



INTEGRATING NUTRIENT STOICHIOMETRY, POLLUTION INDICES, AND WATER QUALITY GUIDELINES TO ASSESS COASTAL ECOSYSTEM HEALTH IN QATAR

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ABSTRACT

Qatar, located within the environmentally stressed Arabian-Persian Gulf, has waters vulnerable to natural and anthropogenic pressures. A year-long monitoring programme used standardised protocols for organic matter, nutrients, and trace metals, along with nutrient stoichiometry, Enrichment Factor (EF), and Index of Geo-accumulation (Igeo). Total organic carbon (1.1–3.6 mg/L) and oil and grease (11–23 µg/L) remained below the Qatar regulatory discharge limit of 10 mg/L, although episodic spikes highlighted localised hydrocarbon inputs. Nutrient enrichment was pronounced in Doha Bay, where nitrate (77.2 µg/L) and phosphate (11.3 µg/L) remained below Qatari marine water quality limits but indicated localised bloom risk. Meanwhile, stoichiometric ratios indicated episodic phosphorus (DIN:PO₄ > 90) and transient nitrogen limitation (DIN:PO₄ < 10) without regulatory exceedance. Trace metals were generally within Qatari, USEPA and WHO guidelines. Copper slightly exceeded the USEPA chronic criterion (3.1 µg/L) at Doha Bay but remained below its acute limit and within the Qatari standard. Zinc concentrations (up to 33.8 µg/L) were observed at semi-urban sites but remained within national and international guidelines. Enrichment factor and Igeo analyses confirmed predominantly natural origins, with minor to moderate enrichment at industrial and residential stations, while reference sites like RasRakan and Salwa represented background conditions. Seasonal dynamics, including summer organic enrichment and winter nutrient surges were confirmed as significant change points. This study underscored dual influences of natural forcing and human activity. Overall, a robust framework for compliance assessment through multi-year monitoring is needed to capture interannual variability and strengthen coastal management strategies in Qatar.

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Introduction

Coastal marine ecosystems of the Arabian-Persian Gulf are shaped by their shallow semi-enclosed basin and extreme climatic forcing. This causes sea surface temperatures to exceed 34°C during summer, hypersaline conditions (> 40‰), and high evaporation rates (Hereher, 2020). Risks are possible when rapid urbanisation, industrial expansion, and large-scale desalination activities discharge effluents directly into nearshore waters. If water quality

deteriorates, fisheries and ecological impacts could be devastating. Fortunately, the Ministry of Environment and Climate Change (MECC) routinely monitors marine water quality in Qatar through its Section of Marine and Soil Environmental Quality under the Environmental Monitoring and Inspection Department (Sawh *et al.*, 2024). Despite these efforts, monitoring is conducted at different intervals. As a result, spatial-temporal variability in organic matter,

nutrients, and trace metals in coastal waters remains fragmented. It leaves critical gaps in understanding the interplay between natural variability and anthropogenic enrichment at a given time and place.

In the last decade of Gulf monitoring, Al-Yamani *et al.* (2017) reported elevated (1.5–4.2 mg/L) Total Organic Carbon (TOC) concentrations in Kuwait Bay which exceeded the 1.1–3.6 mg/L recorded in Dukhan and Salwa in Qatar (Al-Awah *et al.*, 2026). Also, oil and grease inputs (15.5–23.4 µg/L) originating from Persian refineries suggest an absence of sheen (Eldos *et al.*, 2022; Karam & Al-Saleh, 2024). Although these values remain below the Qatari regulatory discharge limit of 10 mg/L (10,000 µg/L), continuous yet substantial inputs within the Gulf region can lead to ecological imbalances, as Qatar is positioned as a barrier between the Persian and Arabian seas (Abdulkareem *et al.*, 2021).

Nitrate (10–60 µg/L) and phosphate (2–8 µg/L) discharges from land-based wastewater influence the chemistry of coastal waters of Qatar (Mirza *et al.*, 2021; Durvasula *et al.*, 2024; Fakhraldeen *et al.*, 2025). Previous studies have reported nutrient enrichment and its potential ecological implications in the Gulf region. For instance, nitrate (< 77.2 µg/L) and phosphate (< 11.3 µg/L) enrichment that exceeded the ecological thresholds of 0.55 mg/L (*c.a.* Li *et al.*, 2022) may increase the risk of algal blooms in the northern waters of Qatar (Ershadifar *et al.*, 2023a). This issue warrants further investigation because guidelines for bloom ecology remain limited in Qatar. Hence, without nutrient-specific management protocols, the dissolved inorganic nitrogen-to-phosphate (DIN:PO₄) stoichiometry of the Gulf region remains high, exceeding the Redfield ratio of 16 at multiple locations (Garcia, 2022; Ershadifar *et al.*, 2023b). Previously, in the Gulf of Oman, excess nitrate over phosphorus changed planktonic community structure (between diatoms and dinoflagellates) (Al-Hashmi *et al.*, 2015).

The Arabian-Persian seas were also affected by metal introductions. Seawater and sediments

near Dammam, Saudi Arabia, were found to be enriched with copper (< 4.2 µg/L) and zinc (< 40 µg/L) (Ghanimeh *et al.*, 2025). Comparable ranges were also previously detected in Doha Bay and Al-Saffliya in Qatar (Al-Naimi *et al.*, 2015; Loganathan *et al.*, 2019) and coastal waters adjacent to ports and industries in the Persian Gulf (Rezaei *et al.*, 2021; Swetha *et al.*, 2025). However, copper saturations (1.2–3.8 µg/L) in coastal waters of Qatar now fall between the chronic-acute threshold (3.1–4.8 µg/L) set by United States Environmental Protection Agency (USEPA) (Elkhatat *et al.*, 2021). In addition, lead (1.5–7.0 µg/L) was detected in coastal waters adjacent to industrial sites in Saudi Arabia (Alharbi *et al.*, 2024; Al-Khatany *et al.*, 2024). Comparable ranges of arsenic (2.0–6.5 µg/L), copper (2.5–6.0 µg/L), nickel (1.5–4.2 µg/L), and lead (2.0–5.6 µg/L) were recorded in waters adjacent to harbours, industrial, and desalination plants in Oman (AlKasbi, 2016; Okati *et al.*, 2021; Jupp *et al.*, 2023). Further, zinc ranged 10–45 µg/L along mangrove areas and was < 60 µg/L within tourism areas surrounding the coasts of Oman (Alamri *et al.*, 2021; Jupp *et al.*, 2023). Overall, the recorded values were safe although approaching the WHO (8.2–10 µg/L) and USEPA (< 81 µg/L) guidelines.

However, the findings were not reliably normalised against reference elements or background values, nor distinguished between natural geochemical variability and anthropogenic inputs, especially using indices such as the Enrichment Factor (EF) and Index of Geo-accumulation (Igeo). Following regional water quality inspections and attaining values below WHO and USEPA guidelines, altogether, achieving EF > 2 and Igeo values > 1 for both copper and zinc highlighted concerns related to anthropogenic sources (Ram *et al.*, 2018; Vilhena *et al.*, 2021; Kanellopoulos *et al.*, 2022; Arif & Aldosary, 2023). Therefore, EF and Igeo could be used to assess the quality of coastal waters surrounding Qatar if it complied with existing guidelines.

The detection of multiple indicators such as TOC, oil and grease, nutrients, and trace metals in all locations at a single point in time provides

a more holistic understanding of coastal water quality than previous approaches. Moreover, using single parameters or one-off approaches has overlooked the synergistic effects of organic enrichment, eutrophication, and metal contamination. Also, the application of pollution indices (EF and Igeo) and nutrient stoichiometry further strengthens the distinction between natural variability and anthropogenic enrichment (Li *et al.*, 2024; Hei *et al.*, 2025). Therefore, this study aims to evaluate the spatiotemporal variability of organic matter, nutrients, and trace metals in coastal waters of Qatar by integrating concentration data, stoichiometric ratios, and pollution indices across industrial, residential, and reference sites. This outcome improves on previous approaches in the Arabian-Persian Gulf that used offshore or reference sites rather than monitoring waters adjacent to semi-urban and industrialised areas. The findings also support continuous improvement of nutrient monitoring guidelines by the Ministry of Environment and Climate Change.

Materials and Methods

Study Site Description

This study was conducted in coastal waters surrounding Qatar, a state positioned between the Arabian and Persian Gulf (approximately 24° N to 26° N latitude; Figure 1). The coastal area of Qatar is defined by a shallow, semi-enclosed basin characterised by severe climatic forcing, including extreme summer temperatures where sea surface temperatures frequently exceed 34°C and naturally elevated hyper-salinity often reaches > 40‰, which is further exacerbated by high annual evaporation. The entire coastline is subject to intense anthropogenic pressure due to rapid urbanisation, extensive industrial development, and large-scale desalination activities. To fulfil the aim of this study, a network of multiple, representative coastal sampling locations was strategically established (Figure 1). The selection of these sites was spatially explicit and designed to capture the full range of pressures observed along the Qatari coast. These sites were divided into industrial

or effluent zones and lay adjacent to major industrial facilities, hydrocarbon operations, and the outfalls of large-scale thermal and desalination plants. Therefore, Site 1 (Sealine) and Site 2 (Doha Bay) were expected to exhibit localised thermal anomalies and elevated levels of total suspended solids and organic contaminants, such as biological and chemical oxygen demand.

Site 3 (Al-Safliya), Site 4 (RasImlaiji), and Site 6 (Dukhan) were bays associated with urbanisation. These locations are within densely populated areas and receive runoff and discharges from domestic wastewater and storm sewer systems. These sites are critical for assessing nearshore organic pollution loads and capturing variability across the main population centres. Meanwhile, Site 5 (RasRakan) and Site 7 (Salwa) were reference coastal areas with minimal localised industrial or major urban development. These locations were selected to represent regional natural background variability and the influence of thermal salinity on water quality parameters. Overall, these locations were away from major outfalls and urban centres. Sampling was restricted to the immediate nearshore environment (depths < 10 m) where most land-based discharges interact with marine critical habitats such as seagrass meadows and coral reefs. The distance from shore of 3–5 km was associated with intake waters. This coastal zone had the highest potential to exceed regulatory limits for recreational activities. This range allows robust assessment of contamination gradients and seasonal fluctuations in physicochemical parameters driven by stratification, temperature, and human activity.

Post-sampling Analysis

All glassware and sampling containers were acid-washed and rinsed with ultrapure water prior to use. Field blanks and triplicate samples were collected at 10% of stations to assess contamination and reproducibility. Calibration standards were prepared fresh daily, and instrument performance was verified

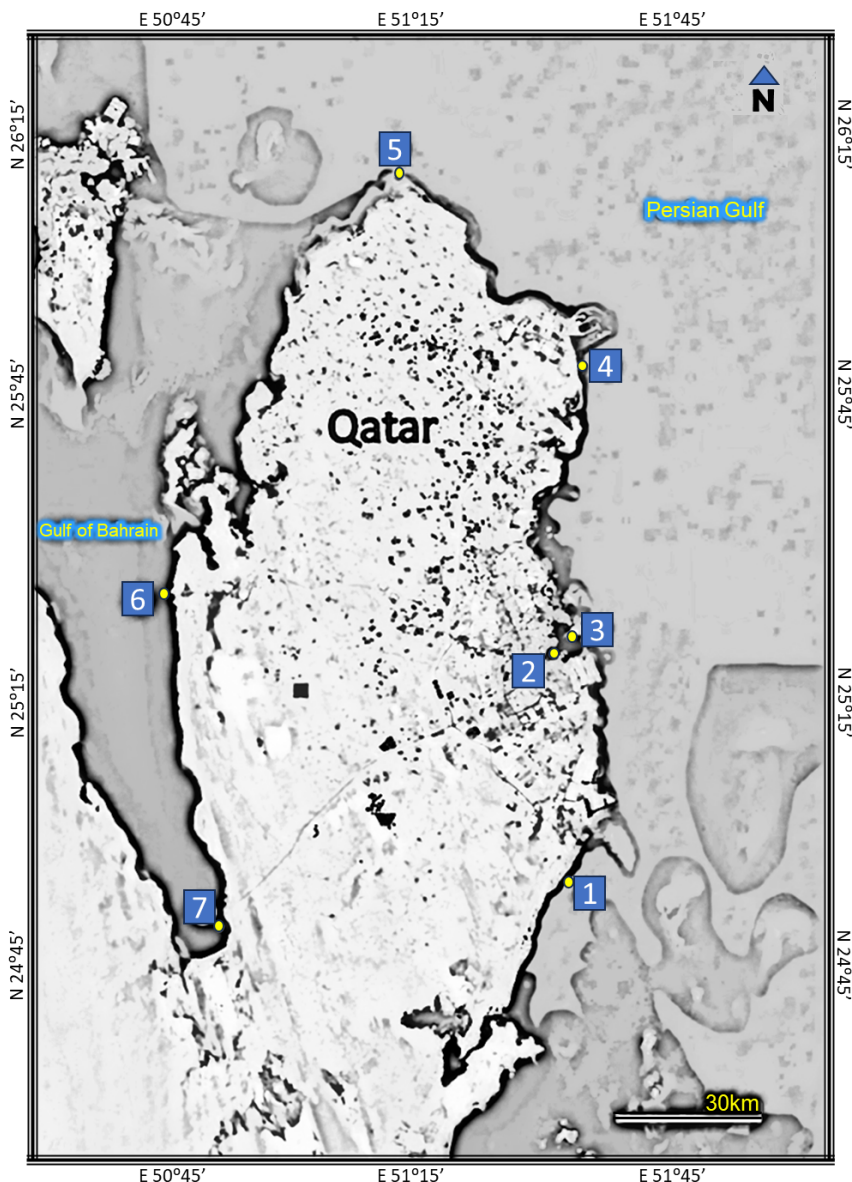


Figure 1: Sampling sites indicated with numbers to represent the area where coastal waters were sampled. Site 1 = Sealine, Site 2 = Doha Bay, Site 3 = Al-Safliya, Site 4 = RasImlajji, Site 5 = RasRakan, Site 6 = Dukhan, and Site 7 = Salwa

with certified reference materials. Data were accepted only when recovery rates were within $\pm 10\%$ of certified values and Relative Standard Deviations (RSD) were $< 5\%$. Water samples for TOC determination were collected in pre-combusted glass bottles and preserved with phosphoric acid ($\text{pH} < 2$) to minimise microbial

degradation. Analyses were performed using a high-temperature catalytic oxidation method with a TOC analyser (Shimadzu TOC-L series; Tupas *et al.*, 1994). Prior to injection, samples were filtered through pre-combusted GF/F filters ($0.7 \mu\text{m}$). Calibration was conducted with potassium hydrogen phthalate standards, and

instrument blanks were run routinely to ensure accuracy.

Meanwhile, chlorophyll-a concentrations were determined fluorometrically following extraction in 90% acetone (Ershadifar *et al.*, 2023a). Seawater samples (500 mL–1 L) were filtered through GF/F filters under low vacuum pressure. Filters were stored at -20°C in the dark until analysis. Pigments were extracted for 24 hours at 4°C , and fluorescence was measured using a calibrated fluorometer from Turner Designs. Acidification with 0.1 N HCl was applied to correct for phaeophytin interference.

Nutrient concentrations in 0.1 L seawater samples were analysed using standard colourimetric methods (Grasshoff *et al.*, 2009), where phosphate (PO_4^{3-}) was determined by the molybdenum blue method with ascorbic acid reduction. A spectrophotometer was set to an absorbance of 885 nm to determine the concentration of PO_4^{3-} in water samples. Similarly, nitrite (NO_2^-) was quantified by diazotisation with sulphanilamide and N-(1-naphthyl)-ethylenediamine at an absorbance of 543 nm. Then, nitrate (NO_3^-) analysis was performed by reduction to nitrite using a cadmium reduction column. The same diazotisation procedure was followed. Ammonium (NH_4^+) was determined by the indophenol blue method and measured at an absorbance of 640 nm, while silicate (SiO_2) was measured by the formation of silica-molybdate complex before reduction with ascorbic acid. This was followed by spectrophotometric analysis at 810 nm. All analyses were conducted using a continuous flow autoanalyser (Skalar SAN++), with calibration curves prepared from certified reference standards (McGrath *et al.*, 2019). Analytical precision was verified through replicate analyses and participation in inter-laboratory comparisons.

In addition, trace metals were quantified following a 0.1L seawater sample preparation that used 65% nitric acid for digestion before analysis by Inductively Coupled Plasma–Mass Spectrometry (ICP-MS; Agilent 7,900; Sun *et al.*, 2018). Seawater samples were collected

in acid-cleaned polyethylene bottles and immediately acidified to $\text{pH} < 2$ with ultrapure HNO_3 . Prior to analysis, samples underwent pre-concentration using Chelex-100 resin or evaporation under clean-lab conditions, depending on the element. Digestion blanks and certified reference materials (e.g., NASS-6, CASS-6) were included to ensure accuracy. Detection limits were maintained below 0.1 $\mu\text{g/L}$ for all metals analysed. Oil and grease were determined gravimetrically following liquid — liquid extraction of 0.1 L seawater sample with n-hexane, in accordance with APHA Standard Methods (5520B; Mohana *et al.*, 2023). Extracts were dried over anhydrous sodium sulfate, concentrated, and weighed to determine total oil and grease content. Quality control included solvent blanks and recovery tests with spiked samples.

Nutrient Stoichiometry Analysis

To evaluate nutrient limitation regimes across seven Qatari coastal stations from May 2023 to April 2024, molar ratios of Dissolved Inorganic Nitrogen (DIN) to phosphate (PO_4^{3-}) and silica (SiO_2) were calculated using monthly nutrient assessments from the seawater (Hartmann *et al.*, 2011). DIN was defined as the sum of nitrate (NO_3^-), nitrite (NO_2^-), and ammonium (NH_4^+), each converted from micrograms per liter ($\mu\text{g/L}$) to micromoles per liter (μM) using their respective molecular weights: $\text{NO}_3^- = 62 \text{ g/mol}$, $\text{NO}_2^- = 46 \text{ g/mol}$, $\text{NH}_4^+ = 18 \text{ g/mol}$, $\text{PO}_4^{3-} = 95 \text{ g/mol}$, and $\text{SiO}_2 = 60 \text{ g/mol}$ (Equation 1). The resulting DIN values were then used to compute stoichiometric ratios for each station-month combination. DIN: PO_4 ratios exceeding the canonical Redfield ratio of 16 were interpreted as indicative of phosphorus limitation (Equation 2), while DIN: SiO_2 ratios below 1 suggested nitrogen limitation relative to silica, favouring diatom dominance (Equation 3). The following equations were used:

$$\text{DIN } (\mu\text{M}) = [\text{NO}_3^- (\mu\text{g/L}) \div 62] + [\text{NO}_2^- (\mu\text{g/L}) \div 46] + [\text{NH}_4^+ (\mu\text{g/L}) \div 18] \quad (\text{Equation 1})$$

$$\text{DIN:PO}_4 = \text{DIN } (\mu\text{M}) \div [\text{PO}_4^{3-} (\mu\text{g/L}) \div 95]$$

(Equation 2)

$$\text{DIN:SiO}_2 = \text{DIN } (\mu\text{M}) \div [\text{SiO}_2 (\mu\text{g/L}) \div 60]$$

(Equation 3)

Pollution Indices

To evaluate the degree of anthropogenic influence on trace metal concentrations, EF were calculated for each element across all stations and sampling months. The enrichment factor normalises observed concentrations against natural background levels, distinguishing natural variability from potential contamination. These two reference sites were selected because they represent minimally impacted coastal environments in Qatar, and their monthly averages capture natural seasonal variability. The EF values were interpreted according to standard classification thresholds: EF < 1 (no enrichment), 1–2 (minimal), 2–5 (moderate), 5–20 (significant), 20–40 (very high), and > 40 (extremely high enrichment). The EF was computed as:

$$\text{EF} = \text{Cn} / \text{Bn} \quad (\text{Equation 4})$$

where:

Cn = Concentration of the target metal at a given station and month ($\mu\text{g/L}$).

Bn = Background concentration, defined as the monthly mean of Ras Rakan and Salwa stations for the same metal.

Meanwhile, Igeo was also applied to further assess the extent of metal contamination relative to natural background conditions (Nowrouzi & Pourkhabbaz, 2014). Values of Igeo were classified into seven pollution classes where ≤ 0 (unpolluted), $0 < \text{Igeo} \leq 1$ (unpolluted to moderately polluted), $1 < \text{Igeo} \leq 2$ (moderately polluted), $2 < \text{Igeo} \leq 3$ (moderately to strongly polluted), $3 < \text{Igeo} \leq 4$ (strongly polluted), $4 < \text{Igeo} \leq 5$ (strongly to extremely polluted), and $\text{Igeo} > 5$ (extremely polluted). The Igeo was calculated as:

$$\text{Igeo} = \log_2 \left(\text{Cn} / (1.5 \times \text{Bn}) \right) \quad (\text{Equation 5})$$

where:

Cn = Measured concentration of the metal at a given station and month ($\mu\text{g/L}$).

Bn = Background concentration, defined as the monthly mean of Ras Rakan and Salwa for the same metal.

1.5 = Constant factor to account for natural lithogenic variability.

Statistical Analyses

For cross-category comparisons, stations were first grouped into three categories based on dominant land use and anthropogenic influence: Industrial (Al-Safliya, Ras Imlaiji, Dukhan), residential (Sealine, Doha Bay), and reference (RasRakan, Salwa). Monthly water quality parameters, including TOC, nutrients, chlorophyll-a, oil and grease, and trace metals, were then aggregated within each category. Pearson's correlation coefficients were calculated to examine relationships both within and between categories, allowing assessment of how strongly parameters co-varied across different site types. Comparisons were made pairwise (industrial vs. residential, industrial vs. reference, residential vs. reference) and further stratified by season to capture temporal variability. Positive correlations were interpreted as evidence of shared drivers such as productivity coupling, while negative or weak correlations highlighted contrasts in water quality regimes. Finally, these statistical outcomes were contextualised against international and national water quality guidelines to identify where observed differences aligned with or exceeded compliance thresholds.

Results

General Observations

The spatiotemporal analysis of physicochemical and trace metal parameters across the seven coastal locations in Qatar revealed clear spatial heterogeneity and seasonal variability (Table 1). Total organic carbon concentrations ranged 1.1–3.6 mg/L, with the highest values consistently recorded at Dukhan (Site 6) and Salwa (Site 7), while the lowest were observed at RasImlaiji (Site 4) and RasRakan (Site 5). Although no numeric criteria for TOC were suggested under

Table 1: Spatiotemporal dynamics of physicochemical and heavy metal indicators across seven coastal stations in Qatar over May 2023 to April 2024

	Criteria	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
TOC (mg/L)	1. Sealine	1.8	1.9	1.7	1.8	2.7	2.2	1.9	2.0	1.3	1.6	1.7	1.9
	2. Doha Bay	2.1	2.2	2.1	2.6	2.9	2.2	2.2	2.1	1.7	1.3	2.2	2.3
	3. Al-Safiya	2.1	2.1	2.1	2.7	2.8	2.2	2.3	2.1	1.7	1.6	1.9	1.9
	4. RasImlajji	2.1	1.6	2.1	2.3	2.2	1.8	1.8	1.7	1.2	1.1	1.6	1.5
	5. RasRakan	1.8	1.7	1.5	1.6	2.2	1.7	1.7	1.6	1.6	1.1	1.6	2.1
	6. Dukhan	2.7	2.8	2.5	3.0	3.1	2.9	2.9	3.0	2.4	2.0	2.4	2.5
	7. Salwa	2.9	2.8	2.7	3.1	3.6	3.1	3.3	3.1	2.3	2.4	2.7	3.0
Oil-grease (µg/L)	1. Sealine	0.5	0.5	1.5	0.5	0.6	0.5	0.5	15.5	0.5	0.5	0.5	0.5
	2. Doha Bay	0.5	0.5	1.7	2.7	0.5	2.7	2.7	3.2	0.5	0.5	0.5	0.5
	3. Al-Safiya	0.5	0.5	0.9	0.5	1.0	0.5	0.5	23.4	0.5	0.5	0.5	0.5
	4. RasImlajji	0.8	0.5	0.5	0.5	1.5	0.5	0.8	1.2	0.5	3.7	0.5	2.7
	5. RasRakan	0.5	0.5	0.5	0.5	0.5	0.5	0.5	2.7	0.5	0.5	0.5	0.8
	6. Dukhan	0.5	0.9	0.5	0.5	1.8	0.5	0.5	0.5	0.5	0.5	0.5	13.3
	7. Salwa	0.5	0.5	0.5	0.5	1.0	0.5	0.5	11.0	0.5	4.8	0.5	0.5
Chlorophyll-a (µg/L)	1. Sealine	0.7	0.6	0.7	0.6	0.7	1.7	0.3	0.8	0.8	0.1	0.3	0.4
	2. Doha Bay	1.0	1.0	1.3	0.8	1.1	1.3	0.3	1.1	1.0	1.2	0.9	1.5
	3. Al-Safiya	0.7	1.8	1.2	1.2	4.1	1.4	0.1	1.3	1.7	0.3	0.9	1.2
	4. RasImlajji	1.9	1.6	1.9	1.8	2.4	1.3	0.1	0.9	0.6	0.7	0.5	0.7
	5. RasRakan	0.2	0.6	0.2	0.1	0.3	0.3	0.3	0.3	0.4	0.4	0.5	0.3
	6. Dukhan	0.1	0.3	0.2	0.3	2.1	1.1	0.3	1.4	0.2	0.3	0.3	0.3
	7. Salwa	0.7	0.6	0.5	0.5	3.5	0.6	0.0	0.6	0.7	0.1	0.8	0.2

PO ₄ (µg/L)	1. Sealine	1.9	2.9	0.8	3.2	0.0	1.0	2.0	1.4	1.7	2.0	1.9	2.3
	2. Doha Bay	2.5	2.9	0.8	11.3	0.0	3.5	3.2	2.4	2.1	1.6	6.0	2.1
	3. Al-Safliya	3.0	1.0	0.8	7.6	0.0	1.7	3.5	1.6	2.3	3.3	3.0	1.0
	4. RasImlaiji	2.6	1.7	0.8	8.7	0.0	1.0	2.4	3.9	3.4	3.7	5.6	5.1
	5. RasRakan	2.4	1.7	0.8	4.3	0.0	4.6	3.9	2.8	2.6	1.6	3.4	3.0
	6. Dukhan	3.4	2.8	0.8	7.6	0.0	2.5	3.5	2.4	1.6	2.9	3.8	4.3
	7. Salwa	2.5	1.9	0.8	5.0	0.0	1.7	2.8	3.2	3.4	2.4	4.3	3.8
SiO ₂ (µg/L)	1. Sealine	8.5	75.4	147.0	72.6	30.8	102.7	60.1	72.7	42.4	38.6	20.7	10.7
	2. Doha Bay	135.9	404.1	599.0	650.1	695.1	314.1	381.4	232.1	98.6	137.4	401.4	142.5
	3. Al-Safliya	129.8	267.3	176.0	130.1	209.5	72.1	108.7	129.4	90.5	39.3	122.3	25.6
	4. RasImlaiji	46.2	41.6	85.0	27.6	24.8	47.4	52.7	85.4	19.3	34.6	34.2	30.6
	5. RasRakan	61.3	22.3	99.0	30.0	62.0	54.1	64.1	35.1	38.0	25.5	30.4	58.1
	6. Dukhan	67.6	91.6	378.0	300.8	262.0	143.1	41.4	54.1	44.3	50.5	14.8	60.6
	7. Salwa	30.4	56.0	230.0	193.3	274.5	291.4	246.1	116.7	34.9	52.4	51.0	28.1
NO ₂ (µg/L)	1. Sealine	3.0	7.9	2.5	3.2	1.9	4.1	2.7	0.7	3.0	0.0	2.5	3.3
	2. Doha Bay	1.0	1.7	5.0	2.9	2.3	2.9	3.1	4.9	1.1	0.0	2.7	2.2
	3. Al-Safliya	0.7	0.9	6.0	1.7	2.8	3.6	0.7	1.3	2.7	0.0	1.0	1.5
	4. RasImlaiji	2.5	1.4	4.0	2.4	1.1	2.5	1.2	1.8	1.0	0.0	1.2	1.4
	5. RasRakan	3.6	0.9	6.0	2.6	1.8	3.9	1.6	2.0	2.2	0.0	1.0	5.4
	6. Dukhan	0.7	1.6	3.0	2.0	1.4	3.2	1.2	1.6	5.3	0.0	1.0	6.2
	7. Salwa	4.8	0.8	5.0	1.6	1.0	3.1	2.6	2.0	2.2	0.0	0.7	1.6

NO ₃ (µg/L)	1. Sealine	12.3	9.4	7.0	10.6	7.0	1.9	8.6	6.8	7.9	17.8	1.4	1.0
	2. Doha Bay	6.5	11.2	37.0	35.0	36.0	53.8	40.1	20.1	6.0	18.7	77.2	13.7
	3. Al-Safiya	10.6	2.2	6.5	1.9	6.2	10.5	7.7	6.4	5.0	5.9	3.4	1.0
	4. RasImlajji	5.1	4.1	7.4	5.1	1.7	6.1	5.0	19.2	5.2	3.9	3.7	2.0
	5. RasRakan	26.3	2.0	22.8	26.2	19.9	36.2	17.0	14.8	4.4	5.4	1.0	6.8
	6. Dukhan	5.7	4.4	4.8	6.0	3.8	3.4	3.0	7.7	1.7	5.9	1.0	5.9
	7. Salwa	4.4	2.6	8.1	6.5	5.2	3.2	13.6	11.8	4.0	12.0	11.1	4.7
NH ₄ (µg/L)	1. Sealine	9.0	8.0	8.0	4.0	4.0	7.0	5.0	6.0	8.0	9.0	6.0	9.0
	2. Doha Bay	11.0	7.0	8.0	4.0	6.0	5.0	5.0	5.0	7.0	6.0	5.0	8.0
	3. Al-Safiya	12.0	7.0	6.0	7.0	7.0	8.0	7.0	4.0	10.0	6.0	8.0	9.0
	4. RasImlajji	5.0	7.0	4.0	7.0	6.0	3.0	7.0	7.0	11.0	7.0	9.0	10.0
	5. RasRakan	5.5	7.0	7.0	6.0	3.0	6.0	5.0	8.0	7.7	8.0	8.0	7.0
	6. Dukhan	7.0	4.0	6.0	6.0	7.0	8.0	5.0	6.0	3.0	7.0	8.0	7.0
	7. Salwa	7.0	7.0	4.0	5.0	9.0	4.0	7.0	8.0	5.0	5.0	12.0	8.0
Ni (µg/L)	1. Sealine	1.1	1.3	1.3	1.2	1.0	1.0	1.0	1.3	1.3	0.9	0.4	0.9
	2. Doha Bay	1.1	1.4	1.2	1.3	1.1	1.2	1.2	1.5	1.3	0.9	0.4	2.3
	3. Al-Safiya	1.1	1.2	0.8	1.4	1.0	1.1	1.1	1.6	1.4	0.9	0.4	1.0
	4. RasImlajji	1.0	0.1	0.7	1.4	1.0	1.1	1.1	1.8	1.2	1.0	0.4	0.7
	5. RasRakan	1.1	0.7	0.7	1.5	1.0	1.1	1.1	1.8	0.7	1.0	0.4	0.6
	6. Dukhan	1.4	1.4	0.8	1.7	1.0	1.2	1.2	2.1	1.6	1.1	0.5	0.7
	7. Salwa	1.8	1.8	0.7	1.7	1.0	1.1	1.3	2.3	1.6	1.1	0.5	0.9

Fe (µg/L)	1. Sealine	4.0	3.9	4.0	4.4	3.2	3.5	3.7	3.1	3.7	3.9	3.8	3.5
	2. Doha Bay	3.7	3.9	4.1	4.4	3.5	4.1	3.9	3.2	3.8	4.1	4.4	4.9
	3. Al-Safiya	3.6	3.7	4.1	4.3	2.8	3.8	3.7	3.2	3.8	4.0	4.1	3.5
	4. RasImlajji	3.0	0.7	3.9	4.1	3.3	3.8	3.7	3.1	3.7	4.3	3.9	3.6
	5. RasRakan	4.0	3.3	4.0	4.4	4.1	3.6	3.7	3.1	3.8	4.0	3.8	3.6
	6. Dukhan	3.5	3.8	4.3	5.0	2.2	3.7	3.6	3.2	3.9	4.2	4.2	4.0
	7. Salwa	4.0	3.9	4.2	4.7	3.5	3.6	3.6	3.2	4.0	3.9	4.1	4.1
Cu (µg/L)	1. Sealine	1.2	1.1	1.3	1.4	1.2	1.4	1.6	1.3	0.8	1.3	1.1	1.3
	2. Doha Bay	0.7	1.0	1.1	1.4	1.8	1.8	1.0	1.4	0.9	1.3	1.3	3.4
	3. Al-Safiya	0.6	1.0	1.0	1.5	2.0	2.2	1.0	1.6	0.9	1.3	1.3	1.6
	4. RasImlajji	1.2	0.0	1.0	1.6	2.1	2.4	1.1	1.7	1.0	1.5	1.4	1.3
	5. RasRakan	1.6	1.1	1.3	1.7	2.3	2.2	1.2	1.9	1.3	1.4	1.4	1.0
	6. Dukhan	0.7	1.2	1.0	2.1	3.0	2.5	1.3	2.3	1.0	1.6	1.6	1.4
	7. Salwa	0.9	1.4	1.0	2.0	3.4	3.0	1.5	2.7	1.0	1.6	1.7	1.7
Pb (µg/L)	1. Sealine	0.1	1.8	0.2	0.4	0.1	0.1	0.2	0.4	0.7	0.6	0.1	0.3
	2. Doha Bay	0.0	0.7	2.5	0.1	0.5	0.1	0.3	0.0	0.7	0.0	0.1	1.0
	3. Al-Safiya	0.0	2.3	0.4	3.7	0.1	0.1	0.1	0.0	0.7	0.0	0.1	0.2
	4. RasImlajji	0.9	0.7	1.3	1.3	0.2	0.1	1.2	0.0	0.7	6.2	0.1	0.0
	5. RasRakan	1.3	2.1	2.9	0.1	0.1	0.1	0.4	0.3	0.8	0.0	0.3	1.9
	6. Dukhan	0.1	1.9	0.0	0.6	0.0	0.1	0.1	0.0	0.7	0.1	0.1	0.0
	7. Salwa	0.0	2.2	4.9	1.2	0.1	0.1	0.1	0.0	0.7	0.0	0.1	0.1

V (µg/L)	1. Sealine	1.7	1.9	1.5	1.9	1.4	1.4	1.3	1.2	2.4	1.8	1.3	1.4
	2. Doha Bay	2.3	1.8	1.7	1.8	1.4	1.5	1.3	1.2	2.1	1.9	1.6	1.8
	3. Al-Safiya	2.2	1.8	2.4	1.8	1.3	1.3	1.4	1.2	2.0	1.9	1.6	1.7
	4. RasImlajji	1.5	0.5	2.6	1.8	1.2	1.4	1.3	1.2	1.5	1.8	1.6	1.7
	5. RasRakan	1.9	1.6	2.8	2.0	1.3	1.4	1.2	1.2	1.7	1.9	1.6	1.7
	6. Dukhan	1.7	1.8	2.7	2.2	1.2	1.5	1.1	1.2	1.9	2.1	1.7	1.8
	7. Salwa	1.4	1.9	2.7	2.1	1.2	1.3	1.0	1.2	1.5	1.9	1.6	1.8
As (µg/L)	1. Sealine	1.9	1.9	2.0	2.2	1.5	1.6	1.9	1.2	3.1	2.1	2.0	4.5
	2. Doha Bay	3.0	2.1	2.2	2.2	1.3	1.8	1.8	1.4	2.7	2.0	2.1	4.3
	3. Al-Safiya	2.9	2.2	3.3	2.2	1.3	1.6	1.9	1.3	2.7	2.0	2.1	3.3
	4. RasImlajji	1.9	0.6	3.5	2.1	1.2	1.6	1.7	1.3	2.2	2.0	2.1	3.7
	5. RasRakan	2.4	2.5	3.7	2.2	1.3	2.3	1.5	1.2	2.5	2.0	2.2	3.3
	6. Dukhan	2.8	2.1	3.8	2.4	1.1	2.3	1.4	1.0	2.7	2.1	2.4	3.3
	7. Salwa	2.4	2.2	3.8	2.2	1.1	1.4	1.3	1.0	2.3	2.1	2.3	2.8
Cr (µg/L)	1. Sealine	0.2	0.4	0.6	0.3	0.2	0.2	0.3	0.4	0.4	0.3	0.2	1.1
	2. Doha Bay	0.6	0.4	0.6	0.3	0.2	0.2	0.2	0.4	0.4	0.3	0.3	0.4
	3. Al-Safiya	0.6	0.4	0.7	0.3	0.2	0.2	0.3	0.4	0.3	0.3	0.3	0.5
	4. RasImlajji	0.4	0.4	0.8	0.3	0.2	0.2	0.2	0.4	0.2	0.2	0.3	0.8
	5. RasRakan	0.5	0.4	0.8	0.3	0.2	0.3	0.2	0.4	0.4	0.2	0.3	0.6
	6. Dukhan	0.2	0.4	0.7	0.3	0.2	0.3	0.2	0.4	0.3	0.2	0.3	0.4
	7. Salwa	0.1	0.4	0.7	0.3	0.2	0.2	0.2	0.4	0.1	0.2	0.3	0.2

Zn (µg/L)	1. Sealine	7.8	1.4	2.6	3.9	2.7	1.5	7.9	0.9	16.7	7.7	1.3	5.8
	2. Doha Bay	7.8	5.4	2.6	1.7	2.8	2.0	2.8	0.9	2.1	7.7	1.3	33.8
	3. Al-Safiya	7.8	5.6	2.6	1.3	2.9	2.2	1.4	0.9	2.6	7.7	1.3	23.3
	4. RasImlajji	3.3	6.1	2.6	1.4	3.2	2.2	0.2	0.9	1.7	7.7	1.3	8.5
	5. RasRakan	3.2	5.6	2.6	1.2	3.2	1.8	0.2	0.9	5.7	7.7	1.3	8.0
	6. Dukhan	7.8	5.8	2.6	1.7	1.9	1.8	0.2	0.9	1.2	7.7	1.3	1.7
	7. Salwa	7.8	5.1	2.6	1.3	2.4	1.0	0.2	0.9	1.7	7.7	1.3	1.7
Mn (µg/L)	1. Sealine	0.5	0.4	0.0	0.8	0.7	0.4	0.7	0.0	2.3	1.2	0.4	0.1
	2. Doha Bay	0.5	0.4	0.3	2.9	2.1	1.4	2.1	0.2	2.3	1.2	0.4	0.1
	3. Al-Safiya	0.5	0.4	0.1	0.7	1.7	0.6	1.1	0.0	2.3	1.2	0.4	0.1
	4. RasImlajji	0.5	0.4	0.0	1.1	0.6	0.4	0.8	0.0	2.3	1.2	0.4	0.1
	5. RasRakan	0.6	0.4	0.0	1.5	0.6	0.4	0.6	0.0	2.3	1.2	0.4	0.1
	6. Dukhan	0.5	0.4	0.0	2.0	1.0	0.7	0.5	0.0	2.3	1.2	0.4	0.1
	7. Salwa	0.5	0.4	0.0	1.1	0.7	0.7	0.8	0.0	2.3	1.2	0.4	0.1
Mo (µg/L)	1. Sealine	12.4	13.9	13.4	13.8	10.7	11.3	14.7	10.2	11.0	12.8	11.3	11.5
	2. Doha Bay	10.9	12.2	12.7	13.2	11.0	12.7	17.3	10.5	11.1	13.2	12.7	14.2
	3. Al-Safiya	10.4	11.4	11.8	13.7	10.0	11.7	14.4	10.5	11.6	13.1	11.9	11.1
	4. RasImlajji	8.9	0.2	11.3	13.6	10.4	12.1	15.2	10.4	11.1	13.9	11.4	10.8
	5. RasRakan	10.9	7.2	11.5	14.2	10.6	12.3	18.1	10.3	11.7	13.2	11.4	10.6
	6. Dukhan	10.6	13.2	12.7	16.9	11.2	13.3	24.4	11.0	11.7	14.3	12.3	11.3
	7. Salwa	11.8	15.8	12.6	16.2	11.3	13.0	28.4	11.0	13.2	13.8	12.2	11.7

1. Sealine	452	135.3	11.2	35.4	51.5	113.6	145.6	17.5	9.1	63.6	48.8	490
2. Doha Bay	45.8	63.5	10.7	32.7	47.1	58.6	73.0	15.2	9.1	38.2	64.3	112.8
3. Al-Safliya	43.4	58.7	18.2	27.2	64.7	53.5	3.5	16.8	9.1	46.1	115.2	48.7
4. RasImlajji	34.7	9.4	15.0	88.5	25.8	39.4	3.5	14.4	9.1	46.1	26.5	37.3
5. RasRakan	36.9	46.2	12.3	51.8	37.1	73.7	3.5	14.5	9.1	46.6	32.2	40.0
6. Dukhan	44.0	65.0	23.0	35.4	30.8	62.1	3.5	10.8	9.1	47.2	32.2	33.1
7. Salwa	49.4	80.2	14.4	25.9	21.4	43.4	3.5	10.2	9.1	44.8	76.8	53.1
1. Sealine	0.4	2.0	0.9	0.6	0.2	0.3	1.2	0.6	1.0	0.8	0.8	0.3
2. Doha Bay	0.4	2.0	0.9	0.6	0.2	0.3	1.2	0.6	1.0	0.8	0.8	0.3
3. Al-Safliya	0.4	2.0	0.9	0.6	0.2	0.3	1.2	0.6	1.0	0.8	0.8	0.3
4. RasImlajji	0.4	2.0	0.9	0.6	0.2	0.3	1.2	0.6	1.0	0.8	0.8	0.3
5. RasRakan	0.4	2.0	0.9	0.6	0.2	0.3	1.2	0.6	1.0	0.8	0.8	0.3
6. Dukhan	0.4	2.0	0.9	0.6	0.2	0.3	1.2	0.6	1.0	0.8	0.8	0.3
7. Salwa	0.4	2.0	0.9	0.6	0.2	0.3	1.2	0.6	1.0	0.8	0.8	0.3

USEPA, WHO, or the Ministry of Environment and Climate Change, Doha, guidelines, these values fall within typical coastal ranges and were not considered directly regulated (Table 2). Strong positive correlations were found between Dukhan and Salwa ($p = 0.84$), while Sealine (Site 1) and RasRakan (Site 5) showed moderate correlation ($r = 0.62$). Oil and grease levels were generally low but exhibited episodic spikes, particularly at Sealine (15.5 $\mu\text{g/L}$ in December), Al-Safliya (23.4 $\mu\text{g/L}$ in December), Dukhan (13.3 $\mu\text{g/L}$ in April), and Salwa (11.0 $\mu\text{g/L}$ in November; Table 1). While these values are far below Qatar's discharge limit of 10 mg/L (10,000 $\mu\text{g/L}$), they may warrant attention under USEPA and WHO narrative criteria; although no visible sheen was observed, inter-site correlation ($p = 0.28$) suggests localised inputs (Table 2).

Chlorophyll-a concentrations peaked at Al-Safliya (4.1 $\mu\text{g/L}$ in September) and Salwa (3.5 $\mu\text{g/L}$ in September) and were positively correlated with TOC ($p = 0.71$) to suggest a coupling effect between organic matter and phytoplankton biomass (Table 1). Although no numeric thresholds were set by USEPA, WHO, or the Ministry of Environment and Climate Change of Qatar, elevated chlorophyll-a was widely recognised as a proxy for eutrophication risk (Table 2). Nutrient enrichment was most pronounced in Doha Bay (Site 2), where phosphate reached 11.3 $\mu\text{g/L}$ in August and nitrate peaked at 77.2 $\mu\text{g/L}$ in March (Table 1). Both USEPA and Qatar guidelines stipulate that nutrient levels should not cause algal blooms or oxygen depletion, although no numeric thresholds exist. The observed values, particularly in Doha Bay, indicate enrichment well above background conditions and were thought to exceed ecological thresholds for bloom risk (Table 2).

Industrial sites (3, 4, 6) showed strong inter-correlation for nutrients ($p = 0.76$), while reference sites (5, 7) correlated negatively with industrial sites ($p = -0.48$). Trace metals such as nickel, iron, copper, lead, and zinc were generally stable across sites, although Doha Bay and Dukhan exhibited higher variability

Table 2: Compliance assessment of marine water quality parameters with USEPA, WHO, and Qatar guidelines

Parameter	Observed Range	USEPA Guideline (Marine)	WHO Guideline (Marine/Recreational)	Qatar Guideline (Marine)	Compliance Notes
TOC	1.1–3.6 mg/L	No numeric criterion	No numeric criterion	No numeric criterion	Typical coastal values; not regulated directly
Oil & Grease	0.5–23.4 µg/L	No visible sheen	Should not be visible	≤ 10 mg/L (10,000 µg/L)	Spikes (11–23 µg/L) may cause sheen
Chlorophyll-a	0.0–4.1 µg/L	No numeric criterion	No numeric criterion	No numeric criterion	Elevated at Al-Safliya and Salwa
PO ₄	0.0–11.3 µg/L	Not cause blooms	No numeric criterion	Must not cause blooms	Doha Bay (11.3 µg/L) enriched
NO ₃	1.0–77.2 µg/L	Not cause blooms	No numeric criterion	Must not cause blooms	Doha Bay (77.2 µg/L) exceeds thresholds
NO ₂	0.0–7.9 µg/L	No numeric criterion	No numeric criterion	Must not cause blooms	Within expected ranges
NH ₄	3–12 µg/L	No numeric criterion	No numeric criterion	Must not cause blooms	Elevated but within natural variability
SiO ₂	8.5–695 µg/L	No numeric criterion	No numeric criterion	No numeric criterion	Doha Bay extremely high (695 µg/L)
Cu	0.6–3.4 µg/L	3.1 (chronic), 4.8 (acute)	No numeric criterion	≤ background, no harm	Doha Bay (3.4 µg/L) slightly exceeds USEPA chronic
Pb	0.0–6.2 µg/L	8.1 (chronic), 210 (acute)	≤10 µg/L (drinking water)	≤ background	Ras Imlajji spike (6.2 µg/L) near WHO
Zn	0.9–33.8 µg/L	81 (chronic), 90 (acute)	No numeric criterion	≤ background	Doha Bay (33.8 µg/L) enriched
Ni	0.1–2.3 µg/L	8.2 (chronic), 74 (acute)	No numeric criterion	≤ background	All values within safe range
As	1.0–4.5 µg/L	36 µg/L	≤10 µg/L (drinking water)	≤ background	All values below WHO guideline
Fe	2.2–5.0 µg/L	No numeric criterion	No numeric criterion	≤ background	Within natural variability
Al	3.5–145.6 µg/L	No numeric criterion	No numeric criterion	≤ background	Elevated at Sealine (135 µg/L)
V	0.5–2.7 µg/L	No numeric criterion	No numeric criterion	≤ background	Within expected ranges
Mo	0.2–28.4 µg/L	No numeric criterion	No numeric criterion	≤ background	Salwa (28.4 µg/L) enriched

Note: USEPA guidelines for marine water followed USEPA (2012) and Duggan and Kotalik (2020); WHO recreational water quality guidelines followed WHO (2021) and Leonard and Eaton (2021); Qatari water quality criteria followed the environmental recommendations outlined in Law 32 as discussed by Lisiyani and Said (2018) and Ajjur and Al-Ghamdi (2022)

Source: Adapted from USEPA (2012), WHO (2021), Leonard and Eaton (2021), Lisiyani and Said (2018), and Ajjur and Al-Ghamdi (2022)

(Table 1). For copper, observed values ranged from 0.6 µg/L to 3.4 µg/L, with the upper end slightly exceeding the USEPA chronic criterion of 3.1 µg/L (though still below the acute limit of 4.8 µg/L). Lead concentrations (0.0–6.2 µg/L) remained below the USEPA chronic criterion of 8.1 µg/L and the WHO guideline of 10 µg/L, despite the threshold-approaching concentrations observed in RasImlaiji. Zinc ranged 0.9–33.8 µg/L, below the USEPA chronic limit of 81 µg/L but was enriched at Doha Bay. Nickel (0.1–2.3 µg/L) and arsenic (1.0–4.5 µg/L) were well below the respective chronic thresholds (USEPA Ni = 8.2 µg/L; WHO As = 10 µg/L). Iron (2.2–5.0 µg/L), aluminium (3.5–145.6 µg/L), vanadium (0.5–2.7 µg/L), and molybdenum (0.2–28.4 µg/L) showed variability but remained unregulated by numeric criteria, with Qatar requiring only that levels not exceed the natural background (Table 2). Industrial sites showed positive correlations for metals ($p = 0.58–0.70$), while reference sites showed strong internal correlation ($p = 0.82$).

Specific Observations

Seasonal patterns were evident across the dataset (Table 1). During summer (June–September), elevated TOC, phosphate, silica, and chlorophyll-a were observed, particularly at Dukhan and Salwa, with strong correlations between TOC and chlorophyll-a ($r = 0.74$) and between phosphate and silica ($p = 0.69$). These values did not breach numeric thresholds but indicated seasonal risks of eutrophication (Table 2). Autumn (October–November) was characterised by stable metal concentrations across sites, with inter-site correlations ranging from $r = 0.65–0.75$. All measured metals remained below USEPA chronic thresholds during this period (Table 2). Winter (December–February) showed pronounced nutrient spikes, especially for nitrate at Doha Bay (77.2 µg/L in March) and RasImlaiji (19.2 µg/L in December) (Table 1). These values exceed ecological thresholds for bloom risk under USEPA and Qatar narrative criteria, although no numeric limits exist (Table 2). Strong correlation between these two sites ($p = 0.81$) suggests shared nutrient

sources. Spring (March–May) represented a transitional period with moderate nutrient and metal values, and weaker correlations across sites ($p = 0.42–0.55$), reflecting variability in productivity and runoff.

When grouped by anthropogenic relevance, industrial sites (Al-Safliya, RasImlaiji, Dukhan) exhibited consistently elevated nutrient and metal concentrations (Table 1). Nutrients such as phosphate, nitrate, and ammonium were strongly correlated among these sites ($p = 0.72–0.85$), while trace metals including copper, zinc, and lead also showed positive correlations ($p = 0.66$). Interestingly, copper at Doha Bay slightly exceeded the USEPA chronic limit of 3.1 µg/L, and zinc was also enriched in the same location (33.8 µg/L) at concentrations that approached one-third of the chronic threshold (81 µg/L) (Table 2). Episodic oil and grease spikes at Al-Safliya and Dukhan, although well below Qatar's 10 mg/L limit, may warrant attention under the USEPA and WHO narrative criteria (Table 2). Residential sites (Sealine and Doha Bay) displayed moderate correlations ($p = 0.58$) with TOC values. However, nutrient enrichment in Doha Bay, particularly phosphate (11.3 µg/L) and nitrate (77.2 µg/L), was thought to exceed ecological thresholds for bloom risk, as reflected in the weaker correlation with Sealine ($p = 0.46$). Chlorophyll-a showed moderate correlation between the two sites ($p = 0.55$), reflecting shared seasonal productivity cycles (Table 1; Table 2). Reference sites (RasRakan and Salwa) exhibited lower and more stable values across most parameters, with strong internal correlation ($p = 0.88–0.90$). All measured metals and nutrients remained within USEPA, WHO, and Qatar safe ranges, underscoring their role as background controls (Table 2). Seasonal fluctuations were present but less pronounced, indicating stable baseline conditions.

Cross-category comparisons further highlighted the pollution gradient across the coastal waters of Qatar. Industrial and reference sites produced negative correlations for nutrients and metals ($p = -0.45$ to -0.60), underscoring

the contrast between impacted and background conditions. Residential and industrial sites exhibited moderate positive correlations for TOC and chlorophyll-a ($p = 0.55\text{--}0.65$), reflecting shared productivity drivers, while residential and reference sites showed weak correlations ($p = 0.30\text{--}0.45$), indicating divergence due to nutrient enrichment in residential areas. Overall, Pearson's correlation analysis revealed strong clustering of industrial sites ($p > 0.70$), high stability of reference sites ($p \approx 0.88$), and moderate similarity among residential sites ($p \approx 0.50\text{--}0.60$).

Compared with international and national guidelines (Table 2) and supported by Bayesian change-point analysis, the results indicate that although most parameters are within regulatory thresholds, Doha Bay experienced localised exceedances of copper levels, occasional spikes in oil and grease, and nutrient enrichment. These incidents are key concerns for compliance with USEPA, WHO, and MECC (Qatar). Seasonal dynamics further accentuate these patterns. Summer was marked by elevated TOC and chlorophyll-a, reflecting enhanced primary productivity, while winter exhibited abrupt nutrient surges, particularly nitrate, confirmed as significant change-points with high posterior probabilities. These seasonal peaks, superimposed on localised anthropogenic pressures, highlight the dual influences of natural variability and human activities towards coastal water quality in Qatar. Together, the findings emphasise the importance of continued monitoring at sites where one or more parameters approached regulatory or ecological guideline values, particularly Doha Bay, Al Safliya, and Ras Imlaiji, where compliance concerns were considered most acute.

Indicators of Enrichment or Pollution

Nutrient stoichiometry further clarified the seasonal and spatial dynamics of enrichment across the coastal waters of Qatar (Table 3). Ratios of dissolved inorganic nitrogen to phosphate (DIN:PO₄) frequently exceeded the canonical Redfield ratio of 16:1, particularly

during summer and winter months. These ratios indicated phosphorus limitation in several locations. For example, RasRakan exhibited extremely elevated DIN:PO₄ ratios in August (232.6) and September (Redfield = 174.5), while Doha Bay and Al-Safliya showed episodic peaks of Redfield > 90 during July. These reflect disproportionate nitrogen loading relative to phosphate availability in the seawater. Conversely, lower ratios at Dukhan (7.1 in August) and Doha Bay (6.1 in August) suggest transient nitrogen limitation during periods of high phosphate input.

The dissolved inorganic nitrogen-to-silica (DIN:SiO₂) ratios showed complementary patterns and were generally low at most sites (Table 3). This observation indicated silica sufficiency relative to nitrogen, but episodic elevations were observed at Sealine (4.78 in April) and RasImlaiji (2.29 in April), suggesting the influence of localised nitrogen dominance that could favour non-diatom phytoplankton. Doha Bay consistently exhibited very low DIN:SiO₂ ratios (< 0.5 across most months), highlighting silica limitation as unlikely in this semi-enclosed basin. In contrast, RasRakan and Salwa displayed moderate ratios (0.7–1.9), reflecting more balanced nutrient conditions. Together, the stoichiometric evidence underscores the heterogeneity of nutrient limitation regimes across the coast. Industrial and semi-urban sites (Doha Bay, Al-Safliya, and RasImlaiji) were characterised by episodic nitrogen surpluses relative to phosphate. In contrast, reference sites (RasRakan and Salwa) maintained more stable but seasonally variable ratios. These findings align with the observed nutrient concentration patterns and reinforce the conclusion that eutrophication risk was driven not only by absolute nutrient levels but also by imbalances in nutrient ratios that promoted algal blooms during the warmer months of summer (June–September).

Beyond absolute concentrations, the application of EF and Igeo provided additional insights into the degree of anthropogenic influence on trace metals across the coastal waters of Qatar (Table 4; Table 5). Overall, EF

values for most metals remained close to 1, indicating predominantly natural origin, with only minor to moderate enrichment observed at selected sites and months. Nickel, copper, and zinc displayed episodic EF values above 1.5, particularly at Doha Bay, Dukhan, and Al-Safliya, suggesting localised anthropogenic inputs. In addition, copper enrichment at Doha Bay in April (EF = 2.3) and zinc enrichment at Al-Safliya in November (EF = 7.0) point to transient but notable contamination events. Lead also showed sporadic moderate enrichment at RasImlaiji and Al-Safliya which was thought to be consistent with localised industrial or urban discharges. In contrast, selenium and iron consistently exhibited EF $\approx$ 1 across all sites, underscoring their lithogenic control from natural rocks due to weathering or soil erosion, rather than pollution. The Igeo results corroborated these patterns, with most values falling within Class 0 (unpolluted) or Class 1 (unpolluted to moderately polluted) (Table 5).

Slightly positive Igeo values for nickel, copper, and zinc were recorded at Doha Bay, Dukhan, and Al-Safliya, aligning with the EF evidence of localised enrichment. Notably, Igeo values for lead at RasImlaiji in February (Igeo = 1.58) and for Arsenic at Sealine in April (Igeo = 0.58) indicated minor to moderate pollution episodes. However, most metals, including iron, manganese, molybdenum, aluminium, and selenium, remained consistently negative or near zero, confirming their dominance by natural background processes. Taken together, the EF and Igeo analyses reinforce the spatial gradient already evident in the raw metal concentrations detected in waters adjacent to industrial and semi-urban sites (Doha Bay, Al-Safliya, RasImlaiji, and Dukhan). These locations exhibit the clearest signatures of anthropogenic enrichment, while reference sites (RasRakan and Salwa) remain stable and unpolluted. These indices highlight the importance of coupling absolute concentration data with relative contamination metrics for better detection of subtle anthropogenic signals in monitoring the coastal waters of Qatar, especially when applied to develop guidelines for alga bloom risk.

Table 3: Ratio of dissolved inorganic nitrogen against orthophosphate and silica in the waters of Qatar from May 2023 to April 2024

Criteria	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
Sealine	20.0	17.4	45.0	13.8	10.4	64.5	27.1	22.7	35.6	26.7	28.0	35.8
Doha Bay	11.9	13.5	131.3	6.1	4.6	34.6	24.7	33.6	20.9	37.0	6.3	45.5
Al-Safliya	13.0	23.0	92.5	8.0	6.0	61.2	18.6	35.6	12.1	7.0	15.3	65.0
Ras Imlaiji	13.8	19.4	71.3	73.6	55.2	64.0	24.6	41.5	16.5	9.2	8.4	13.7
Ras Rakan	32.9	11.2	116.3	232.6	174.5	31.7	24.0	43.1	17.7	10.6	10.0	31.3
Dukhan	10.0	9.3	58.8	7.1	5.3	32.8	15.4	32.9	7.0	11.3	14.7	25.3
Salwa	21.2	18.9	73.8	11.8	8.9	45.3	28.4	31.9	16.3	12.1	21.6	21.6
Sealine	2.86	0.43	0.15	0.39	0.69	0.42	0.57	0.28	0.9	0.88	1.65	4.78
Doha Bay	0.14	0.06	0.11	0.07	0.06	0.24	0.13	0.22	0.28	0.28	0.06	0.42
Al-Safliya	0.3	0.09	0.42	0.47	0.3	0.14	0.36	0.44	0.43	0.17	0.38	0.25
Ras Imlaiji	0.28	0.27	0.67	0.23	0.11	0.4	0.37	0.57	0.56	0.99	1.38	2.29
Ras Rakan	0.77	0.34	0.94	1	0.71	1.35	1.49	1.92	1.2	0.56	1.12	1.62
Dukhan	0.53	0.29	0.07	0.11	0.14	0.57	1.3	1.08	0.4	0.29	0.95	1.08
Salwa	1.04	0.64	0.15	0.18	0.14	0.16	0.23	0.29	0.75	1.02	1.82	2.04

Note: DIN = Dissolved inorganic nitrogen, PO⁴ = Orthophosphate and SiO₂ = Silica oxide

Table 4: Enrichment factor for metals in surrounding waters of Qatar from May 2023 to April 2024

Criteria	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
Ni	Sealine	1.0	1.44*	1.86*	0.8	1.0	0.9	0.8	1.44*	0.9	1.0	1.5*
	Doha Bay	1.0	1.56*	1.71*	0.9	1.1	1.1	0.9	1.44*	0.9	1.0	3.8
	Al-Safiya	1.0	1.33*	1.1	0.9	1.0	1.0	0.9	1.56*	0.9	1.0	1.67*
	Ras Imlaiji	0.9	0.1	1.0	0.9	1.0	1.0	1.1	1.33*	1.0	1.0	1.17*
	Ras Rakan	1.0	0.8	1.0	1.0	1.0	1.0	1.1	0.8	1.0	1.0	1.0
	Dukhan	1.27*	1.56*	1.1	1.1	1.0	1.1	1.2	1.78*	1.1	1.3	1.2
	Salwa	1.64*	2^	1.0	1.1	1.0	1.18*	1.41*	1.78*	1.1*	1.25*	1.5*
Fe	Sealine	1.0	1.18*	1.0	1.0	0.8	1.0	1.0	1.0	1.0	1.0	1.0
	Doha Bay	0.9	1.18*	1.0	1.0	0.9	1.14*	1.05*	1.0	1.0	1.16*	1.36*
	Al-Safiya	0.9	1.1	1.0	1.0	0.7	1.1	1.1	1.0	1.0	1.1	1.0
	Ras Imlaiji	0.8	0.2	1.0	0.9	0.8	1.06*	1.05*	1.0	1.0	1.08*	1.0
	Ras Rakan	1.0	1.0	1.0	1.0	1.0	1.0	1.05*	1.0	1.0	1.0	1.0
	Dukhan	0.9	1.15*	1.08*	1.14*	0.6	1.0	1.0	1.0	1.05*	1.11*	1.11*
	Salwa	1*	1.18*	1.05*	1.07*	0.9	1.0	1.0	1.05*	1.0	1.08*	1.14*
Cu	Sealine	0.8	0.9	1.08*	0.9	0.5	0.6	1.33*	0.7	0.6	0.8	0.9
	Doha Bay	0.4	0.8	0.9	0.9	0.8	0.8	0.8	0.8	0.7	0.9	2.3
	Al-Safiya	0.4	0.8	0.8	1.0	0.9	1.0	0.8	0.9	0.7	0.9	1.07*
	Ras Imlaiji	0.8	0.0	0.8	1.07*	0.9	1.09*	0.9	0.9	0.8	1.07*	1.0
	Ras Rakan	1.0	0.9	1.08*	1.13*	1.0	1.0	1.0	1.06*	1.0	1.0	0.7
	Dukhan	0.4	1.0	0.8	1.4*	1.3*	1.14*	1.08*	1.28*	0.8	1.14*	0.9
	Salwa	0.6	1.17*	0.8	1.33*	1.48*	1.36*	1.25*	1.5*	0.8	1.21*	1.13*

Pb	Sealine	0.1	0.8	0.1	0.4	0.2	0.5	0.4	0.8	0.9	1.2*	0.3	0.1
	Doha Bay	0.0	0.3	1.0	0.1	1.0	0.1	0.6	0.0	0.9	0.0	0.3	0.5
	Al-Safiya	0.0	1.05*	0.2	3.3	1.0	0.1	0.2	0.0	0.9	0.0	0.3	0.1
	Ras Imlajji	0.7	0.3	0.5	1.15*	2.0	0.1	4.8	0.0	0.9	6.0	0.3	0.0
	Ras Rakan	1.0	1.0	1.2	0.1	1.0	0.1	1.6*	0.6	1.0	0.0	0.8	0.9
	Dukhan	0.1	0.9	0.0	0.5	0.0	0.1	0.4	0.0	0.9	0.1	0.3	0.0
	Salwa	0.0	1.0	2^	1.06*	1.0	0.1	0.4	0.0	0.9	0.0	0.3	0.1
	Sealine	0.9	1.1	0.8	1.0	1.17*	1.08*	1.18*	1.0	1.26*	1.0	0.9	0.8
V	Doha Bay	1.21*	1.0	0.9	1.0	1.17*	1.15*	1.18*	1.0	1.11*	1.0	1.07*	1.05*
	Al-Safiya	1.16*	1.0	1.26*	1.0	1.08*	1.0	1.27*	1.0	1.16*	1.0	1.07*	1.0
	Ras Imlajji	0.8	0.3	1.37*	1.0	1.0	1.08*	1.18*	1.0	1.0	1.0	1.07*	1.0
	Ras Rakan	1.0	0.9	1.47*	1.05*	1.08*	1.08*	1.09*	1.0	1.05*	1.0	1.07*	1.0
	Dukhan	0.9	1.0	1.42*	1.16*	1.0	1.15*	1.0	1.0	1.16*	1.11*	1.13*	1.06*
	Salwa	0.7	1.06*	1.42*	1.11*	1.0	1.0	0.9	1.0	1.0	1.11*	1.07*	1.06*
	Sealine	0.8	0.9	0.9	1.0	1.36*	1.23*	1.27*	1.0	1.35*	1.05*	0.9	1.61*
	Doha Bay	1.25*	1.0	1.0	1.0	1.18*	1.38*	1.2*	1.17*	1.18*	1.0	1.0	1.54*
As	Al-Safiya	1.21*	1.0	1.5*	1.0	1.18*	1.23*	1.27*	1.08*	1.18*	1.0	1.0	1.18*
	Ras Imlajji	0.8	0.3	1.59*	1.0	1.09*	1.23*	1.13*	1.08*	1.0	1.0	1.0	1.32*
	Ras Rakan	1.0	1.14*	1.68*	1.0	1.18*	1.77*	1.0	1.0	1.05*	1.0	1.0	1.18*
	Dukhan	1.17*	1.0	1.73*	1.09*	1.0	1.77*	0.9	0.8	1.18*	1.05*	1.09*	1.18*
	Salwa	1.0	1.0	1.73*	1.0	1.0	1.08*	0.9	0.8	1.0	1.05*	1.05*	1.0
	Sealine	0.8	0.9	0.9	1.0	1.36*	1.23*	1.27*	1.0	1.35*	1.05*	0.9	1.61*
	Doha Bay	1.25*	1.0	1.0	1.0	1.18*	1.38*	1.2*	1.17*	1.18*	1.0	1.0	1.54*
	Al-Safiya	1.21*	1.0	1.5*	1.0	1.18*	1.23*	1.27*	1.08*	1.18*	1.0	1.0	1.18*

Cr	Sealine	0.4	1.0	0.7	1.0	1.0	1.0	1.5	1.0	1.0	1.0	1.5*	0.7	2.75 [^]
	Doha Bay	1.2*	1.0	0.7	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.5*	1.0	1.0
	Al-Safiya	1.2*	1.0	0.8	1.0	1.0	1.0	1.0	1.0	0.8	1.5*	1.0	1.0	1.3
	Ras Imlajji	0.8	1.0	0.9	1.0	1.0	1.0	1.0	1.0	0.5	1.0	1.0	1.0	2.0
	Ras Rakan	1.0	1.0	1.0	1.0	1.0	1.5*	1.0	1.0	1.0	1.0	1.0	1.0	1.5
	Dukhan	0.4	1.0	0.8	1.0	1.0	1.5*	1.0	1.0	0.8	1.0	1.0	1.0	1.0
	Salwa	0.2	1.0	0.8	1.0	1.0	1.0	1.0	1.0	0.3	1.0	1.0	1.0	0.5
	Sealine	1.42*	0.3	1.0	3.12 [^]	1.0	1.07*	3 [^]	1.0	3.2 [^]	1.0	1.0	1.0	1.2*
	Doha Bay	1.42*	1.0	1.0	1.36*	1.0	1.43*	1.4*	1.0	0.6	1.0	1.0	1.0	2.97 [^]
	Al-Safiya	1.42*	1.1	1.0	1.0	1.0	1.57*	7.0	1.0	0.7	1.0	1.0	1.0	2.81 [^]
Zn	Ras Imlajji	0.6	1.1	1.0	1.1	1.1	1.57*	1.0	1.0	0.5	1.0	1.0	1.0	1.75*
	Ras Rakan	0.6	1.1	1.0	1.0	1.1	1.29*	1.0	1.0	1.54*	1.0	1.0	1.0	1.65*
	Dukhan	1.42*	1.1	1.0	1.36*	0.7	1.29*	1.0	1.0	0.3	1.0	1.0	1.0	0.4
	Salwa	1.42*	1.0	1.0	1.0	0.9	0.7	1.0	1.0	0.5	1.0	1.0	1.0	0.4
	Sealine	0.9	1.0	1.0	0.5	1.17*	1.0	1.17*	1.0	1.0	1.0	1.0	1.0	1.0
Mn	Doha Bay	0.9	1.0	1.0	1.93*	3.5 [^]	3.5 [^]	3.5 [^]	1.0	1.0	1.0	1.0	1.0	1.0
	Al-Safiya	0.9	1.0	1.0	0.5	2.83 [^]	1.5*	1.83*	1.0	1.0	1.0	1.0	1.0	1.0
	Ras Imlajji	0.9	1.0	1.0	0.7	1.67*	1.0	1.33*	1.0	1.0	1.0	1.0	1.0	1.0
	Ras Rakan	1.09*	1.0	1.0	1.36*	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	Dukhan	0.9	1.0	1.0	1.82*	1.67*	1.75*	0.8	1.0	1.0	1.0	1.0	1.0	1.0
Mo	Salwa	0.9	1.0	1.0	1.0	1.17*	1.75*	1.33*	1.0	1.0	1.0	1.0	1.0	1.0
	Sealine	1.1*	1.08*	1.05*	1.0	0.9	0.9	0.7	1.0	0.9	1.0	0.9	0.9	1.0
	Doha Bay	1.0	1.0	1.0	0.9	1.0	1.0	0.8	1.0	0.9	1.0	1.0	1.0	1.21*
	Al-Safiya	0.9	0.9	0.9	1.0	0.9	0.9	0.7	1.0	1.0	1.0	1.0	1.0	1.0
	Ras Imlajji	0.8	0.0	0.9	1.0	0.9	1.0	0.7	1.0	0.9	1.05*	0.9	0.9	0.9
	Ras Rakan	1.0	0.6	0.9	1.0	0.9	1.0	0.9	1.0	0.9	1.0	0.9	0.9	0.9
	Dukhan	0.9	1.0	1.0	1.2*	1.0	1.06*	1.17*	1.0	0.9	1.08*	1.0	1.0	1.0
	Salwa	1.07*	1.27*	1.0	1.15*	1.0	1.0	1.35*	1.0	1.09*	1.05*	1.06*	1.06*	1.0

Al	Sealine	1.06*	1.65*	0.9	1.09*	1.39*	2^	2.46^	1.15*	1.0	1.39*	0.8	0.9
	Doha Bay	1.05*	0.8	0.8	1.0	1.27*	1.0	1.23*	1.0	1.0	0.8	1.0	2.2
	Al-Safiya	1.0	0.7	1.4*	0.8	1.75*	0.9	0.1	1.1	1.0	1.0	1.83*	0.9
	Ras Imlajji	0.8	0.1	1.2	2.74^	0.7	0.7	0.1	0.9	1.0	1.0	0.4	0.7
	Ras Rakan	1.0	1.0	1.0	1.7*	1.21*	1.5*	0.1	1.0	1.0	1.0	0.5	0.8
	Dukhan	1.19*	1.41*	1.87*	1.16*	1.0	1.27*	0.1	0.7	1.0	1.0	0.5	0.6
	Salwa	1.34*	1.73*	1.17*	0.8	0.7	0.9	0.1	0.7	1.0	1.0	1.23*	1.0
Se	Sealine	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	Doha Bay	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	Al-Safiya	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	Ras Imlajji	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	Ras Rakan	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	Dukhan	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	Salwa	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Note: Ni = Nickel, Fe = Iron, Cu = Copper, Pb = Lead, V = Vanadium, As = Arsenic, Cr = Chromium, Zn = Zinc, Mn = Manganese, Mo = Molybdenum, Al = Aluminium, Se = Selenium; Symbol * = Minor enrichment, ^ = Moderate enrichment

Table 5: Index of geo-accumulation for metals present in waters of Qatar from May 2023 to April 2024

Criteria	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
Ni	Sealine	-0.97	-0.07	0.23	-0.67	-0.58	-0.74	-1.00	0.00	-0.74	-1.58	-0.74
	Doha Bay	-0.97	0.07	0.00	-0.58	-0.46	-0.42	-0.67	0.00	-0.74	-1.58	0.62
	Al-Safiya	-0.97	-0.22	-0.58	-0.46	-0.58	-0.58	-0.58	0.07	-0.74	-1.58	-0.58
	Ras Imlajji	-1.07	-3.91	-0.74	-0.46	-0.58	-0.58	-0.42	-0.22	-0.58	-1.58	-1.00
	Ras Rakan	-0.97	-1.00	-0.74	-0.42	-0.58	-0.58	-0.42	-1.00	-0.58	-1.58	-1.22
	Dukhan	-0.58	0.07	-0.58	-0.22	-0.58	-0.42	0.00	0.23	-0.42	-1.32	-1.00
	Salwa	0.00	0.36	-0.74	-0.22	-0.58	-0.58	0.36	0.23	-0.42	-1.32	-0.74
Fe	Sealine	-0.58	-0.07	-0.58	-0.42	-0.74	-0.58	-0.42	-0.42	-0.58	-0.58	-0.74
	Doha Bay	-0.74	-0.07	-0.42	-0.42	-0.58	-0.42	-0.58	-0.42	-0.42	-0.42	-0.22
	Al-Safiya	-0.80	-0.22	-0.42	-0.46	-1.00	-0.46	-0.58	-0.42	-0.50	-0.42	-0.74
	Ras Imlajji	-1.22	-3.91	-0.58	-0.50	-0.67	-0.46	-0.58	-0.42	-0.36	-0.58	-0.67
	Ras Rakan	-0.58	-0.58	-0.58	-0.42	-0.46	-0.58	-0.58	-0.42	-0.50	-0.58	-0.67
	Dukhan	-0.80	-0.22	-0.36	-0.22	-1.58	-0.46	-0.67	-0.42	-0.36	-0.42	-0.58
	Salwa	-0.58	-0.07	-0.36	-0.36	-0.58	-0.58	-0.67	-0.42	-0.50	-0.42	-0.58

Cu	Sealine	-0.58	-0.74	-0.42	-0.36	-0.58	-0.36	-0.22	-0.58	-1.22	-0.58	-0.74	-0.58
	Doha Bay	-1.22	-0.80	-0.74	-0.36	-0.22	-0.22	-0.74	-0.36	-1.00	-0.58	-0.58	0.58
	Al-Safiya	-1.32	-0.80	-0.74	-0.22	0.00	0.07	-0.74	-0.42	-1.00	-0.58	-0.58	-0.36
	Ras Imlaiji	-0.58	-0.70	-0.74	-0.22	0.15	0.22	-0.67	-0.36	-1.00	-0.42	-0.50	-0.58
	Ras Rakan	-0.22	-0.74	-0.42	-0.15	0.29	0.22	-0.58	-0.22	-0.74	-0.50	-0.50	-1.00
	Dukhan	-1.22	-0.58	-0.74	0.15	0.58	0.36	-0.42	0.00	-1.00	-0.36	-0.36	-0.74
	Salwa	-1.00	-0.36	-0.74	-0.07	0.74	0.58	-0.22	0.29	-1.00	-0.36	-0.29	-0.36
Pb	Sealine	-3.91	0.26	-3.91	-1.91	-3.91	-3.91	-2.91	-1.91	-1.00	-1.22	-3.91	-2.58
	Doha Bay	-1.49	-1.22	0.74	-3.91	-1.58	-3.91	-2.58	-2.08	-1.00	-1.89	-3.91	-0.58
	Al-Safiya	-1.46	0.00	-2.91	1.00*	-3.91	-3.91	-3.91	-2.27	-1.00	-2.04	-3.91	-2.91
	Ras Imlaiji	-0.58	-1.22	-0.58	-0.58	-2.91	-3.91	-0.74	-1.66	-1.00	1.58	-3.91	-1.52
	Ras Rakan	-0.22	0.15	0.36	-3.91	-3.91	-3.91	-1.91	-2.22	-0.91	-1.83	-2.22	0.00
	Dukhan	-0.22	0.15	0.36	-3.91	-3.91	-3.91	-1.91	-2.22	-0.91	-2.34	-2.22	0.00
	Salwa	-3.91	0.22	-1.85	-1.58	-1.78	-3.91	-3.91	-2.79	-1.00	-3.91	-3.91	-2.44
V	Sealine	-0.09	0.00	-0.26	0.00	-0.09	-0.09	-0.09	-0.26	0.26	0.00	-0.26	-0.26
	Doha Bay	0.26	-0.09	-0.17	-0.09	-0.09	0.00	-0.09	-0.26	0.09	0.09	0.00	0.00
	Al-Safiya	0.22	-0.09	0.26	-0.09	-0.17	-0.17	0.00	-0.26	0.17	0.09	0.00	-0.09
	Ras Imlaiji	-0.26	-1.91	0.36	-0.09	-0.26	-0.09	-0.09	-0.26	-0.09	0.00	0.00	-0.09
	Ras Rakan	0.00	-0.26	0.49	0.09	-0.17	-0.09	-0.26	-0.26	0.00	0.09	0.00	-0.09
	Dukhan	-0.09	-0.09	0.44	0.22	-0.26	0.00	-0.36	-0.26	0.17	0.17	0.09	0.00
	Salwa	-0.26	0.00	0.44	0.17	-0.26	-0.17	-0.49	-0.26	-0.09	0.09	0.00	0.00
As	Sealine	-0.26	-0.22	-0.17	-0.09	-0.36	-0.26	-0.17	-0.49	0.22	-0.09	-0.17	0.58
	Doha Bay	0.22	-0.09	-0.09	-0.09	-0.49	-0.09	-0.22	-0.42	0.09	-0.17	-0.09	0.49
	Al-Safiya	0.17	-0.07	0.36	-0.09	-0.49	-0.26	-0.17	-0.42	0.09	-0.17	-0.09	0.36
	Ras Imlaiji	-0.26	-2.32	0.49	-0.15	-0.58	-0.26	-0.22	-0.42	-0.09	-0.17	-0.09	0.26
	Ras Rakan	0.00	0.07	0.58	-0.09	-0.49	0.09	-0.36	-0.49	0.00	-0.17	-0.09	0.36
	Dukhan	0.36	-0.09	0.62	0.00	-0.67	0.09	-0.42	-0.58	0.09	-0.09	0.00	0.36
	Salwa	0.00	-0.07	0.62	-0.09	-0.67	-0.36	-0.49	-0.58	0.00	-0.09	0.00	0.17

Cr	Sealine	-1.91	-0.91	-0.42	-1.58	-1.91	-1.91	-1.58	-0.91	-0.91	-1.22	-1.91	0.22
	Doha Bay	-0.91	-0.91	-0.42	-1.58	-1.91	-1.91	-1.91	-0.91	-0.91	-1.22	-1.58	-1.58
	Al-Safiya	-0.91	-0.91	-0.26	-1.58	-1.91	-1.91	-1.58	-0.91	-1.22	-1.22	-1.58	-1.00
	Ras Imlajji	-1.22	-0.91	-0.09	-1.58	-1.91	-1.91	-1.91	-0.91	-1.58	-1.58	-1.58	-0.26
	Ras Rakan	-1.00	-0.91	-0.09	-1.58	-1.91	-1.91	-1.91	-0.91	-0.91	-1.58	-1.58	-0.74
	Dukhan	-1.91	-0.91	-0.26	-1.58	-1.91	-1.58	-1.91	-0.91	-1.22	-1.58	-1.58	-1.58
	Salwa	-2.32	-0.91	-0.26	-1.58	-1.91	-1.91	-1.91	-0.91	-2.32	-1.58	-1.58	-2.32
	Sealine	0.22	-1.58	-0.74	-0.26	-0.74	-1.32	0.22	-1.91	1.22	0.22	-1.58	-0.09
	Doha Bay	0.22	-0.42	-0.74	-0.74	-0.67	-0.74	-0.67	-1.91	-0.74	0.22	-1.58	1.58
	Al-Safiya	0.22	-0.36	-0.74	-1.00	-0.62	-0.67	-0.80	-1.91	-0.58	0.22	-1.58	1.22
Zn	Ras Imlajji	-0.74	-0.22	-0.74	-0.91	-0.58	-0.67	-3.91	-1.91	-0.80	0.22	-1.58	0.36
	Ras Rakan	-0.74	-0.36	-0.74	-1.07	-0.58	-0.80	-3.91	-1.91	0.00	0.22	-1.58	0.29
	Dukhan	0.22	-0.29	-0.74	-0.74	-0.91	-0.80	-3.91	-1.91	-1.07	0.22	-1.58	-1.58
	Salwa	0.22	-0.49	-0.74	-1.00	-0.80	-1.22	-3.91	-1.91	-0.80	0.22	-1.58	-1.58
	Sealine	-0.58	-0.74	-0.35	-0.22	-0.09	-0.74	-0.09	-0.37	0.58	0.00	-0.74	-1.58
	Doha Bay	-0.58	-0.74	-1.22	0.74	0.49	0.36	0.49	-2.91	0.58	0.00	-0.74	-1.58
Mn	Al-Safiya	-0.58	-0.74	-2.58	-0.26	0.26	-0.58	0.22	-0.61	0.58	0.00	-0.74	-1.58
	Ras Imlajji	-0.58	-0.74	-0.20	0.00	0.15	-0.74	0.00	-0.25	0.58	0.00	-0.74	-1.58
	Ras Rakan	-0.42	-0.74	-0.08	0.36	0.15	-0.74	-0.09	-0.19	0.58	0.00	-0.74	-1.58
	Dukhan	-0.58	-0.74	0.15	0.62	0.26	-0.42	-0.26	-0.06	0.58	0.00	-0.74	-1.58
	Salwa	-0.58	-0.74	-0.11	0.00	0.09	-0.42	0.00	-0.20	0.58	0.00	-0.74	-1.58
	Sealine	0.22	0.29	0.26	0.22	0.00	0.07	0.36	-0.07	0.00	0.15	0.07	0.15
Mo	Doha Bay	-0.07	0.00	0.07	0.15	0.00	0.15	0.22	0.00	0.00	0.22	0.22	0.36
	Al-Safiya	-0.15	-0.07	0.00	0.22	-0.09	0.07	0.29	0.00	0.07	0.22	0.15	0.00
	Ras Imlajji	-0.42	-3.91	-0.09	0.22	-0.07	0.15	0.36	0.00	0.00	0.29	0.07	-0.07
	Ras Rakan	-0.07	-0.91	-0.07	0.29	-0.02	0.15	0.42	-0.02	0.07	0.22	0.07	-0.07
	Dukhan	-0.15	0.07	0.07	0.49	0.02	0.22	0.74	0.07	0.07	0.29	0.22	0.07
	Salwa	0.07	0.29	0.07	0.42	0.02	0.22	1.00*	0.07	0.22	0.29	0.22	0.15

Al	Sealine	-0.09	0.58	-1.58	-0.22	0.07	0.49	0.74	-0.91	-1.00	0.22	0.00	0.00
	Doha Bay	-0.07	-0.22	-1.65	-0.36	-0.07	-0.22	0.00	-1.07	-1.00	-0.26	0.00	0.58
	Al-Safiya	-0.15	-0.29	-0.91	-0.58	0.15	-0.36	-3.91	-1.00	-1.00	0.00	0.62	0.00
	Ras Imlajji	-0.42	-2.32	-1.15	0.74	-0.42	-0.09	-3.91	-1.07	-1.00	0.00	-0.74	-0.22
	Ras Rakan	-0.36	-0.58	-1.42	0.15	-0.22	0.22	-3.91	-1.07	-1.00	0.00	-0.49	-0.15
	Dukhan	-0.15	-0.15	-0.58	-0.22	-0.29	0.07	-3.91	-1.32	-1.00	0.00	-0.49	-0.36
Se	Salwa	0.00	0.07	-1.22	-0.74	-0.58	-0.22	-3.91	-1.42	-1.00	-0.07	0.36	0.07
	Sealine	-0.91	0.74	-0.22	-0.58	-1.58	-1.22	0.22	-0.58	0.00	-0.26	-0.26	-1.22
	Doha Bay	-0.91	0.74	-0.22	-0.58	-1.58	-1.22	0.22	-0.58	0.00	-0.26	-0.26	-1.22
	Al-Safiya	-0.91	0.74	-0.22	-0.58	-1.58	-1.22	0.22	-0.58	0.00	-0.26	-0.26	-1.22
	Ras Imlajji	-0.91	0.74	-0.22	-0.58	-1.58	-1.22	0.22	-0.58	0.00	-0.26	-0.26	-1.22
	Ras Rakan	-0.91	0.74	-0.22	-0.58	-1.58	-1.22	0.22	-0.58	0.00	-0.26	-0.26	-1.22
	Dukhan	-0.91	0.74	-0.22	-0.58	-1.58	-1.22	0.22	-0.58	0.00	-0.26	-0.26	-1.22
	Salwa	-0.91	0.74	-0.22	-0.58	-1.58	-1.22	0.22	-0.58	0.00	-0.26	-0.26	-1.22

Note: Ni = Nickel, Fe = Iron, Cu = Copper, Pb = Lead, V = Vanadium, As = Arsenic, Cr = Chromium, Zn = Zinc, Mn = Manganese, Mo = Molybdenum, Al = Aluminium, Se = Selenium; Symbol * = Minor pollution

Discussion

This study is the only long-term, in-depth study covering multiple indicators across industrial, residential, and reference sites in Qatar. Previous investigations focused on coastal waters of Qatar with single-to-limited parameters, single-location inspection or short-term monitoring (Loganathan *et al.*, 2019; Rivers *et al.*, 2019; Al-Shamary *et al.*, 2023; Al-Awah *et al.*, 2026). In addition, this study goes beyond the single-season or short-term campaigns seen in Bahrain (Ali, 2022; Naser, 2022) and Kuwait (Al-Said *et al.*, 2017; Durvasula *et al.*, 2024; Karam & Al-Saleh, 2024).

Generally, TOC and oil and grease were low across sites, with episodic spikes in waters of Sealine, Al-Safiya, Dukhan, and Salwa. These values, 11–23 µg/L for oil and grease and 1.1–3.6 mg/L for TOC, were well below Qatar’s discharge limit of 10 mg/L (10,000 µg/L). In fact, it was consistent with ranges reported in waters of Kuwait Bay (1.5–4.2 mg/L) (Al-Said *et al.*, 2017; Al-Yamani *et al.*, 2017) and Bahrain (1.0–3.8 mg/L) (Al-Said *et al.*, 2018). However, episodic spikes were thought to bring ecological risks similar to those occurring in Bahrain and the UAE, where transient hydrocarbon inputs disturbed the benthic communities and impaired seagrass productivity (Mirza *et al.*, 2015; Al-Said *et al.*, 2018; Hereher, 2020; Rezaei *et al.*, 2021; Ali, 2022; Subraelu *et al.*, 2022; Darvasula *et al.*, 2024). Fortunately, the concentrations of TOC and oil and grease were “no visible sheen” in USEPA (*c.f.* Suter II, 2023) and WHO (*c.f.* Alao *et al.*, 2025). Meanwhile, elevated TOC and chlorophyll-a occurred during the warmer summer months, although correlation scores were poor. In addition, algal blooms were common in coastal waters of Qatar during the summer months (Ershadifar *et al.*, 2023a). Similar observations occurred in Bahrain and Kuwait, where summer stratification and winter runoff promoted productivity (Al-Yamani *et al.*, 2017; Ali, 2022; Durvasula *et al.*, 2024). However, productivity was considered low and did not affect fisheries or consumer health in Qatar.

In contrast, nutrient enrichment was most pronounced in Doha Bay, with nitrate and phosphate peaking at 77.2 µg/L and 11.3 µg/L, respectively. Although nitrate concentrations remained within Qatari regulatory limits, they exceeded ecological thresholds associated with the USEPA guidance, indicating localised bloom risk. Generally, the 65 µg/L nitrate concentration reported in Bahrain (Ali, 2022; Naser, 2022) and phosphate detections at 8–12 µg/L in the northern Gulf originate from municipal wastewater input into poorly circulated waters (Al-Yamani *et al.*, 2017). In Bahrain, industrial and urbanised sites contain higher nutrient and metal concentrations than reference sites (Naser, 2022), whereas in the UAE, areas with hydrocarbon industries have higher organic matter and chlorophyll-*a* (Al-Said *et al.*, 2018; Subraelu *et al.*, 2022). With episodic phosphorus (DIN:PO₄ > 90 at Doha Bay and Al-Safliya) and transient nitrogen limitations (DIN:PO₄ < 10 at Dukhan and Doha Bay), it appears that nutrient circulation in waters of Qatar was seasonal and this affirms that climate conditions, especially the summer months can temporarily promote primary productivity. While the literature describes productivity as seasonal in Qatar (Ajur & Al-Ghamdi, 2022; Sawh *et al.*, 2024), algal blooms were possible due to increased nitrate, as witnessed in the Gulf of Oman (Ershadifar *et al.*, 2023a,b). Basically, nutrient limitation ends the bloom cycle, and coastal waters receive land input to recover their nutrient grades.

On the contrary, consistently low DIN:SiO₂ ratios in Doha Bay (< 0.5) do not suggest silica limitation in this semi-enclosed basin, but rather conform with observations in the northern Gulf where silica depletes with diatom productivity (Hartmann *et al.*, 2011; Al-Yamani *et al.*, 2017). Again, nutrient enrichment was associated with productivity but limited to a seasonal course. Meanwhile, trace metal concentrations were generally stable and remained within regulatory thresholds, with only minor exceedances. Copper values (0.6–3.4 µg/L) slightly exceeded the USEPA chronic criterion of 3.1 µg/L at Doha Bay but remained below the acute limit of 4.8 µg/L. Copper has a lithogenic origin and was

a common discharge from desalination plants (Loganathan *et al.*, 2019).

In addition, lead concentrations (0.0–6.2 µg/L) were below both the USEPA chronic criterion (8.1 µg/L) and the WHO guideline (10 µg/L), although Ras Imlaiji approached these thresholds. Zinc enrichment (up to 33.8 µg/L) was observed at Doha Bay but remained well below the USEPA chronic limit of 81 µg/L. Nickel (0.1–2.3 µg/L) and arsenic (1.0–4.5 µg/L) were well below their respective thresholds in USEPA and WHO (Nickel = 8.2 µg/L; Arsenic = 10 µg/L). The present findings recorded values lower than the > 4.2 µg/L copper and > 40 µg/L zinc in waters of Saudi Arabia (Alharbi *et al.*, 2024). The values were definitely lower than the “moderate enrichment” of nickel, copper, and zinc in Persian Gulf sediments (Rezaei *et al.*, 2021).

Comparatively, the EF and Igeo analyses corroborated these findings, showing predominantly natural origins (EF ≈ 1) with only minor to moderate enrichment at industrial and semi-urban sites. Previous studies suggested copper and zinc enrichment in Doha Bay and Al-Safliya in Qatar (Al-Naimi *et al.*, 2015; Loganathan *et al.*, 2019), with EF ~1.5. In addition, monthly trends showed metal enrichment, with copper at Doha Bay in April (EF = 2.3), zinc at Al-Safliya in November (EF = 7.0), and zinc at Dukhan in December (EF = 1.9). This suggests localised anthropogenic inputs with seasonal-temporal fluctuations that coincide with coastal water circulation. Meanwhile, Igeo values for Pb at RasImlaiji (1.58) and As at Sealine (0.58) indicated minor to moderate pollution episodes, but iron, manganese, molybdenum, aluminium, and selenium remained consistently negative or near zero, confirming lithogenic control from sediment weathering.

Taken together, integrating nutrient stoichiometry, pollution indices, and regulatory comparisons provided a robust framework for distinguishing natural variability from anthropogenic inputs. This study fills critical knowledge gaps in coastal water monitoring

around Bahrain, Saudi Arabia, and Iran. In addition, continued monitoring, Sites approaching regulatory or ecological guideline values such as Doha Bay, Al-Safliya, and RasImlajji, was considered essential for compliance and to pre-empt ecological risks associated with eutrophication and trace metal accumulation. Further, all measured parameters remained within safe limits recommended by the Ministry of Environment and Climate Change (MECC) of Qatar, WHO, and USEPA, except for localised copper exceedances and episodic oil and grease spikes. Thus, the results indicate broad compliance towards regulatory standards for water quality in Qatar.

Conclusions

This study provides the first integrated, year-long assessment of coastal water quality in Qatar that simultaneously evaluates organic matter, nutrients, and trace metals through the combined application of nutrient stoichiometry, enrichment factors, and index of geo-accumulation. Firstly, the findings demonstrate that while episodic enrichment events occur such as elevated nitrate and phosphate in Doha Bay, transient oil and grease spikes at Al-Safliya and Dukhan, and localised copper exceedances over concentrations of TOC, nutrients, and metals were within recommendations of USEPA and WHO, guidelines for nutrients should be set by the Ministry of Environment and Climate Change especially to monitor background levels in reference sites (Ras Rakan and Salwa).

Secondly, the novelty of this work lies in its holistic integration of multiple indicators that distinguish natural seasonal variability from anthropogenic pressures in a region where most previous studies have been limited to single parameters, localised explanations, or short-term campaigns. Thirdly, this study advances regional understanding of the Gulf water quality dynamics through detection technologies and innovative water quality monitoring techniques.

Lastly, to better capture eutrophication risks and anthropogenic contamination in Qatar, offshore waters and temporal coverage beyond a single annual cycle are both recommended.

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Conflict of Interest Statement

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Author Contributions Statement

HOA conceptualised the study, performed the analysis, and prepared the manuscript. AE contributed to data interpretation, validation, and manuscript revision. Both authors reviewed and approved the final version of the manuscript.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Ethical Conduct

All information communicated in this article does not require ethical approval because no human or animal subjects were involved in this study.

Declaration of AI-usage

During the preparation of this manuscript, the authors used AI tools for language editing and clarity improvement. The authors reviewed and edited the content and take full responsibility for the final version of the manuscript.

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