.6 NTU), falling within acceptable limits for drinking water. Electrical conductivity showed significant variation, ranging from 472 to 1284 µS/cm, with the highest values observed in GW-5 and GW-6, suggesting increased ion concentrations likely influenced by both anthropogenic activities and lithological sources.

TDS values spanned from 306.8 to 834.6 mg/L, with a mean of 642.31 mg/L, well below the Iraqi maximum permissible limit for drinking water (1000 mg/L). Nevertheless, higher TDS levels in GW-3 to GW-6 suggest spatial accumulation of dissolved solids, possibly associated with refinery-related leachates (Al-Tameemi *et al.* 2020).

Nitrate concentrations varied widely between 18 and 71 mg/L, with an average of 43 mg/L. Four of the six samples remained within Iraqi permissible limits (<50 mg/L), whereas GW-5 and GW-4 exceeded this threshold, indicating contamination likely from surface infiltration of organic waste or agricultural runoff (Al-Tameemi *et al.* 2020).

Sulfate and chloride levels ranged from 98 to 306 mg/L and 22 to 82 mg/L, respectively (Chnaray 2003; Hassan *et al.* 2020). Sodium concentrations reached up to 72 mg/L, with an average of 57.33 mg/L. Although these values are within permissible limits, they contribute to elevated total hardness, which ranged from 224 to 457 mg $CaCO_3$/L.

Organic Load and Dissolved Oxygen

Dissolved oxygen (DO) levels ranged from 4.8 to 7.1 mg/L, reflecting relatively aerobic conditions. In contrast, BOD_5 values fluctuated widely, from 2.4 mg/L in GW-1 to a peak of 52 mg/L in GW-3, indicating severe organic pollution in certain locations. COD concentrations followed a similar pattern, ranging from 5.4 to 102 mg/L and exceeding safe drinking water thresholds. The elevated BOD_5 and COD levels observed at GW-3 and GW-4 suggest the presence of untreated organic effluents, likely originating from industrial or domestic sources.

Heavy Metals and Petroleum Hydrocarbons

Heavy metal analysis revealed concerning levels of arsenic and lead across the sampled wells. Arsenic concentrations exceeded the Iraqi drinking water standard (0.01 mg/L) in four wells—GW-1, GW-3, GW-4, and GW-5, with peak levels reaching 0.0813 mg/L. Lead concentrations were above the permissible limit (0.01 mg/L) in all wells, with the highest observed in GW-3 (1.087 mg/L), posing a serious threat to human health, particularly in children and pregnant women.

Copper levels ranged from 0.045 to 0.0986 mg/L, well below the allowable limit of 1.0 mg/L, while chromium remained low (<0.0088 mg/L). Zinc levels varied from 0.013 to 0.224 mg/L and did not exceed threshold values.

Of particular concern were Total Petroleum Hydrocarbons (TPH), which ranged from 0.07 to 4.60 mg/L, far surpassing the Iraqi guideline of 0.01 mg/L. Elevated TPH levels across all sampling sites provide direct evidence of hydrocarbon contamination, likely due to leakage or percolation from refinery operations. Similar patterns of groundwater contamination with hydrocarbons and heavy metals such as arsenic and lead, have been reported in the Niger Delta region ((Ite *et al.* 2018; Anyanwu *et al.* 2023). A study in southern Iraq by Khalefah *et al.* (2024) also documented the direct impact of refinery discharges on adjacent water bodies. Physical and heavy metal parameters analyzing results for groundwater are shown in table 3.

Groundwater Quality Index (WQI)

Groundwater quality was evaluated using the Canadian Council of Ministers of the Environment (CCME) Water Quality Index. The overall WQI score for groundwater was 67.79, classified as "Fair". Individual site scores ranged from 68.30 at GW-4 to 84.62 at GW-2, with the highest quality observed in wells located furthest from the refinery. Although some wells fell into the "Good" category (GW-1, GW-2, GW-6), the majority showed compromised water quality, necessitating treatment prior to use for drinking (Figure 3).

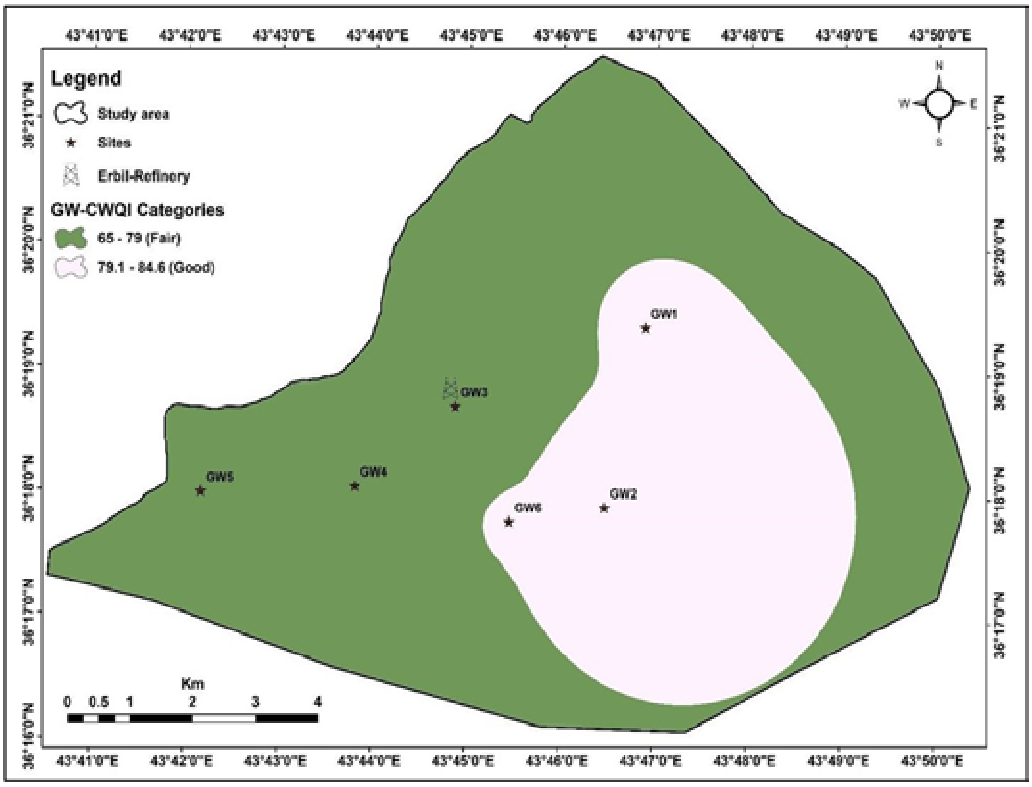

Figure 3. Groundwater quality index map

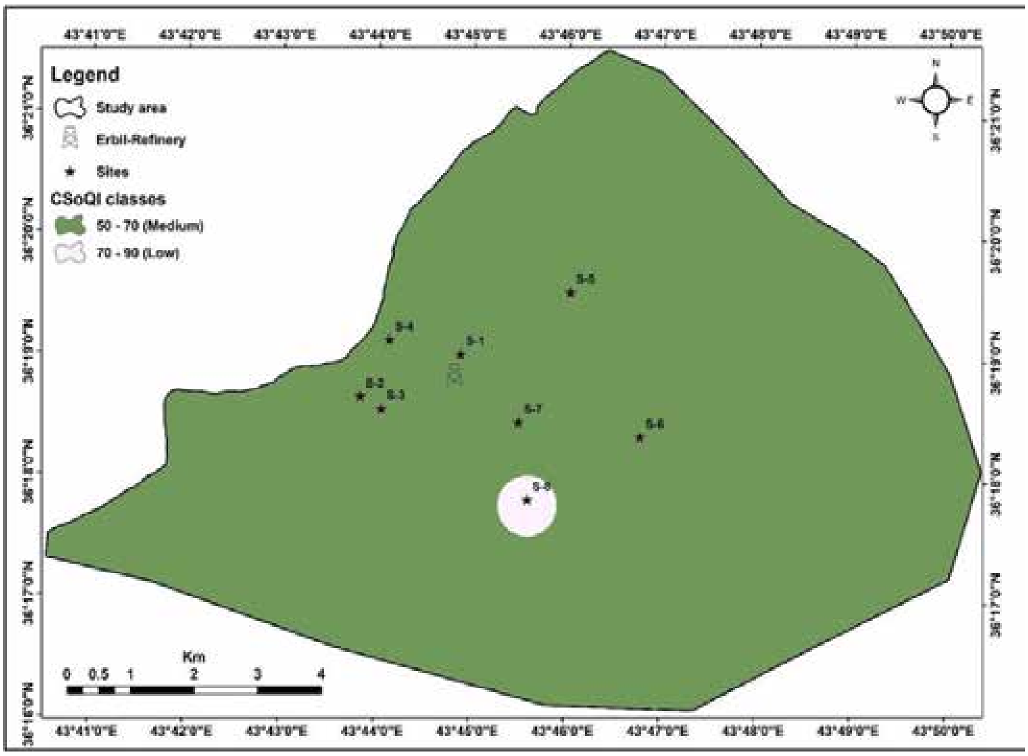

Figure 4. Soil quality index map

Soil Quality

Physicochemical Properties

Eight soil samples (S-1 to S-8) were collected from a depth of 0–15 cm in the vicinity of the Erbil Oil Refinery to assess potential contamination of surface soils. Soil pH of all samples ranged from 8.10 to 9.60, indicating alkaline conditions. These values are typical of arid and semi-arid soils with minimal leaching and may enhance the mobility of certain metals under alkaline oxidation-reduction conditions.

Electrical conductivity (EC) values varied significantly, ranging from 3.02 to 9.11 dS/m, with the highest values was observed at S-3 and S-6, suggesting localized salt accumulation. This variability may be associated with petroleum hydrocarbon inputs or saline groundwater infiltration. Moisture content was

Table 2. Physicochemical and heavy metals analyzes in surface water(Great Zab River)

Parameters (mg/L)	Sampling Sites			WHO/International Standard	Source/Note
	SW1	SW2	SW3		
Turbidity (NTU)	17.6	14.2	8.3	<5 (aesthetic); <1 (disinfection)	WHO (2017) Drinking Water Quality
pH	8.2	8.1	7.9	6.5 – 8.5	WHO (2017)
E.C (dS/cm)	1.027	0.943	0.981	<0.75 (ideal), up to 3 (max for irrigation)	FAO (1985), WHO does not set EC limit
T.D.S	667.55	612.95	637.65	<1000 (aesthetic), <600 preferred	WHO (2017)
T.Alk.(mg. $CaCO_3$./L)	278	312	289	No guideline	WHO: no health-based limit
T.H.(mg. $CaCO_3$/L)	294	310	288	<500 (aesthetic), >300 = “hard” water	WHO (2017)
Ca(mg. $CaCO_3$/L)	105	98	94	No guideline	WHO: no adverse health effects
Mg(mg. $CaCO_3$/L)	89	68	54	<125	WHO (2017)
Na	34	32	28	<200 (aesthetic); <70 (health-sensitive groups)	WHO (2017)
K	2.3	1.9	3	No guideline	Generally <10 mg/L in natural waters
Cl	24	26	31	<250	WHO (2017)
NO_3	25	27	34	<50	WHO (2017)
SO_4	82	67	105	<250	WHO (2017)
DO	4.3	6.1	4	>5 mg/L (good aquatic life support)	USEPA / FAO guidelines
BOD_5	19.3	17.4	15	<3 (moderate pollution); <6 = acceptable	UN WHO/UNEP, surface water classification
COD	42	56	49	<10 (clean); >30 = heavily polluted	UNEP classification (non-drinking threshold)
E coli (MPN/100ml)	<2.2	<2.2	<2.2	0 (drinking); <1000 for irrigation	WHO (2017)
Coliform (MPN/100ml)	<2.2	<2.2	<2.2	0 (drinking); <1000 for irrigation	WHO (2017)

low across all sites (1.4–3.6%), consistent with dry, compacted, and possibly hydrophobic soils impacted by hydrocarbons.

Heavy Metals and Trace Elements

Analysis of soil samples revealed notable concentrations of several heavy metals and trace elements. Lead (Pb) concentrations ranged from 36.0 to 185.0 mg/kg, with the highest level recorded at site S-1. Although all values fell below the Canadian Soil Quality Guidelines for commercial/industrial land use (260 mg/kg), the upper range approaches levels associated with chronic exposure risks, especially for children.

Copper (Cu) levels varied between 20.35 and 48.63 mg/kg, also with the highest detected at S-3. Chromium (Cr) ranged from 13.95 to 35.19 mg/kg, well below the Canadian threshold of 87 mg/kg. Arsenic (As) values ranged from 1.30 to 5.60 mg/kg, which is within safe commercial land-use standards but warrants monitoring due to the compound’s known toxicity and potential for groundwater migration.

Elevated levels of beryllium (Be) were found at S-1 (111.25 mg/kg), although no specific soil guideline exists for Be in Iraq, this element is recognized as toxic at high concentrations. Thallium (Tl), selenium (Se), vanadium (V), and zinc (Zn) were also detected at varying levels, with some values suggesting industrial enrichment.

The accumulation of metals in soils around the Erbil Oil Refinery reflects a common global issue in refinery zones. For example, in Tarragona County, Spain, Nadal *et al.* (2004) identified elevated heavy metal concentrations near refinery

Table 2. Physicochemical and heavy metals analyze in surface water (Great Zab River) (Continued…)

Parameters (mg/L)	Sampling Sites			WHO/International Standard	Source/Note
	SW1	SW2	SW3		
Arsenic	0.005	0.005	0.00493	0.01	WHO (2017)
Barium	0.0005	0.0344	0.032	0.7	WHO (2017)
Beryllium	<0.0002	<0.0002	<0.0002	No WHO standard; 0.004 mg/L (USEPA chronic)	USEPA/ATSDR
Boron	0.01	0.0237	0.024	2.4 (drinking); 0.5–1 (irrigation sensitive)	WHO & FAO
Cadmium	<0.0004	<0.0004	<0.0004	0.003	WHO (2017)
Chromium	0.001	0.0017	0.00192	0.05	WHO (2017)
Cobalt	0.002	<0.0020	<0.0020	No WHO standard	Typical background <0.01 mg/L
Copper	0.0226	0.0229	0.6269	2.0	WHO (2017); aesthetic taste threshold 1.0
Lead	0.0658	0.0521	0.0267	0.01	WHO (2017)
Lithium	0.001	0.0035	0.0037	No WHO guideline	Usually <0.01 mg/L in natural water
Manganese	0.00187	0.00437	0.00457	0.4	WHO (2017)
Molybdenum	<0.0020	<0.0020	<0.0020	0.07	WHO (2017)
Nickel	0.002	<0.0020	<0.0020	0.07	WHO (2017)
Selenium	0.01	<0.0100	<0.0100	0.04	WHO (2017)
Silver	0.001	<0.0010	<0.0010	0.1	WHO (2017)
Vanadium	0.001	0.0094	0.0132	No WHO guideline	USEPA RfD = 0.003 mg/kg/day; 0.1 mg/L used in some regional standards
Zinc	0.002	4.13	0.655	3.0 (aesthetic)	WHO (2017)
TPH	0.0574	0.291	0.128	<0.01 (Iraqi/FAO); <0.05 (UNEP advisory)	Iraqi Ministry of Environment / UNEP guidelines

waste disposal areas, consistent with this study's findings of elevated Pb (up to 185 mg/kg) and Cu (up to 48.63 mg/kg) in soils near the Erbil refinery.

Petroleum Hydrocarbons

Total Petroleum Hydrocarbons (TPH) in soil ranged from 21 to 151 mg/kg dry weight, with the highest values at S-1 and S-2, nearest to the refinery. These levels are indicative of chronic hydrocarbon contamination, likely due to surface spills, leakages, and atmospheric deposition from burning processes. TPH levels above 100 mg/kg are commonly associated with toxic effects on soil microbiota and vegetation, reducing soil fertility and ecological function.

Similar observations have been reported in northern Shaanxi Province, China, where Gao *et al.* (2022) found that TPH contamination significantly affected ecological forms, alpha diversity and soil microbial communities across sites including Dingbian (DB), Jingbian (JB), Wuqi (WQ), Zhidan (ZD), Ansai (AS), Zichang (ZC), Suide (SD), Yanan (YA), Fuxian (FX), and Yanchang (YC). Although maximum TPH levels in Erbil (~151 mg/kg) are comparable, similar ecological risks are anticipated given the arid soil conditions and limited natural attenuation capacity. Soil quality parameters analyzing results are shown in table 4.

Soil Quality Index (SoQI)

The Canadian Council of Ministers of the Environment (CCME) Soil Quality Index (SoQI) was calculated for each site. Index values ranged from 51.21 (S-1) to 73.77 (S-8), with an average of 59.45. Based on CCME classification, all sites fall within the "Medium Concern" category, except S-8, which was classified as "Low Concern." Notably, the sites closest to the refinery had the lowest SoQI scores, highlighting spatial trends in contamination severity (Figure 4) (CCME 2007). These findings align with results from studies conducted near petroleum refineries in similar environments, where heavy metals and hydrocarbons have been found to persist in surface soils for extended periods due to low microbial degradation rates and high binding affinity to organic matter.

Ambient Air Quality

Air Pollutants Monitored

Ambient air quality was assessed seasonally at eight sites around the Erbil Oil Refinery, including three locations within the refinery complex (K-1 to K-3) and five sites at radial distances of 250 to 2000 meters (S-250 to S-2000). The primary pollutants measured included particulate matter

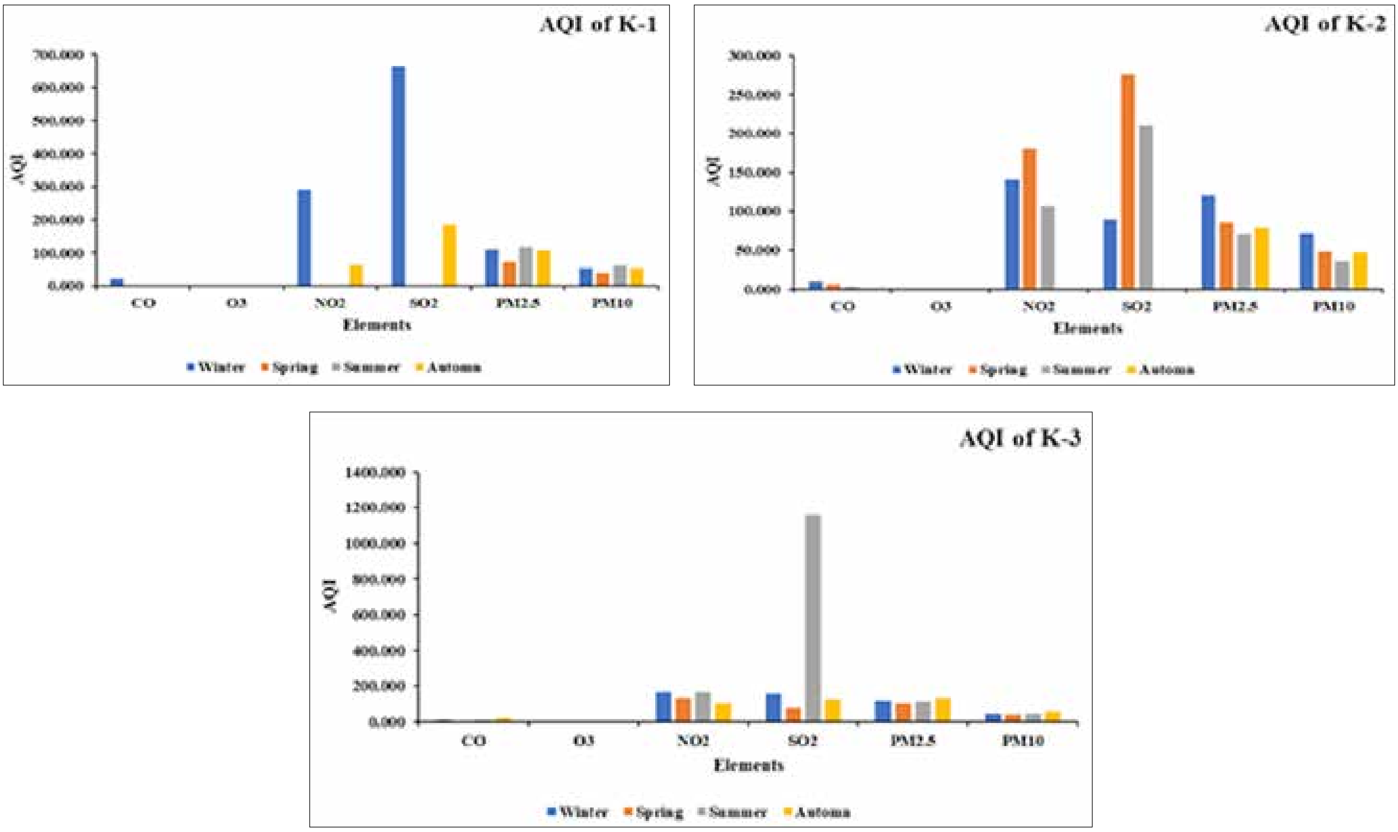

Figure 5. Air quality index

($PM_{2.5}$ and PM_{10}), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), volatile organic compounds (VOCs), hydrogen sulfide (H_2S), carbon dioxide (CO_2), and ozone (O_3). Ambient air quality of the study area (K-1, K-2, and K-3) during 2024 seasonally is illustrated in Table 5 and 6.

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

$PM_{2.5}$ concentrations ranged from 21.9 to 49.7 µg/m³, exceeding the USEPA 24-hour standard of 15 µg/m³ at all sites. In contrast, PM_{10} values were within acceptable limits (35–98.3 µg/m³) and remained below the 24-hour standard of 150 µg/m³. Notably, higher $PM_{2.5}$ levels were recorded closer to the refinery (e.g., K-1 and S-250), and seasonal peaks were observed during autumn and winter, likely due to increased combustion and stagnant atmospheric conditions.

The observed air quality degradation near the Erbil refinery, characterized by elevated $PM_{2.5}$, SO_2, NO_2, and VOCs, is similarly well-documented in studies from other oil-producing regions. In Gela, İtaly, Bosco *et al.* (2005) reported airborne particualte matter included metals and metalloids. Similarly, in Yunling County, Taiwan, near a refinery complex, Shie and Chan (2013) reported $PM_{2.5}$ levels near refineries approaching 75 µg/, more than triple the WHO limit, matching the seasonal peak of 49.7 µg/m³ observed in Erbil.

Gaseous Pollutants

Sulfur dioxide (SO_2) ranged from non-detectable to 1.153 ppm, exceeding the USEPA standard of 0.075 ppm at several locations during winter, particularly at S-2000.

Nitrogen dioxide (NO_2) levels fluctuated between 0.0 and 0.753 ppm, with the maximum value recorded at S-500 during winter, significantly surpassing the permissible limit of 0.1 ppm.

Carbon monoxide (CO) ranged from 0.0 to 2.0 ppm, remaining below the USEPA threshold of 9 ppm across all sites.

Hydrogen sulfide (H_2S) concentrations peaked at 7.433 mg/L near the refinery. Although no USEPA ambient air standard exists for **H_2S**, these levels pose olfactory and neurological hazards.

Volatile organic compounds (VOCs) varied widely (0–46 mg/L), with the highest levels recorded at K-1 during autumn and winter. While no specific USEPA ambient VOC threshold exists, high concentrations are linked to smog formation and respiratory irritation.

Ozone (O_3) was below detection limits at all locations, suggesting minimal photochemical smog formation during the study period.

In Philadelphia, USA, after a major refinery explosion, Auchincloss and De Roos (2019) linked short-term increases in $PM_{2.5}$ and VOCs to higher emergency room visits for asthma and cardiac conditions, highlighting the acute and chronic health risks associated with poor air quality near refinery operations.

Air Quality Index (AQI) Evaluation

AQI was calculated following the USEPA methodology for $PM_{2.5}$, PM_{10}, SO_2, NO_2, and CO. AQI for K-1, K-2 and K-3 zone illustrated in Figure 5. The results indicated the following trends:

$PM_{2.5}$ AQI values ranged from 71.0 to 135.6, placing most sites in the “Unhealthy for Sensitive Groups” to “Unhealthy” categories.

Table 3. Physical and heavy metal parameters analyzing results for groundwater

Parameters (mg/L)	Sampling Sites						WHO Standard
	GW1	GW2	GW3	GW4	GW5	GW6	
Turb.(NTU)	4.6	0.84	1.2	0.54	0.63	0.78	<5.0 NTU
PH	8.1	7.9	7.89	7	7.64	7.5	6.5–8.5
E.C (dS/cm)	0.472	0.481	1.233	1.265	1.284	1.194	<1.5 (drinking water)
T.D.S	306.8	312.65	801.45	822.25	834.6	776.1	<1000 mg/L
T.Alk.(mg.$CaCO_3$/L)	215	233	221	256	253	218	<500 mg/L (aesthetic)
T.H (mg.$CaCO_3$/L)	226	224	457	362	302	334	<5.0 NTU
Ca	67	91	88	71	67	102	-
Mg	44.57	48.6	82.4	62.3	66	42.8	-
Cl	22	28	62	71	44	82	<250 mg/L
SO_4	98	102	247	102	108	306	<250 mg/L
Na	32	47	72	70	61	62	<200 mg/L
K	4.2	4	7.9	8.2	8	7.4	-
NO_3	18	44	42	57	71	26	<50 mg/L
Nickel	0.048	0.056	0.038	0.053	0.042	0.033	<0.07 mg/L
Selenium	0.01	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.04 mg/L
Silver	0.001	<0.0010	<0.0010	<0.0010	<0.0010	<0.0010	-
Vanadium	0.001	0.0048	0.0099	0.0066	0.0111	0.0092	~0.01 mg/L
Zinc	0.054	0.013	0.201	0.215	0.224	0.0617	<3.0 mg/L
Arsenic	0.061	0.00896	0.027	0.0365	0.0813	0.00261	<0.01 mg/L
Barium	0.084	0.0532	0.063	0.054	0.048	0.0239	<0.7 mg/L
Beryllium	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	-
Boron	0.024	0.0985	0.0264	0.0273	0.127	0.0925	-
Cadmium	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	-
Chromium	0.001	0.0015	0.0025	0.0035	0.0039	0.0088	<0.05 mg/L
Cobalt	0.002	<0.0020	<0.0020	<0.0020	<0.0020	<0.0020	-
Copper	0.0974	0.0986	0.088	0.0712	0.045	0.057	<2.0 mg/L
Lead	0.06464	0.01024	1.087	0.516	0.302	0.07454	<0.01 mg/L
Lithium	0.001	0.0142	0.004	0.0067	0.017	0.0102	-
Manganese	0.00187	0.01507	0.00487	0.00757	0.01787	0.01107	-
Molybdenum	<0.0020	<0.0020	<0.0020	<0.0020	<0.0020	<0.0020	-
TPH	0.29	0.34	4.6	1.08	0.12	0.07	<0.01 mg/L
DO	7.1	7	5	4.8	6.2	5.8	>5 mg/L desirable
BOD_5	2.4	47	52	36	12.3	3.2	<3 mg/L for potable use
COD	5.4	82	74	102	62	14.3	No WHO limit, but >10 = high
Coliform (MPN/100ml)	<2.2	<2.2	16	16	16	16	0 MPN/100mL
E coli (MPN/100ml)	<2.2	<2.2	16	16	16	16	0 MPN/100mL

Table 4. Soil quality parameters analyzing results

Parameters mg/ kg DW	Sampling Sites								Standard (mg/kg)	Regulations
	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8		
Ag	0.75	0.86	0.74	0.74	0.88	0.78	0.85	0.96	-	
Al	6038	7038	10458	6748	6758	10958	10348	11068	-	
As	4.65	3.89	3.61	3.20	2.10	1.30	5.60	2.10	12	CCME (2007)
B	9.31	7.04	5.13	4.79	7.45	5.39	5.38	4.96	-	
Ba	142.05	131.75	59.69	59.89	104.86	47.55	35.68	53.89	500	US EPA / Dutch Target Values
Be	111.25	73.50	51.19	41.75	71.99	65.22	35.63	27.47	2	ATSDR / USEPA soil screening (approximate)
Ca	34774	47394	19184	32394	63894	63794	49594	35194	-	
Cd	3.67	4.68	3.26	2.36	1.35	2.37	4.68	1.39	22	CCME (2007)
Co	6.60	4.87	4.28	4.27	7.67	8.86	10.05	5.98	~50	Dutch Guidelines / EU typical background
Cu	45.97	36.57	48.63	20.35	26.81	32.65	48.36	21.36	91	CCME (2007)
Cr	35.19	18.98	16.46	13.95	21.78	25.83	25.03	14.99	87 (total Cr)	CCME (2007)
K	136.16	703.16	641.16	385.16	1208.16	1366.16	1296.16	1341.16	-	
Mg	1647	1407	957.00	1177	2607	3007	2277	1997	-	
Mn	368.50	338.50	278.50	298.50	348.50	424.50	363.50	318.50	~1600	Typical background (not commonly regulated)
Mo	3.39	3.12	2.60	2.59	3.28	2.95	2.70	2.65	40	Dutch / UK Soil Guidelines
Na	1149	2309	1379	1269	1329	2179	1639	1609	-	
Ni	15.46	17.76	14.37	14.90	20.83	21.56	20.46	16.76	50	CCME (2007)
Pb	185.00	143.00	127.00	52.14	41.30	64.00	97.26	36.00	260	CCME (2007)
Sb	0.25	0.28	0.23	0.25	0.30	0.31	0.28	0.25	-	
Se	0.55	0.50	0.34	0.49	0.22	1.05	0.70	0.44	3	CCME (2007)
Th	1.59	1.53	0.99	1.36	2.14	2.68	2.18	1.47	1	Dutch Target / Screening Levels
Ti	44.97	43.89	29.61	43.89	713.69	447.03	68.52	39.27	-	
V	82.33	88.25	83.76	97.42	102.36	111.18	114.31	89.80	130	CCME (Interim, 2007)
Zn	102.38	100.06	94.68	47.68	54.28	59.10	112.54	51.23	360	CCME (2007)
TPH	151.00	148.00	102.00	82.00	21.00	107.00	24.00	124.00	100–200 (industrial soils)	Dutch and CCME guidelines; ecotoxicological concern at >100 mg/kg
pH	9.60	9.01	8.74	8.30	8.20	8.10	9.00	8.70	-	
EC ds/ m	8.47	6.71	9.11	3.02	3.12	7.28	3.10	6.98	-	
MC %	3.40	2.80	3.60	2.04	1.40	1.60	1.80	2.00	-	

Table 5. Ambient air quality of the study area(K-1, K-2 and K-3) during 2024 seasonally

Parameters			CO_2 (%)	CO (ppm)	O_3 (ppm)	H_2S (ppm)	NO_2 (ppm)	SO_2 (ppm)	VOC (ppm)	$PM_{2.5}$ (μg/m³)	PM_{10} (μg/m³)
Standard*			0.04[4]	9.00[1]	0.05[1]	0.005[2]	0.021[1]	0.005[1]	0.001[3]	15.00[1]	45.00[1]
Sampling sites	K-1	Wint.	0.0053	1.8667	0.00	0.8667	1.2000	1.3333	13.7333	39.3333	64.2667
		Spr.	0.0107	0.0000	0.00	1.4000	0.0000	0.0000	15.8000	22.9333	42.0667
		Sum.	0.008	0.0000	0.00	1.2667	0.0000	0.0000	33.0000	42.0000	77.3333
		Aut.	0.0027	0.1333	0.00	7.4333	0.0667	0.2667	46.0000	38.7333	64.0000
	K-2	Wint.	0.0233	0.8667	0.00	0.4000	0.4000	0.0667	2.1333	43.4667	98.2667
		Spr.	0.0013	0.5333	0.00	0.4667	0.5333	0.5333	0.6667	28.7333	52.1333
		Sum.	0.0113	0.2667	0.00	0.1333	0.1333	0.3333	4.4000	21.8667	39.2000
		Aut.	0.000	0.000	0.00	0.1933	0.0000	0.0000	4.2667	25.6667	50.6000
	K-3	Wint.	0.0107	0.8667	0.00	0.2667	0.4667	0.2000	0.6667	42.2000	49.3333
		Spr.	0.0167	0.4444	0.00	0.2222	0.2778	0.0556	2.0840	38.3333	46.3556
		Sum.	0.0073	0.9333	0.00	0.9333	0.4667	2.3333	0.8667	41.1333	53.2667
		Aut.	0.0013	2.0000	0.00	0.0000	0.1333	0.1333	1.5347	49.6667	68.4667

[1]**WHO (2021).** *Global Air Quality Guidelines – Particulate matter (PM2.5 and PM10), Ozone, Nitrogen dioxide, Sulfur dioxide and Carbon monoxide*
[2]**WHO (2003).** *Hydrogen sulfide: Human health aspects. Concise International Chemical Assessment Document 53*
[3]**USEPA (2023).** *Toxicological profiles and air toxics standards.*
[4]**ASHRAE (2022).** *Ventilation for Acceptable Indoor Air Quality*

PM_{10} AQI values (36.3–72.2) generally fell within the "Good" to "Moderate" range.
SO_2 and NO_2 AQI values were highly variable; peak SO_2 AQI reached **1164.5**, categorized as "Hazardous," particularly during winter.
NO_2 AQI values ranged from 0 to 291.8, with several sites classified as the "Very Unhealthy".
CO AQI values remained low (mean 7.5), indicating no acute risk from carbon monoxide exposure.

Spatial and Seasonal Trends

All pollutants demonstrated clear spatial gradients, with the highest concentrations observed at or near the refinery and a general decline with increasing distance. Seasonal variations were also evident, with pollutant levels peaking during winter, likely due to reduced atmospheric dispersion and increased fuel combustion. These patterns suggest a direct correlation between refinery operations and ambient pollution load.

Health Risk Implications

Elevated levels of $PM_{2.5}$, SO_2, NO_2, and VOCs pose significant risks to respiratory and cardiovascular health, particularly among vulnerable populations such as children, the elderly, and individuals with pre-existing conditions. Chronic exposure in communities residing within 1 km of the refinery may increase the incidence of asthma, bronchitis, and potentially carcinogenic outcomes due to long-term VOC inhalation.

Conclusions

This study provides a comprehensive environmental impact assessment of the Erbil Oil Refinery by integrating multidisciplinary analyses of surface water, groundwater, soil, and ambient air. The findings highlight significant environmental degradation in the vicinity of the refinery, with direct implications for ecological integrity and public health.

Surface water quality in the Greater Zab River revealed elevated levels of biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), and localized copper contamination, indicating the presence of organic and heavy metal pollutants. While water quality was classified as "good" under the Canadian Water Quality Index (CWQI), it was unsuitable for drinking without treatment due to the presence of hydrocarbons and trace metals.

Groundwater analysis exposed critical contamination concerns, with Total Petroleum Hydrocarbons (TPH), arsenic, and lead levels exceeding Iraqi drinking water standards in nearly all sampled wells. Although the overall groundwater quality was rated as "fair," the presence of toxic metals and hydrocarbons presents serious health risks, particularly through ingestion.

Soil quality assessments confirmed the accumulation of petroleum hydrocarbons and heavy metals, particularly lead, copper, and beryllium, in areas close to the refinery. Most contaminant levels were below Canadian industrial soil guidelines; however, the Soil Quality Index (SoQI) indicated

Table 6. Ambient air quality of the study area outside Erbil Refinery with different distance away of refinery

Distance (m)	CO_2 (ppm)	CO (ppm)	H_2S (ppm)	NO_2 (ppm)	SO_2 (ppm)	VOC (ppm)	$PM_{2.5}$ (µg/m^3)	PM_{10} (µg/m^3)
250	0.018	0.115	0.558	0.282	1.048	16.307	39	49
500	0.014	0.000	0.348	0.753	0.000	17.922	39	63
750	0.001	0.000	0.000	0.000	0.000	17.222	33	43
1000	0.001	0.000	0.000	0.000	0.000	14.337	20	35
2000	0.000	0.504	0.167	0.000	1.153	12.916	29	54

"medium" concern in most locations, with TPH levels exceeding safe thresholds at some sites. These findings suggest threatens to soil fertility and potential human exposure through dermal contact or crop uptake.

Air quality measurements demonstrated elevated concentrations of $PM_{2.5}$, NO_2, SO_2, and VOCs, especially near the refinery and during colder seasons. Air Quality Index (AQI) evaluations categorized the air as "unhealthy" at multiple sites, particularly for $PM_{2.5}$ and SO_2, suggesting an increased burden of respiratory and cardiovascular disease among local populations.

In summary, the Erbil Oil Refinery has a clear and measurable impact on surrounding environmental compartments. These findings reinforce the urgent need for:

- Strengthened environmental regulations and enforcement;
- Installation of advanced emission and wastewater treatment technologies;
- Implementation of groundwater and soil remediation strategies;
- Establishment of continuous air and water quality monitoring programs;
- Public health risk assessments and long-term epidemiological studies.

The research provides critical data for policymakers, environmental planners, and public health authorities to develop informed and sustainable strategies aimed at mitigating the refinery's environmental footprint while safeguarding the health of Erbil's population and ecosystems.

Authors' Contributions

Ethical approval (for researches involving animals or humans)

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Conflict of Interests

The authors declare that there are no conflicts of interest related to this article

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