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# Carbon Dynamics and $CO_2$ Fluxes in Coastal Waters and Sediments Along the Zubair Creek in Southern Iraq

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**Abstract**

This study aimed to assess the role of Khor Al-Zubair as a carbon sink within coastal ecosystems and to understand the dynamics of carbon exchange between the atmosphere, water, and sediments under the influence of tides and industrial activities. The study was conducted at three main stations stretching from Khor Al-Zubair Port to Umm Qasr Port, with a field and laboratory monitoring program carried out over a period of 13 hours during a semi-diurnal tidal cycle. The results showed a statistically significant spatial variation in water temperature ($F= 685.00$, $P < 0.001$), which affected gas solubility and carbonate system reactions. At the same time, pH values ranged from 7.0 to 7.2, primarily influenced by tidal fluctuations ($P= 0.001$). Salinity also reached its highest value at Station 3 near the Arabian Gulf (52.416 ppt) and its lowest value at Station 2 (44.864 ppt), while total alkalinity ranged from 170–212 mg/L and dissolved carbon dioxide from 5.9–15.9 mg/L. Calculations of the partial pressure of carbon dioxide ($pCO_2$) showed high values ranging from 3,616–11,950 µatm compared to atmospheric levels (478–576 µatm), confirming that Khor Al-Zubair acts as a net source of carbon emissions rather than a carbon sink. In the sediments, the average total organic carbon (TOC) was 1.59%, with a maximum value of 4.39%, while the calcium carbonate ($CaCO_3$) content ranged from 7.83–26.58%, and the average total alkalinity was 428.44 mg/L, indicating that the sediments possess buffering capacity that helps limit the effects of water acidification and maintain the stability of the carbonate system. The study concludes that Khor Al-Zubair is a source of carbon dioxide emissions; however, its high alkalinity and abundance of bicarbonate and carbonate contribute to maintaining chemical equilibrium and limiting water acidification.

**Keywords:** Khor al-Zubair, carbon dioxide, total organic carbon, Alkalinity, Water quality, coastal pollution, southern Iraq, Climate change, Global Warming.

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## Introduction

Climate change is one of the most significant environmental challenges facing the world in the 21st century. It is primarily linked to the continuous increase in concentrations of greenhouse gases, particularly carbon dioxide ($CO_2$), which leads to increased carbon uptake by the oceans and seas, a decrease in pH values, and the acceleration of ocean acidification, thereby threatening marine ecosystems and calcareous organisms that are sensitive to chemical changes (IPCC, 2019; NOAA, 2024). Coastal environments play a pivotal role in the global carbon cycle by regulating carbon exchange between the atmosphere, water, and sediments. Blue carbon ecosystems, such as seagrass beds, salt marshes, and mangrove forests, serve as important natural carbon sinks that help mitigate the effects of climate change by sequestering carbon over long periods (Feng *et al.*, 2023; Macreadie *et al.*, 2021). Conversely, these environments may become sources of carbon emissions as a result of organic matter decomposition, industrial pollution, and hydrodynamic disturbances. The increased uptake of carbon dioxide from human activities by seawater has led to a decrease in pH values and a decline in carbonate ion concentrations, which negatively affects marine organisms that form calcareous structures and biodiversity, particularly in shallow and semi-enclosed coastal environments (Doney *et al.*, 2020; EPA, 2025; EEA, 2025). Khor Al-Zubair is considered one of the most sensitive coastal systems in southern Iraq, as petrochemical and fertilizer plants, oil facilities, and other industrial activities are major sources of carbon dioxide emissions (Sultan *et al.*, 2013).

Carbon dioxide is the primary greenhouse gas responsible for approximately 55% of the greenhouse effect (Amin and Taghlab, 1990); it is also characterized by its high solubility in seawater due to its acidic nature (Al-Saad and Shukri *et al.*, 2024), which enhances heat trapping in the atmosphere and raises surface water temperatures in shallow coastal systems (IPCC, 2021; Chen and Borges, 2009). Carbon dynamics in Khor Al-Zubair are influenced by the prevailing quasi-diurnal tidal system, which facilitates continuous mixing between the waters of the Basra Coast and the Arabian Gulf, thereby regulating sediment transport and the carbon cycle within the coastal system (Chen *et al.*, 2017; Lafta, Al-Taei, and Al-Hashimi, 2019). Groundwater, tidal pumping, phytoplankton photosynthesis, microbial respiration, and industrial discharges also contribute to regulating the transport of dissolved organic carbon (DOC) and dissolved inorganic carbon (DIC) within this system (Alongi, 2014; Idan *et al.*, 2019; Sánchez Rodríguez *et al.*, 2025). Dissolved carbon dioxide reacts with water to form carbonic acid, which dissociates into bicarbonate and carbonate ions, leading to an increase in hydrogen ion concentration and a decrease in pH (Sulpis *et al.*, 2018; Al Fartusi and Al-Siyab, 2021). Seasonal temperature changes, microbial decomposition, increased nutrient levels, and phytoplankton activity also influence the dynamics of dissolved oxygen and pH levels; a decrease in dissolved oxygen during the summer poses a threat to sensitive aquatic organisms (Hazza and Jassim, 2024; Hazza and Jassim, 2025).

Furthermore, a decrease in pH reduces the concentration of carbonate ions and the saturation level of calcite and aragonite, thereby increasing the dissolution of calcium carbonate ($CaCO_3$), which is a major component of marine sediments and the calcareous structures of marine organisms (Cyronak and Eyre, 2016; Drylie *et al.*, 2019; Zeebe and Wolf-Gladrow, 2001). Since the calcium carbonate content in the Khor Al-Zubair sediments ranges from 7.83–26.58%, and most of it comes from mollusk shells and foraminifera, this area is considered more vulnerable to the effects of coastal water acidification and its resulting environmental impacts (Nasser and Al-Mahmood, 2009).

## Aim of the study

To investigate the extent to which Khor Al-Zubair participates in the primary carbon cycle and its contribution, as a coastal system, to local and regional climate change, by understanding the mechanisms of carbon transfer between the atmosphere and the waters of the creek through tidal phenomena, groundwater flow and microbial analysis.

In addition, to identify the forms of carbon (organic and inorganic carbon) present in the creek's waters and sediments and determine their role in climate change.

Furthermore, to determine the extent of pollution caused by local emissions of carbon dioxide resulting from human activities and offshore oil ports in the region.

Finally, to determine the role of Khor Al-Zubair sediments in increasing alkalinity through carbonate accumulation and supporting the formation of calcareous shells.

## Research Problem

The research problem lies in the lack of knowledge regarding the impact of carbon dioxide and hydrodynamic processes on the characteristics of marine water and sediments in Khor Al-Zubair, despite the area's exposure to increasing industrial and climatic pressures, which limits the effectiveness of managing this coastal system.

## Materials And Methods

### Study Area and Climate

The study area, located in the south-western part of Basra Governorate, is one of the most important coastal environments, given its maritime extension connected to the Arabian Gulf. It is one of the most important shipping routes in southern Iraq, as it includes major commercial and industrial ports such as Khor Al-Zubair Port and Umm Qasr Port (Alainachi and Nasser, 2009; Albadran and Al-Fartusi, 2016), as well as its connection to the Shatt al-Basra Canal, which links to the Euphrates River at Karma Ali via the Hamar Marshes. This has made the area a key focus for economic, hydrodynamic and environmental studies due to the interaction between natural factors (salinity, tides and sediments) and industrial and maritime transport factors. (Al Fartusi and Al-Siyab, 2014), (Sultan *et al.*, 2012) .

The study area is home to major industrial complexes such as iron and steel, petrochemicals, a fertiliser plant and cement, as well as a power station. These industries rely on their proximity to the canal to discharge industrial waste from the factories and to facilitate maritime transport. (Sultan *et al.*, 2012).

## Study sites

Three main sites were selected for the present study, starting from the first site at Khor Al-Zubair Port near Nazim Shat Al-Basra, and ending at the final site near Umm Qasr Port, as shown in Figure (1). The study sites were identified using a Global Positioning System (GPS) device, as shown in Table (1)

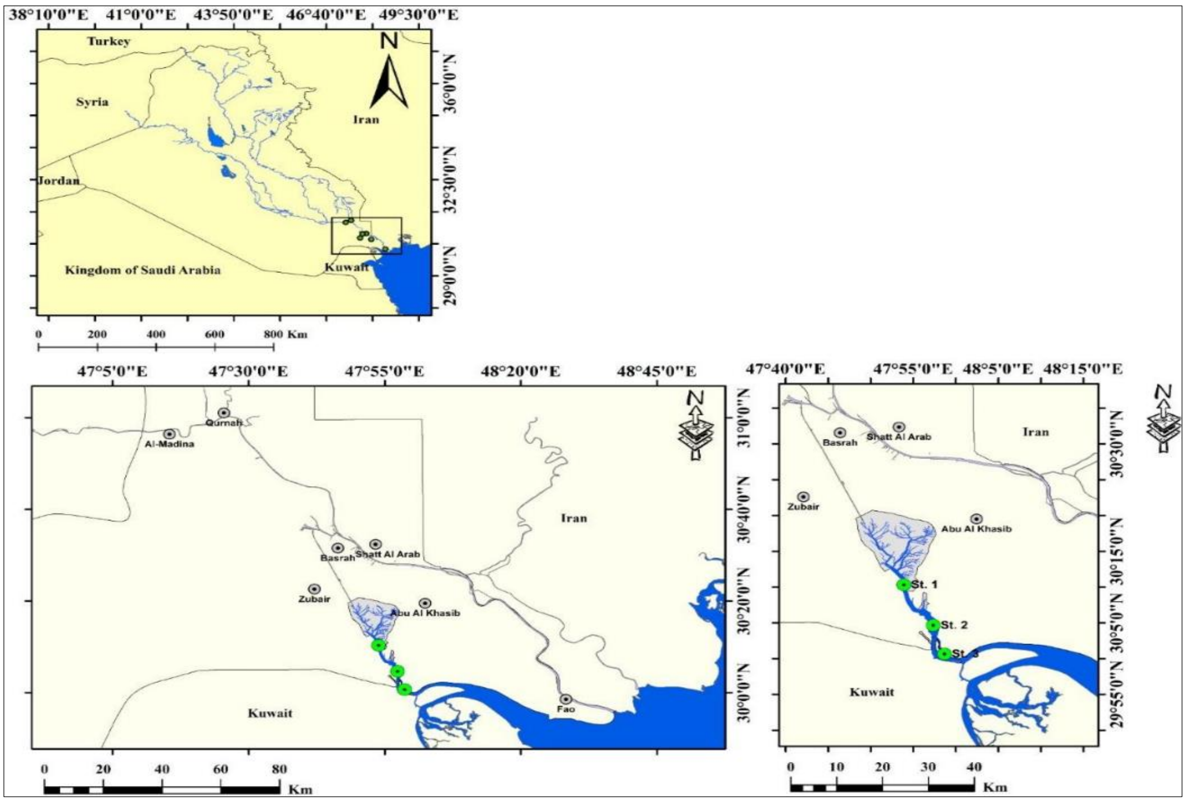


**Figure (1):** A map showing the three stations in the study area.

**Table** (1) Geographic coordinates of the study stations.

| Station | Longitude | Latitude |
|---|---|---|
| Khor Al-Zubair Port | E = 47° 53′ 53.4″ | N = 30° 10′ 20.8″ |
| Liquefied Natural Gas Port | E = 47° 57′ 21.2″ | N = 30° 4′ 41″ |
| Umm Qasr Port | E = 47° 58′ 40.3″ | N = 30° 00′ 41.1″ |

## Sample Collection

## Water sampling

Water samples were collected from three stations stretching from Khor Al-Zubair Port to Umm Qasr Port, including a mid-channel station at the beginning of the sandbars (5–6 m), using a water sampler. Thirteen samples were collected from each station, for a total of 39 samples. The samples were placed in clean, sterilized plastic bottles, rinsed three times with on-site water before being filled, then immediately stored in a field cooler containing ice and transported to the laboratory in accordance with standard procedures for conducting physical and chemical analyses.

### Sediment sampling

Sediment samples were collected from the study sites using a grab sampler at the three locations, where samples were taken from the left bank, the right bank, and the middle of the channel, The samples were preserved in aluminum foil until they were transported to the laboratory, where they were ground using a ceramic mortar and sieved through a 2 millimeter sieve to prepare them for analysis and measurement.

### Atmospheric $CO_2$ concentration

Atmospheric $CO_2$ concentration is one of the key variables in studies of the carbonate system, as it influences gas exchange between the atmosphere and water and helps determine the values of dissolved inorganic carbon (DIC), the partial pressure of carbon dioxide ($pCO_2$), pH, and total alkalinity (Dickson *et al.*, 2007; NOAA, 2024). $CO_2$ concentration was measured using a Wintact WT8807 instrument based on non-dispersive infrared (NDIR) technology, after running it for 5–10 minutes to ensure sensor stability, then placed at a height of 1.5 m in an open area away from direct emission sources, and readings were recorded once they had stabilized, with measurements repeated throughout the study period (13 hours) (WMO, 2023).

### Physical and chemical measurements

### Water sampling

Field water measurements were conducted at the three study stations during a semi-daily monitoring cycle lasting 13 hours, and included measurements of water temperature, electrical conductivity (EC), salinity, pH, total dissolved solids (TDS), and dissolved oxygen (DO), using a Digital Salinometer and a Multimeter after calibrating them according to the manufacturer's instructions. Water levels were also continuously recorded using a Vale Port Tide Master Tide Gauge, and all readings were referenced to the FAW 1997 Datum, which allowed for tracking tidal fluctuations and correlating them with the physical and chemical changes in the water. Dissolved carbon dioxide ($CO_2$) was measured by volumetric titration according to Lind (1979), while total alkalinity (TA) was determined by titrating the sample with standard sulfuric acid. These measurements were used to calculate bicarbonate ($HCO_3^-$) and monitor the carbonate system balance in the waters of Khor Al-Zubair (Hem, 1985; Lind, 1979; Stumm and Morgan, 1996).

### Sediment sampling

Laboratory analyses were conducted on sediment samples to determine their physical and chemical properties, including measurements of pH, electrical conductivity (EC), and salinity; they also included the determination of calcium carbonate ($CaCO_3$) by titration, as it is one of the main components of marine sediments and is responsible for regulating the carbonate system's equilibrium and mitigating the effects of ocean acidification. Total organic carbon (TOC) was also measured according to the method described by Gaudette *et al.* (1974), as it is an important indicator for assessing the organic matter content in sediments, reflects the intensity of sedimentation and biodegradation processes as well as sources of organic pollution, and contributes to explaining carbon production and decomposition processes within sediments and their role in the coastal carbon cycle. In addition, the concentration of bicarbonate ($HCO_3^-$) in the sediment extract was measured by titration using standard sulfuric acid, with blank samples used to correct the results and ensure the accuracy of the measurements (Gaudette *et al.*, 1974).

## Results and Discussion

### Water samples

Water Temperature is a one-way analysis of variance (UNIANOVA) showed that water temperature was significantly influenced by the overall model ($F = 94.21$, $P < 0.001$) with high explanatory power ($R^2 = 0.984$); geographic location had the greatest effect ($F = 685.00$, $P < 0.001$), followed by time ($P = 0.022$), while the effect of tides was not significant ($P = 0.089$). These results indicate that temperature variation is primarily associated with the local characteristics of the stations and meteorological conditions rather than with the tidal cycle. Temperature also directly affects the solubility of carbon dioxide and dissolved oxygen, and thus the carbonate system's equilibrium and carbon dynamics between water and sediments (Adkins *et al.*, 2021; IPCC, 2023; Breitburg *et al.*, 2021).

pH is one of the key chemical indicators that determine the nature of the aquatic environment and its ability to support marine life. The pH values measured in the field at the three stations ranged between 7 and 7.2, meaning they fall within the slightly basic range. The statistical model showed statistical significance ($F = 2.543$, $P = 0.021$, $R^2 = 0.624$), whereas time ($P = 0.089$) and location ($P = 0.878$) had no significant effect, and the tides had a clear effect ($F = 14.229$, $P = 0.001$). The LSD test also revealed limited differences between only some of the measurement times. These results indicate that pH changes are primarily associated with tidal movement and carbon dioxide exchange between water and sediments rather than with geographic location; ebb tides lead to increased $CO_2$ accumulation and lower pH, while flood tides refresh the water and raise pH values, given the regulatory role of total alkalinity and the carbonate system (Dickson *et al.*, 2007; Stumm and Morgan, 1996).

Salinity is one of the most important environmental factors determining the nature and balance of an aquatic system. The highest value was recorded at Station 3 (PPt 52.416) due to its proximity to the seawater of the Arabian Gulf, and the lowest value at Station 2 (PPt 44.864). The results of the one-way analysis of variance (UNIANOVA) showed that the overall model for salinity was not statistically significant ($F = 1.860$, $P = 0.087$), with a coefficient of determination of ($R^2 = 0.548$). Neither time ($P = 0.938$) nor station ($P = 0.159$) showed a statistically significant effect, whereas the effect of tides was highly statistically significant (F = 15.779, P = 0.000603), as confirmed by the results of the LSD test. These results indicate that salinity variation is primarily associated with the semi-diurnal cycle, as salinity increases during low tide and decreases during high tide due to water renewal, which affects the solubility of carbon dioxide and the carbonate system balance in the coastal environment (Da *et al*., 2025; Kerr *et al*., 2021).

Electrical conductivity (EC). The results of the one-way analysis of variance (UNIANOVA) showed that the overall model for electrical conductivity was not statistically significant (F = 1.860, P = 0.087), although the coefficient of determination was ($R^2$ = 0.548), indicating that 54.8% of the variation in EC values was explained. Neither time (P = 0.938) nor station (P = 0.159) had a significant effect, whereas the effect of the tidal cycle was significant (F = 15.779, P = 0.000603), which was confirmed by the LSD test results showing no significant temporal or spatial differences. These results indicate that electrical conductivity is primarily influenced by the tidal cycle, which regulates the transport of dissolved ions and the renewal of water masses, directly affecting the carbonate system and the distribution of carbon dioxide in the waters of Khor Al-Zubair (Kerr *et al*., 2021; Goossens *et al*., 2026).

Total Dissolved Solids (TDS). The general model for total dissolved solids was statistically significant (F = 2.273, P = 0.037), with a coefficient of determination of ($R^2$ = 0.597). Time had no significant effect (P = 0.923), while both tide (F = 15.494, P = 0.000659) and station (F = 4.577, P = 0.021) had significant effects. The LSD test also showed no significant differences across time. The results indicate that TDS is influenced by tidal movement and the local characteristics of the stations, resulting from ion transport between sediments and the water column, which affects carbonate chemistry and inorganic carbon transport in Al-Zubair Creek (Goossens *et al*., 2026; Adkins *et al*., 2021).

Total Alkalinity (TA) reflects the aquatic system's ability to resist changes in pH and maintain chemical stability; the highest value was recorded at Station 2 (212 mg/L) and the lowest at Station 1 (170 mg/L), The results of the one-way ANOVA (UNIANOVA) showed that the overall model for total alkalinity was highly statistically significant (F = 6.487, P < 0.001), with a coefficient of determination of $R^2$ = 0.809. Neither time (P = 0.0686) nor station (P = 0.714) had a significant effect, while the tidal effect was the highest among all factors (F = 58.674, P < 0.001). The LSD test also revealed significant differences between only some of the measurement times. These results confirm that total alkalinity is controlled by the semi-diurnal cycle through the regulation of bicarbonate and carbonate transfer between sediments and water, thereby enhancing the regulatory capacity of the carbonate system and limiting the impact of rising carbon dioxide (Kerr *et al*., 2021; Goossens *et al*., 2026).

Dissolved Oxygen (DO). The results of the one-way ANOVA (UNIANOVA) showed that the overall model for dissolved oxygen was highly statistically significant (F = 4.446, P = 0.000703), with an adjusted $R^2$ of 0.744. Time had no significant effect (P = 0.182), while both tidal phase (F = 42.47, P < 0.001) and station (F = 6.607, P = 0.0054) had a significant effect; the LSD test also revealed marginal differences between 5:00 and 8:00 ($P = 0.038$). These results indicate that tides promote water aeration, whereas the decomposition of organic matter during low tide leads to oxygen consumption and increased carbon dioxide production, confirming the inverse relationship between DO and $CO_2$ in the coastal environment (Breitburg *et al*., 2021; IPCC, 2023).

Dissolved Carbon Dioxide ($CO_2$). A one-way ANOVA (UNIANOVA) analysis showed that the overall model for carbon dioxide was highly statistically significant ($F = 5.126$, $P = 0.000248$), with a coefficient of determination of ($R^2 = 0.77$). Neither time ($P = 0.139$) nor station ($P = 0.39$) had a significant effect, while the effect of tides was very high ($F = 46.592$, $P < 0.001$); the LSD test revealed differences only between certain measurement hours. The results indicate that the semi-diurnal cycle is the primary factor controlling $CO_2$ concentration, as low tide leads to increased $CO_2$ production from organic matter decomposition, while high tide contributes to water renewal and increased gas exchange with the atmosphere, thereby maintaining the carbonate system's equilibrium in Khor Al-Zubair (Lehmann and Bach, 2025; Goossens *et al*., 2026).

The results of hierarchical cluster analysis using Ward's method, as shown in Figures (2) and (3), indicated that the samples were distributed into two main clusters based on the degree of similarity in their physical and chemical properties. Each cluster included samples from all three stations, indicating that the similarity among the samples was not based solely on geographic location but was also influenced by common environmental factors, particularly tidal movements and water mixing processes within Al-Zubair Creek. The dendrogram also showed that the merging of the main clusters occurred at a high similarity distance, indicating a relative difference between the two groups while each group retained a high degree of internal homogeneity. These results are consistent with Ward's (1963) observation that the Ward method produces internally homogeneous clusters, and they are also consistent with Hair *et al*. (2019) in that the grouping of samples from different locations within a single cluster indicates that common environmental factors dominate the distribution of the variables. They also align with the study by Lafta and Abdullah (2025), which demonstrated that the hydrodynamic characteristics in Khor Al-Zubair are primarily influenced by tidal forces, thereby reducing spatial variability among stations.

### Sediment Samples

pH values ranged from 7.51 to 7.81, with the highest value recorded at Station 1 (right bank) and the lowest at Station 2 (mid-channel). The overall average pH of the sediments was 7.64, indicating that the sediments of Khor Al-Zubair are weakly alkaline and stable. Station 3 recorded the highest average (7.658), while Station 2 recorded the lowest average (7.605); the differences between stations were minimal. These results suggest that the continuous marine influence and the semi-diurnal cycle maintained the stability of the carbonate system within the sediments, while the decomposition of organic matter led to the production of $CO_2$ in the pore water; however, the dissolution of carbonate minerals

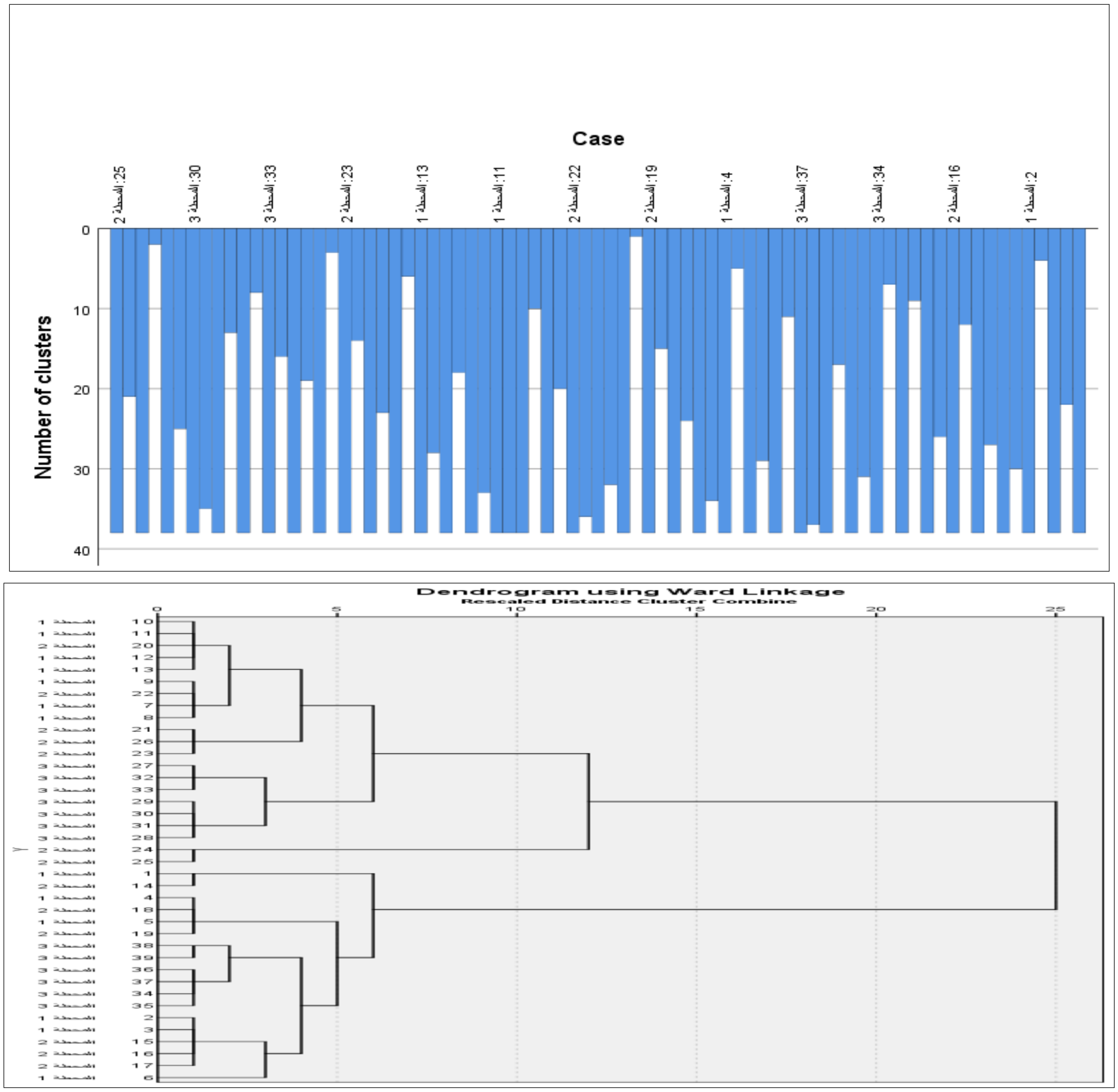


**Figure (2&3):** Cluster Quality Chart and Hierarchical Cluster Analysis (HCA) dendrogram illustrating the classification and similarity of water samples among the study stations based on their physicochemical parameters.

and the buffering capacity of the sediments limited the decrease in pH, thereby maintaining the acid-base equilibrium of the sediments (Kerr *et al.*, 2021; Goossens *et al.*, 2026).

Electrical Conductivity (Sediment EC). The overall average electrical conductivity was 37.82 mS/cm; Station 2 recorded the highest average (39.42 mS/cm), while Station 3 recorded the lowest average (36.83 mS/cm). This reflects the high concentration of dissolved ions in the pore water due to the continuous influence of Arabian Gulf water, with limited spatial variation. The results also confirm the existence of a continuous exchange of ions between the sediments and the water column, making the sediments a reservoir for dissolved salts and contributing to the regulation of ionic equilibrium and the carbonate system in Khor Al-Zubair (Adkins *et al*., 2021; Goossens *et al*., 2026).

Sediment Salinity. The overall average sediment salinity was 22.64 ppt; Station 2 recorded the highest average (23.68 ppt), while Station 3 recorded the lowest average (21.97 ppt). These results indicate a dominant marine influence, with slight spatial variations resulting from differences in salt retention within the pore water. Furthermore, the similarity between sediment and water salinity indicates that the semi-tidal cycle regulates salt transfer between sediments and the water column, which affects the carbonate system's equilibrium and the behavior of carbon dioxide in the coastal environment (Da *et al*., 2025; Kerr *et al*., 2021).

Total Dissolved Solids (Sediment TDS). The overall average for total dissolved solids was 18.88; Station 2 recorded the highest average (19.67), while Station 3 recorded the lowest average (18.40). The results indicate that the Khor Al-Zubair sediments retain high concentrations of dissolved substances due to continuous contact with seawater, with slight variations related to the nature of the sediments and the efficiency of pore water exchange. High TDS contributes to increased transport of ions and bicarbonates, which supports the transport of inorganic carbon between the sediments and the water column (Goossens *et al*., 2026; Adkins *et al*., 2021).

Dissolved Oxygen in Sediment (Sediment DO). The overall average dissolved oxygen concentration was 7.46 mg/L, indicating that the surface layer of the sediment remains under good aeration conditions. Station 1 recorded the highest average (7.55 mg/L), while Station 3 recorded the lowest average (7.37 mg/L) due to its higher total organic carbon (TOC) content, which led to increased oxygen consumption during the decomposition of organic matter and the production of carbon dioxide. The results confirm the inverse relationship between DO and TOC and highlight the importance of tidal action in reoxygenating sediments and maintaining biogeochemical activity in the coastal environment (Breitburg *et al*., 2021; Burdige, 2022).

The overall average total alkalinity was 428.44 mg/L, with the second station recording the highest average (432.00 mg/L) and clear convergence among the stations. The results indicate that the sediments possess a high buffering capacity to neutralize acids and maintain the stability of the carbonate system. High alkalinity is associated with bicarbonate production resulting from the decomposition of organic matter and the dissolution of carbonate minerals, which increases resistance to changes in pH and contributes to the regulation of inorganic carbon transfer to the water column (Kerr *et al*., 2021; Lehmann and Bach, 2025).

Total Organic Carbon (TOC). The overall average for total organic carbon was 1.59%, with the highest average recorded at Station 3 (4.39%) and the lowest at Station 1 (3.93%). This reflects an increased accumulation of organic matter in areas less exposed to runoff, leading to higher microbial activity and increased carbon dioxide production and dissolved oxygen consumption. The results indicate that the sediments represent an important reservoir of organic carbon and a major source of inorganic carbon that is transferred to the water column through biogeochemical decomposition processes (Burdige, 2022; Goossens *et al.*, 2026).

Bicarbonate ($HCO_3^-$). The results showed similar bicarbonate concentrations across stations, reflecting the stability of the carbonate system in the Khor Al-Zubair sediments. Bicarbonate concentrations were higher at stations with higher alkalinity and organic carbon values, resulting from the decomposition of organic matter and the production of carbon dioxide, which is converted to bicarbonate within the pore water. These results confirm that the sediments play a key role in the recycling of inorganic carbon and the maintenance of acid-base balance, thereby enhancing the stability of the coastal ecosystem (Kerr *et al.*, 2021; Da *et al.*, 2025).

The results of the hierarchical cluster analysis using Ward's linkage method, as shown in Figures (4and5), indicated that the sediment samples were grouped into two main clusters based on the degree of similarity in their physical and chemical properties. Each cluster included samples from all three stations, indicating that the similarity among the samples was not solely related to geographic location but was also influenced by shared sedimentological and chemical characteristics, such as pH, electrical conductivity (EC), total dissolved solids (TDS), total alkalinity (TA), total organic carbon (TOC), and bicarbonate ($HCO_3^-$). The dendrogram also showed that the merging of the main clusters occurred at a high similarity distance (Rescaled Distance ≈ 25), indicating the presence of two groups with relatively different characteristics, each maintaining a high degree of internal homogeneity.

This pattern reflects the influence of biogeochemical processes and hydrodynamic conditions in Khor Al-Zubair, as tidal movement and water exchange with the Arabian Gulf contribute to the redistribution of sediments, organic matter, and dissolved ions, leading to a convergence in sediment characteristics among the stations. These results are consistent with the study by Lafta and Abdullah (2025), which demonstrated that hydrodynamic processes in Khor Al-Zubair directly influence the distribution of sediments and the environmental characteristics of the channel, and are also consistent with the study by Hair *et al.* (2019), which noted that grouping samples from different locations within a single cluster indicates the presence of common environmental factors that control the distribution of variables more than the influence of geographic location. Ward (1963) also explained that the Ward method produces clusters with high internal homogeneity and clear differentiation between groups, which is consistent with the results of the present study.

**Atmospheric $CO_2$ concentration**

The results showed that the average concentration of carbon dioxide in the air was 543.77 parts per million (ppm), indicating a relative increase in $CO_2$ concentrations during the measurement period compared to the global average. This may be linked to the impact of industrial and port activities surrounding Khor Al-Zubair, as well as local emissions. The concentration of carbon dioxide in the air directly affects gas exchange with the water surface, as gas transfer toward or away from the water increases depending

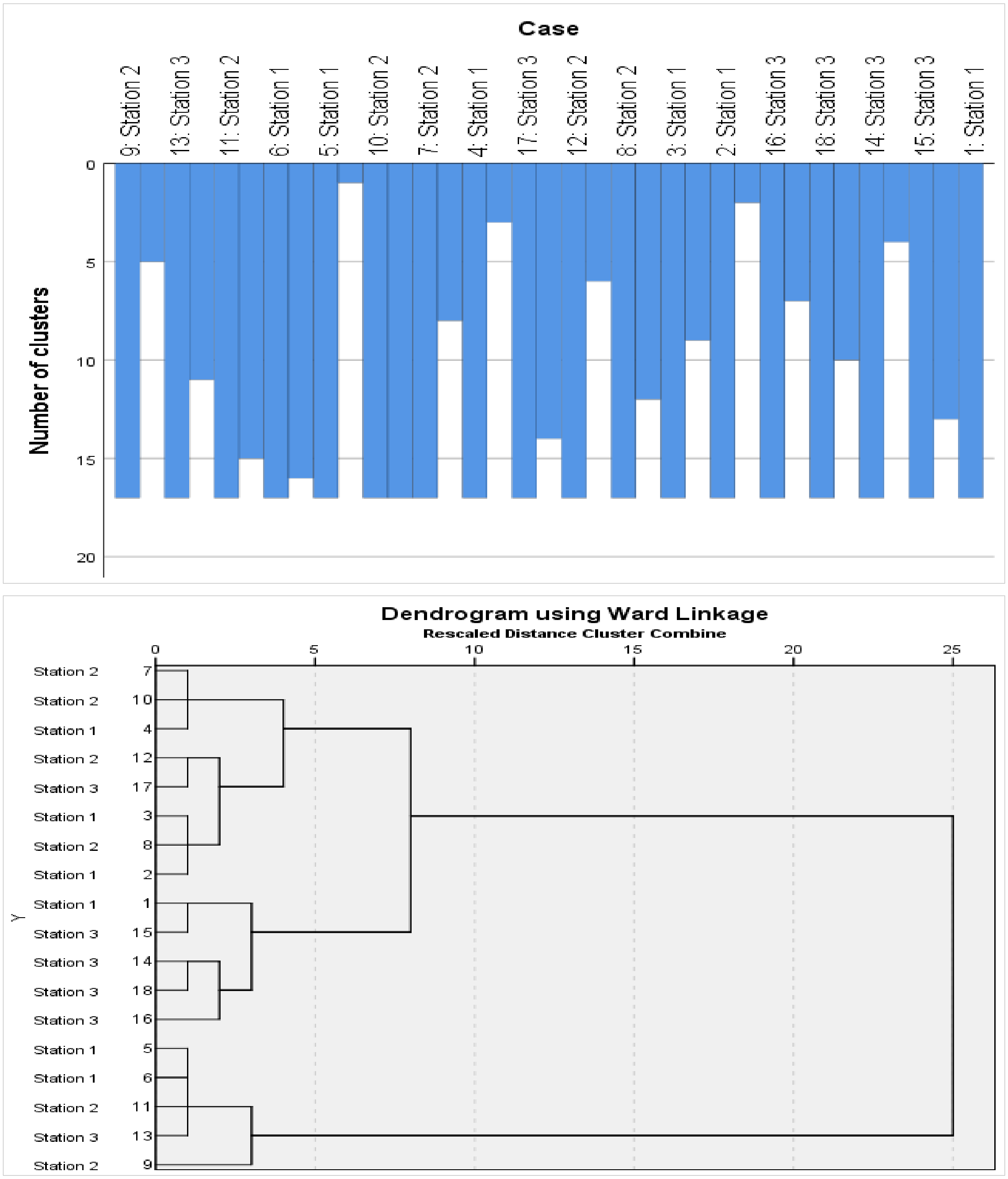


**Figure (4&5):** Cluster Quality Chart and Hierarchical Cluster Analysis (HCA) dendrogram illustrating the classification and similarity of Sediment samples among the study stations based on their physicochemical parameters.

on the partial pressure differences between the two media. Increased atmospheric $CO_2$ concentrations affect coastal water chemistry by enhancing the dissolution of carbon dioxide and altering the carbonate system. (IPCC, 2021). The relationship between atmospheric $CO_2$ and dissolved $CO_2$ in water is one of the most important factors regulating the carbon cycle in marine environments. [133]

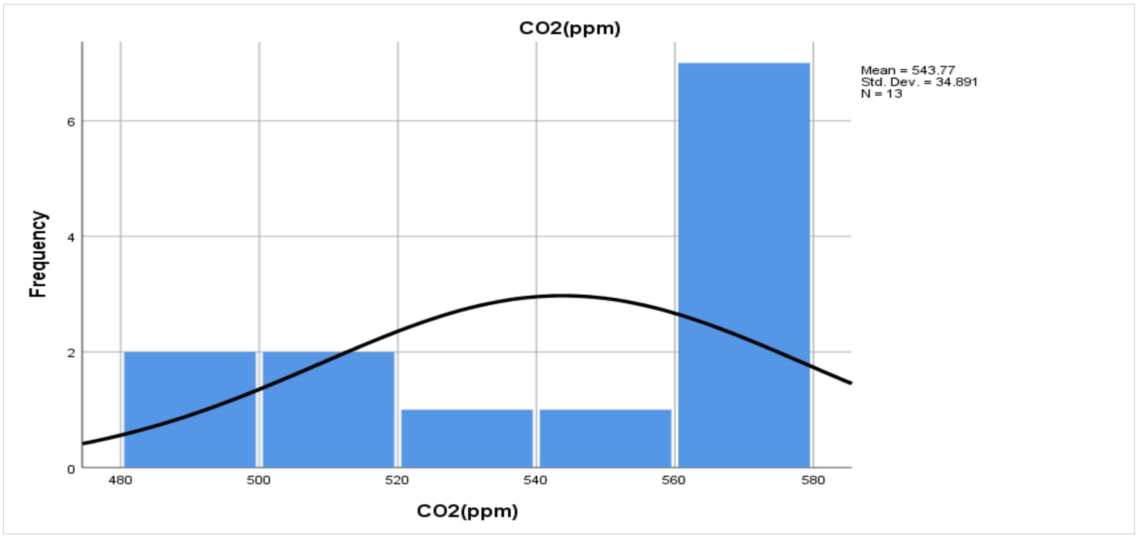


**Figure (6):** The frequency distribution of carbon dioxide gas is illustrated along with the distribution curve.

## Calculation of Atmospheric $CO_2$ Pressure and $CO_2$ Pressure in Water

### Atmospheric $CO_2$ Pressure

The atmospheric $CO_2$ pressure was calculated, given that the atmospheric $CO_2$ concentration ranged from 490 to 580 ppm. Concentration in gases is a unit expressing the molar fraction or volume fraction of the gas. This calculation is based on the total atmospheric pressure surrounding the system and the relationship between the volume fractions of the gases according to Dalton's law of partial pressures, which is calculated using the following equation:

$$pCO_2(\text{atm}) = \frac{\text{Value(ppm)}}{1000000} \times (p_{\text{Total}})$$

$p_{\text{Total}}$: (total atmospheric pressure of the ocean); its value is equal to 1 atm at sea level under standard natural conditions (Dickson et al., 2007).
Convert the resulting value to µatm by multiplying it by $10^6$.

### $CO_2$ Pressure in Water

The pressure of $CO_2$ gas in water was calculated using Henry's Law, which states that the partial pressure of a gas above a liquid is directly proportional to its concentration in solution. The concentration ranged from 5.9 to 15.9 mg/L. Henry's solubility constant was calculated based on temperature and salinity, as these two variables affect water's ability to hold gas. We used the Weiss equation to calculate the KH constant in units of mol/(kg·atm). (Weiss, 1974)

$$\ln kH = A1 + A2\left(\frac{100}{T}\right) + A3\ln\left(\frac{T}{100}\right) + S[\text{B1}+\text{B2}(\text{T}/100)+\text{B3}(\text{T}/100)^2]$$

**S**: Salinity in ppt
**T**: Absolute temperature, calculated in kelvins

$$T_K = T°C + 273$$

A1: Basic thermal constant (the standard value for $CO_2$ is 60.2409-)
A2: Thermal activation energy coefficient (the standard value for $CO_2$ is 93.4517, in kelvins)
A3: Thermal logarithmic coefficient (the standard value for $CO_2$ is 23.3585)
B1: Ionic salinity correction coefficient (the standard value for $CO_2$ is 0.0023517, with units of $PPt^{-1}$)
B2: Linear thermal salinity correction factor (the standard value for $CO_2$ is 0.023656, with the unit $PPt^{-1}$)
B3: Quadratic thermal salinity correction factor (the standard value for $CO_2$ is 0.0047036, with the unit $PPt^{-1}$).
We convert the gas concentration unit from mg/L to micromoles/kg, since the standard coefficient appropriate for the environmental parameters of the measured data—based on temperature and salinity—is 19.49. (Dickson *et al.*, 2007).

$$\text{Value(mol/kg)} = \text{Value(mg/L)} \times \text{Factor}$$

Then we substitute it into the following equation:

$$\text{PCO}_2(atm) = \frac{[CO2]}{KH}$$

We convert the resulting value to μatm by multiplying it by $10^6$.

The results showed that the highest $CO_2$ pressure in water was at Station 2, and the lowest $CO_2$ pressure in water was at Station 1, while the atmospheric $CO_2$ pressure ranged between (490–577 ppm).

We find that the partial pressure of $CO_2$ in the creek water (3,616–11,950 μatm) is many times greater—and significantly higher—than the partial pressure in the atmosphere (478–576 μatm), as this pressure gradient sharply decreases from the water toward the atmosphere. Al-Zubair Creek is therefore classified as a highly dynamic and active source of carbon emissions, compensating for the enormous thermodynamic difference with the atmosphere, rather than a sink (Burdige, 2006).

This explanation is due to several geochemical and environmental factors, including:
1-Extremely high salinity (52 PPt) resulting from intense evaporation in the summer, which leads to the salting-out effect, thereby reducing the water's thermal capacity to retain gas and forcing it to release the gas into the atmosphere at very high pressure (Weiss, 1974).

2- A sharp drop in pH: The system is considered slightly basic, tending toward relative acidity. This system prevents carbonates and bicarbonates from absorbing the gas and converting it into solid precipitates, leaving $CO_2$ free to seek any opportunity to escape and disperse into the atmosphere according to Henry's law (Millero, 2007).
3-Biological pressure of organic matter: The alkalinity values recorded at low pH levels chemically indicate that the estuary system is undergoing continuous organic

decomposition (bacterial respiration), during which free carbon dioxide is released at a rate far exceeding the water column's capacity to dissipate it, resulting in a state of permanent oversaturation throughout the year (Burdige, 2006).

## Conclusions

The study's results showed that Khor Al-Zubair is a coastal system clearly affected by industrial and maritime activities, with the liquefied natural gas port area recording the highest concentrations of carbon dioxide due to combustion processes and industrial emissions. The results also indicated a direct relationship between rising carbon dioxide concentrations and water temperature, reinforcing the impact of local warming in the region. Partial pressure values for carbon dioxide confirmed that Khor Al-Zubair acts as a source of carbon emissions rather than a sink, with a notable accumulation of total organic carbon in sediments due to human activities. Conversely, the study showed that high total alkalinity and an abundance of bicarbonate and carbonate ions provided the system with buffering capacity, which helped maintain chemical equilibrium and limit water acidification. The results also revealed an inverse relationship between carbon dioxide and dissolved oxygen, with oxygen levels remaining within acceptable ecological limits due to the effects of natural mixing and aeration processes.

## Recommendations

The study recommends establishing ongoing environmental monitoring programs to track concentrations of carbon dioxide and greenhouse gases in the industrial and port areas of Khor Al-Zubair, with the aim of assessing changes over time and mitigating their environmental impacts. It also recommends strengthening oversight of industrial and organic waste discharge to limit the accumulation of organic carbon in sediments and preserve water quality and dissolved oxygen levels. The study further emphasizes the importance of protecting carbonate-rich sediments due to their essential role in enhancing the regulatory capacity of the coastal system and resisting water acidification, while stressing the need to direct future studies toward assessing the long-term impacts of rising carbon dioxide levels on calcareous marine organisms and the coastal ecosystem in southern Iraq, thereby contributing to the development of effective strategies for the sustainable management of the region.

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# ديناميكيات الكربون وتدفقات ثاني أكسيد الكربون في المياه الساحلية والرواسب على طول خور زبير في جنوب العراق

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**المستخلص**

هدفت هذه الدراسة إلى تقييم دور خور الزبير كمصرف للكربون ضمن النظم الإيكولوجية الساحلية، وفهم ديناميكيات تبادل الكربون بين الغلاف الجوي والمياه والرواسب تحت تأثير المد والجزر والأنشطة الصناعية. أُجريت الدراسة في ثلاث محطات رئيسية تمتد من ميناء خور الزبير إلى ميناء أم قصر، من خلال برنامج رصد ميداني ومختبري نُفِّذ على مدار 13 ساعة خلال دورة مد وجزر نصف يومية. وأظهرت النتائج تباينًا مكانيًا ذي دلالة إحصائية في درجة حرارة المياه ($F = 685.00$، $P < 0.001$)، مما أثر على قابلية الغازات للذوبان وتفاعلات نظام الكربونات، في حين تراوحت قيم الرقم الهيدروجيني بين 7.0 و7.2، متأثرةً بشكل أساسي بتقلبات المد والجزر ($P = 0.001$). كما بلغت الملوحة أعلى قيمة لها عند المحطة 3 بالقرب من الخليج العربي (52.416 جزء في الألف) وأدنى قيمة لها عند المحطة 2 (44.864 جزء في الألف)، في حين تراوحت القلوية الكلية بين 170 و212 ملغ/لتر، وتراوح تركيز ثاني أكسيد الكربون المذاب بين 5.9 و15.9 ملغ/لتر. وأظهرت حسابات الضغط الجزئي لثاني أكسيد الكربون ($pCO_2$) قيمًا عالية تراوحت بين 3,616 و11,950 ميكروأتم مقارنةً بالمستويات الجوية (478–576 ميكروأتم)، مما يؤكد أن خور الزبير يعمل كمصدر صافٍ لانبعاثات الكربون بدلاً من أن يكون مستودعًا للكربون في الرواسب، بلغ متوسط الكربون العضوي الكلي1.59٪ (TOC) ، بقيمة قصوى تبلغ 4.39٪، بينما تراوح محتوى كربونات الكالسيوم ($CaCO_3$) بين 7.83 و26.58٪، وبلغ متوسط القلوية الكلية 428.44 ملغم/لتر، مما يشير إلى أن الرواسب تمتلك قدرة تخميد تساعد على الحد من آثار تحمض المياه والحفاظ على استقرار نظام الكربونات. وتخلص الدراسة إلى أن خور الزبير يُعد مصدرًا لانبعاثات ثاني أكسيد الكربون؛ ومع ذلك، فإن ارتفاع القلوية فيه ووفرة البيكربونات والكربونات فيه تساهمان في الحفاظ على التوازن الكيميائي والحد من تحمض المياه.

**الكلمات المفتاحية**: خور الزبير، ثاني أكسيد الكربون، الكربون العضوي الكلي، جودة المياه، القلوية، التلوث الساحلي، جنوب العراق .