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A Study of Organochlorine Compounds in Surficial Sediment of Khor Al-Zubair Channel, Southern Iraq

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Abstract - The concentrations of polychlorinated biphenyls (PCBs) in the surface sediments of Khor Al-Zubair channel in southern Iraq from six different stations were estimated. These sediments constitute an active interface between water and the benthic environment, making them a sensitive indicator of contemporary pollution. Using GC-MS techniques, 12 PCB compounds were identified, with concentrations ranging from 0.01 to 2.22 ng/g dw in summer and 0.01 to 1.56 ng/g dw in winter. The highest values were recorded at Station 1 and the lowest at Station 5, reflecting the distinct variation in pollution sources and dynamics. These results represent an important first step toward understanding the environmental challenges in the region.

Additionally, the study included accurate measurements of a range of environmental variables, such as water and air temperature, salinity, TDS, DO, and TOC, which are key factors in determining the fate of organic pollutants. For example, the data suggest that lower winter temperatures may favor the retention of organic compounds in sediments, while lower TOC at Station 5 may explain the low PCB levels there. These data are more than just numbers; they illustrate a complex history of interactions between the environment and pollutants, requiring deeper analysis to understand the factors controlling the behavior of these compounds in Khor Al-Zubair and provide realistic solutions based on science and observations.

دراسة تراكيز مركبات الكلور العضوية في الرسوبيات السطحية لقناة خور الزبير، جنوب العراق

محمد اياد كامل ويوسف شافي جبر وعلاء عادل مزهر
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المستخلص – تم تقدير تراكيز مركبات ثنائي الفينيل متعدد الكلور (PCBs) في الرسوبيات السطحية لقناة خور الزبير بجنوب العراق من ست محطات مختلفة، باعتبارها مؤشراً مهماً للتلوث المعاصر. باستخدام تقنية الكروماتوغرافيا الغازية – مطياف الكتلة(GC-MS) ، تم تحديد 12 مركباً بتراكيز تراوحت بين 0.01- 2.22 نانوغرام/غرام وزن جاف في الصيف 0.01- 1.56 نانوغرام/غرام في الشتاء، وسُجلت أعلى القيم في المحطة 1 وأدناها في المحطة 5، كما قيست المتغيرات البيئية الرئيسة (درجة حرارة الماء والهواء، الملوحة، TDS، DO، TOC) التي تؤثر في مصير الملوثات العضوية. أوضحت النتائج أن انخفاض درجات الحرارة في الشتاء يعزز احتباس الـ PCBs في الرسوبيات، بينما يفسر انخفاض TOC في المحطة 5 المستويات المنخفضة للمركبات هناك. تشير هذه المعطيات إلى تباين ديناميكية التلوث وعلاقته بالخصائص البيئية، مما يشكل خطوة أساسية لفهم التحديات البيئية في خور الزبير.

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كلمات مفتاحية: مركبات ثنائي الفينيل متعدد الكلور، الرواسب السطحية، خور الزبير-العراق، المتغيرات البيئية.

Introduction

Organochlorine compounds (OCs), including polychlorinated biphenyls (PCBs), are a class of synthetic organic compounds characterized by exceptional chemical stability, low aqueous solubility, and high lipid solubility. These inherent properties contribute significantly to their persistence in the environment and their pronounced tendency to bioaccumulate in organisms and bio magnify through aquatic and terrestrial food webs (Li *et al.,* 2023). Historically, PCBs have been widely used in various industrial applications, including as dielectric fluids in transformers and capacitors, hydraulic fluids, lubricants, and plasticizers (IARC, 2016). However, their widespread production has been largely banned worldwide due to growing environmental and health concerns, leading to their classification as persistent organic pollutants (POPs) under international agreements such as the (Stockholm Convention, 2025), Due to their long-term persistence and bioaccumulation potential, PCBs pose a significant threat to both ecosystem integrity and human health. Exposure to these compounds has been associated with a range of adverse effects, including reproductive and developmental abnormalities, immunotoxicity, endocrine disruption, and carcinogenicity in various wildlife species and humans (IARC, 2016).

Estuarine systems, like Khor Al-Zubair, are dynamic transitional areas where salty marine waters meet freshwater supplies from rivers. These environments are recognized for their high biological productivity, functioning as vital nursery grounds and critical habitats for a diverse array of aquatic and terrestrial species. Nevertheless, their unique geographical position at the interface of land and sea renders them particularly susceptible to receiving and accumulating pollutants from various anthropogenic sources, including industrial discharges, agricultural runoff, and urban wastewater. Khor Al-Zubair is specifically identified as an important body of water, serving as a crucial waterway for maritime navigation while simultaneously providing a suitable environment for numerous living organisms. This dual role underscores the critical need for comprehensive environmental quality assessment within this region.

The primary objective of this study was to evaluate the current levels of PCB contamination in the surficial sediments of this vital Iraqi waterway. The study designation as the "first and as a baseline study" for the region highlights a significant gap in existing environmental data. Prior to this research, there was a critical lack of systematic information regarding the presence, concentrations, and spatial distribution of PCBs in the surficial sediments of Khor Al-Zubair. This fundamental data deficit makes the findings of this investigation indispensable, as they establish a foundational dataset. Without such a baseline, it would be impossible to accurately assess future trends in pollution, evaluate the effectiveness of any potential pollution control measures, or fully understand the long-term ecological impacts of industrial or urban development on the Khor Al-Zubair ecosystem. Thus, this study serves as a foundational pillar for subsequent environmental research and informs policy decisions aimed at protecting this valuable aquatic resource.

Study Area:

Khor Al-Zubair is geographically situated in southern Iraq, positioned to the west of the city of Basrah. Its precise coordinates are identified as being between longitudes 29' and 23' and latitudes 58' north-west of the Arabian Gulf. This area is characterized as a significant waterway for maritime navigation, indicating potential anthropogenic pressures from shipping and industrial activities, Simultaneously, it is recognized as a suitable environment supporting a diverse array of living organisms, underscoring its ecological importance (Sultan *et al.*, 2022), as shown in (Figure 1).

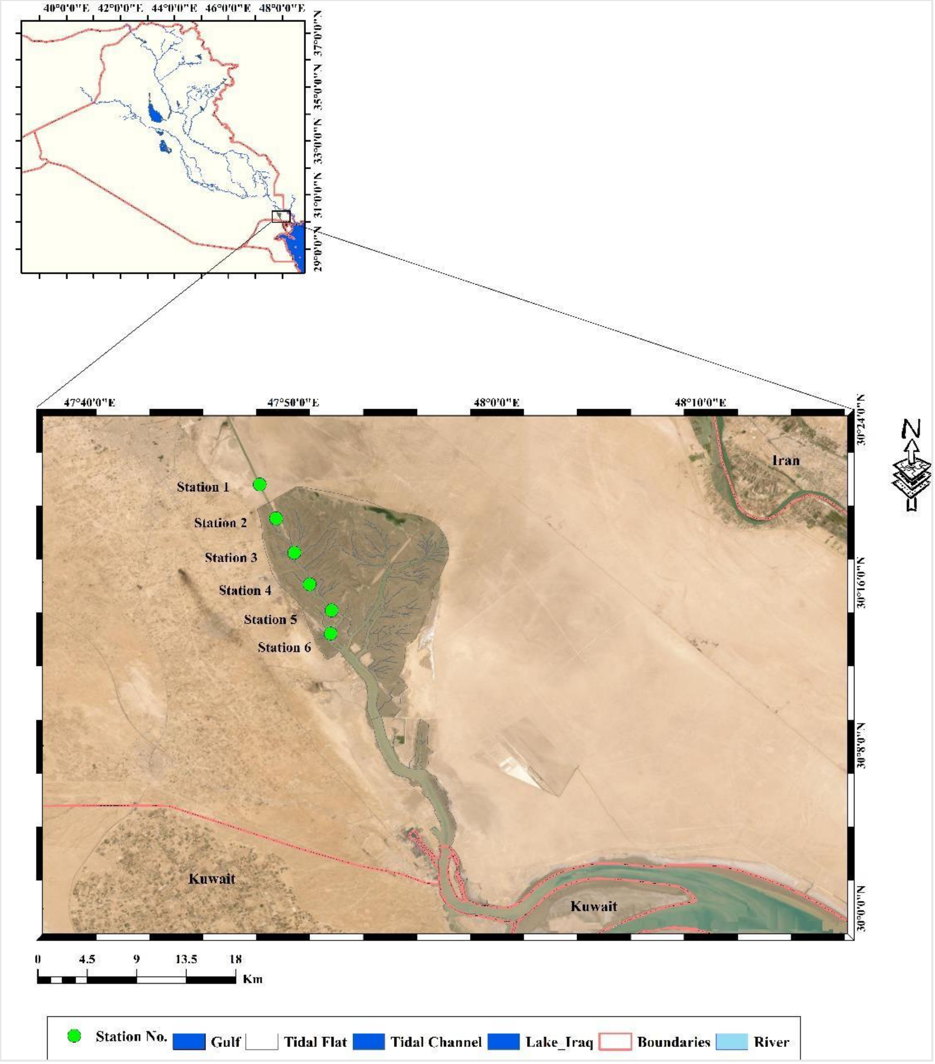


Figure 1. Study station locations.

Collection and Preparation of Samples:

Sediment samples were systematically collected from six distinct locations along Khor Al-Zubair channel. To ensure representative spatial coverage and facilitate comparisons, the selected stations were strategically positioned approximately 4 km apart from each other. The collection of surficial sediment samples was performed using grab samplers, a commonly employed method for obtaining relatively undisturbed sediment samples from the designated aquatic regions. Water samples were collected in Winkler bottles for the purpose of measuring dissolved oxygen, immediately following collection, the sediment samples underwent initial processing, during which excess water was allowed to drip away. Subsequently, the samples were carefully wrapped in aluminum foil, properly identified with unique labels, and then transported to the laboratory for further analytical studies. In the laboratory, the sediment samples were subjected to freeze-drying, a standard preservation technique employed to remove moisture while minimizing the degradation of organic compounds. After the freeze-drying process, any visible pollutants were meticulously removed. The sediment samples were then crushed using a FRITSCH mill to achieve a homogeneous matrix, which is essential for consistent analysis.

Then, the crushed materials were sieved through a fine (63 µm) aperture sieve. This specific methodological detail significantly influences the interpretation of the PCB concentration data. In sedimentology and environmental chemistry, finer sediment particles (silt and clay, generally less than 63 µm) preferentially adsorb hydrophobic organic compounds like PCBs (Farid *et al.,* 2016). This is due to their significantly larger surface area-to-volume ratio and higher organic carbon content compared to coarser sand particles. Organic carbon serves as the primary sorbent for PCBs in sediments. By standardizing the analysis to the (<63 µm) fraction, the sediment fraction most likely to accumulate PCBs, and where their concentrations are typically highest, was focused on by the researchers.

This approach ensures that comparisons of PCB levels across different sampling stations are based on a consistent and relevant matrix, reducing variability introduced by differences in overall sediment granulometry. This provides a more accurate and ecologically relevant measure of PCB contamination and enhances the comparability of the study findings with other research employing similar particle size fractionation.

PCB Extraction and Cleanup Procedure:

The methodology for estimating PCBs in the sediment followed the general procedures for Soxhlet extraction detailed in U.S. EPA Method 3540C (2024). A precise amount of (20 g) of salt was added to a thimble, as a drying agent or to enhance extraction efficiency. Polychlorinated biphenyls (PCBs) were then extracted from the sediment samples using a Soxhlet Intermittent Extraction device, employing (100 ml) of a solvent mixture consisted of hexane and methylene chloride (v/v 1:1), under controlled conditions at 40°C for a duration of 48 hours.

After extraction, the raw extract was cooled and subsequently underwent a saponification step for two hours using (15.0 mL) of 4M potassium hydroxide in methanol for removing interfering fatty acids and lipids that can co-extract with PCBs and hinder subsequent analysis. The saponified contents were then transferred to a separating funnel, and an additional (50.0 mL) of the (1:1 hexane/methylene chloride) combination was added after cooling to facilitate effective phase separation. The separating funnel was firmly shaken, and the solution was allowed to stand until it clearly separated into two distinct layers. The soaped bottom layer, containing the saponified fatty acids, was carefully removed and discarded.

The unsoaped top organic layer, which contained the PCBs, was then transferred to a chromatographic separation column. This column was prepared with glass wool at its base, followed by (2 g) of silica gel, and alumina on top. This multi-layered column is designed for further purification and the removal of residual interfering compounds. (2 g) of anhydrous sodium sulfate were used to remove any remaining water from the purified extract, ensuring a dry sample suitable for analysis. The final, cleaned extract was labeled, dried, and sealed in a glass container, for analysis by the GC-MS.

This detailed and multi-step analytical protocol, encompassing Soxhlet extraction, specific solvent mixtures, controlled temperature and duration, multi-stage cleanup procedures (saponification and column chromatography with silica gel/alumina), and final GC-MS analysis, signifies a highly rigorous and well-established approach for the trace analysis of persistent organic pollutants in environmental matrices (U.S. EPA, 2014; U.S. EPA, 2024). Each of these steps is a standard, validated technique in environmental analytical chemistry. Soxhlet extraction is known for its high efficiency in extracting hydrophobic compounds from solid samples (U.S. EPA, 2024). Saponification is essential for removing co-extracted lipids that can interfere with GC-MS analysis.

The chromatographic column with silica gel and alumina provides further purification by separating target compounds from other matrix interferences. GC-MS offers high sensitivity and specificity for identifying and quantifying PCBs (U.S. EPA, 2014). The meticulous attention to detail and the employment of these established, sequential cleanup steps indicate a strong commitment to analytical quality control. This rigorous approach minimizes matrix effects, enhances the recovery of target PCBs, and ensures the purity of the final extract. This level of methodological rigor significantly increases the reliability and accuracy of the reported PCB concentrations. Furthermore, because these are widely accepted standard methods, the results of this study are more readily comparable with data from other international environmental studies that employ similar robust protocols, thereby strengthening the study value as a baseline for global context.

Measuring environmental variables

A mercury thermometer was used to measure the temperature of water and air, while pH, total dissolved solids, and salinity were measured using a multimeter.

The azide modification method was used for measuring dissolved oxygen according to the Winkler method as described by the American Health Protection Association (APHA, 2017). After field oxygen fixation, (100 ml) of the sample was taken and titrated using sodium thiosulfate (0.0125 N), with starch solution used as a color indicator to determine the end point of the reaction. The results were expressed in mg/L, Deionized was used in all experiment.

Total organic carbon measurement:

Weaver and Clements (1973) method was followed to measure the percentage of total organic carbon content in sediments. Sediment samples were dried, impurities were removed, then ground using a ceramic mortar and sieved through a sieve with a hole diameter of (63 µm). (2 g) of the dry weight of the sample was taken and placed in a bucket of known weight, then it was placed in an incineration furnace at a temperature of (550 °C) for 48 hours. After that, the sample was transferred directly to the desiccator until it returned to the laboratory temperature, and then the samples were weighed, where the difference between the initial weight and the weight after incineration represents the total organic carbon content.

Sediment texture measurement:

The percentage of sediment texture was determined using the hydrometer method. Initially, the sample was sieved using a (2 mm) sieve to remove large particles. A (50 g) sample was then taken and mixed with distilled water to form a suspension. (125 ml) of dispersing agent solution (sodium hexametaphosphate) was then added, and the sample was left to stand for one hour. After the waiting period, the sample was mixed using an electric mixer for one minute. The contents of the mixer were then emptied into a (1 L) cylinder. The volume was filled with distilled water, and the contents were thoroughly mixed to prepare the sample for hydrometer density measurement. The hydrometer readings were taken, taking into account the temperature of the mixture during the measurement. The percentages of sediment components (sand, silt, and clay) were then calculated according to the method (Black, 1965).

Analytical Quantification:

The concentrations of PCBs in the prepared extracts was estimated using a Gas Chromatography-Mass Spectrometry (GC-MS) apparatus, following the general protocols of U.S. EPA Method 8270D (2014). This highly sensitive and selective technique is a standard and robust method for identifying and quantifying trace organic contaminants in complex environmental samples (U.S. EPA, 2014).

Statistical analysis

The data were analyzed using the Genstat statistical software to test the significance of differences between means, employing the Least Significant Difference (L.S.D) test at a significance level of 0.05.

Results:

PCBs Concentrations

The study successfully detected and quantified 12 specific PCB congeners (PCB-18, PCB-31, PCB-28, PCB-44, PCB-52, PCB-101, PCB-141, PCB-149, PCB-138, PCB-153, PCB-189, and PCB-194) in the surficial sediment samples, During the summer season, concentrations ranged from (0.01 - 2.22 ng/g dry weight) as shown in (Table 1) and (Figure 2). During the winter season, concentrations ranged from (0.01 - 1.56 ng/g dry weight) as shown in (Table 2) and (Figure 3).

Table 1. Concentrations and types of PCBs (ng/g dw) during the summer season.

Compound Name	**St1**	**St2**	**St3**	**St4**	**St5**	**St6**
PCB 18	0.74	0.20	0.31	0.61	0.00	0.36
PCB 31	0.01	0.23	0.11	0.20	0.01	0.18
PCB 28	0.06	0.26	0.17	0.05	0.01	0.21
PCB 44	2.22	0.66	0.01	0.02	0.06	0.11
PCB 52	0.44	0.10	0.15	0.01	0.00	0.03
PCB 101	0.67	0.70	0.29	0.01	0.15	0.32
PCB 141	0.02	0.20	0.23	0.09	0.00	0.01
PCB 149	0.81	0.03	0.04	0.01	0.00	0.10
PCB 138	0.29	0.33	0.11	0.03	0.00	0.01
PCB 153	0.38	0.16	0.30	0.34	0.00	0.21
PCB 189	0.32	0.23	0.06	0.02	0.00	0.02
PCB 194	0.05	0.36	0.10	0.04	0.00	0.01
Total	6.02	3.46	1.87	1.43	0.23	1.57

Mean	0.50	0.29	0.16	0.12	0.02	0.13
±SD	0.61045	0.20382	0.10456	0.18407	0.04393	0.12493

0=Not detected

Summers Concentrations:

The highest total PCB concentration during the summer season was (6.02 ng/g dw), at Station1. The lowest total PCB concentration during the summer season was (0.23 ng/g dw), at Station5.

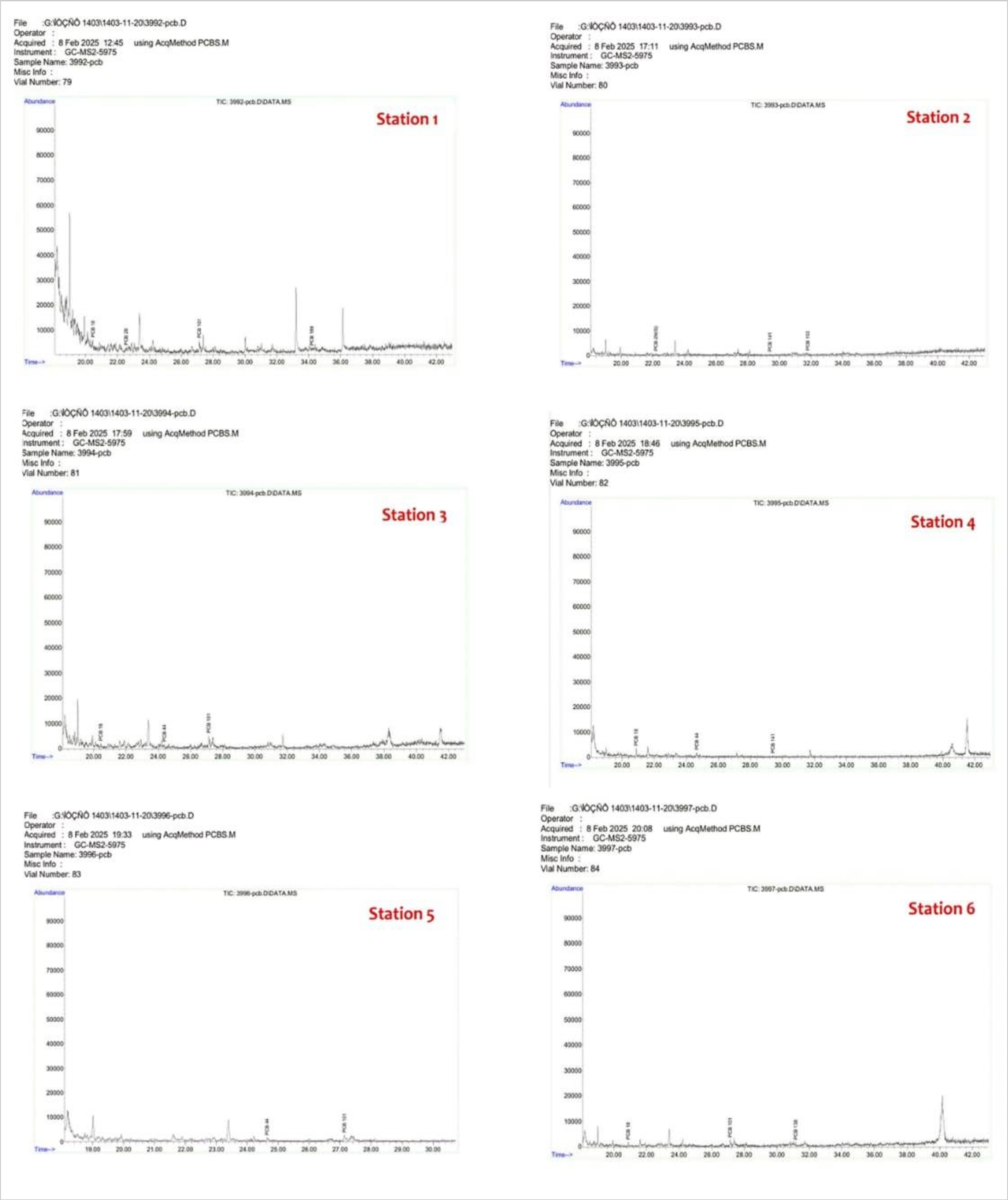


Figure 2. GC-Mass chromatography of PCBs at stations during the summer

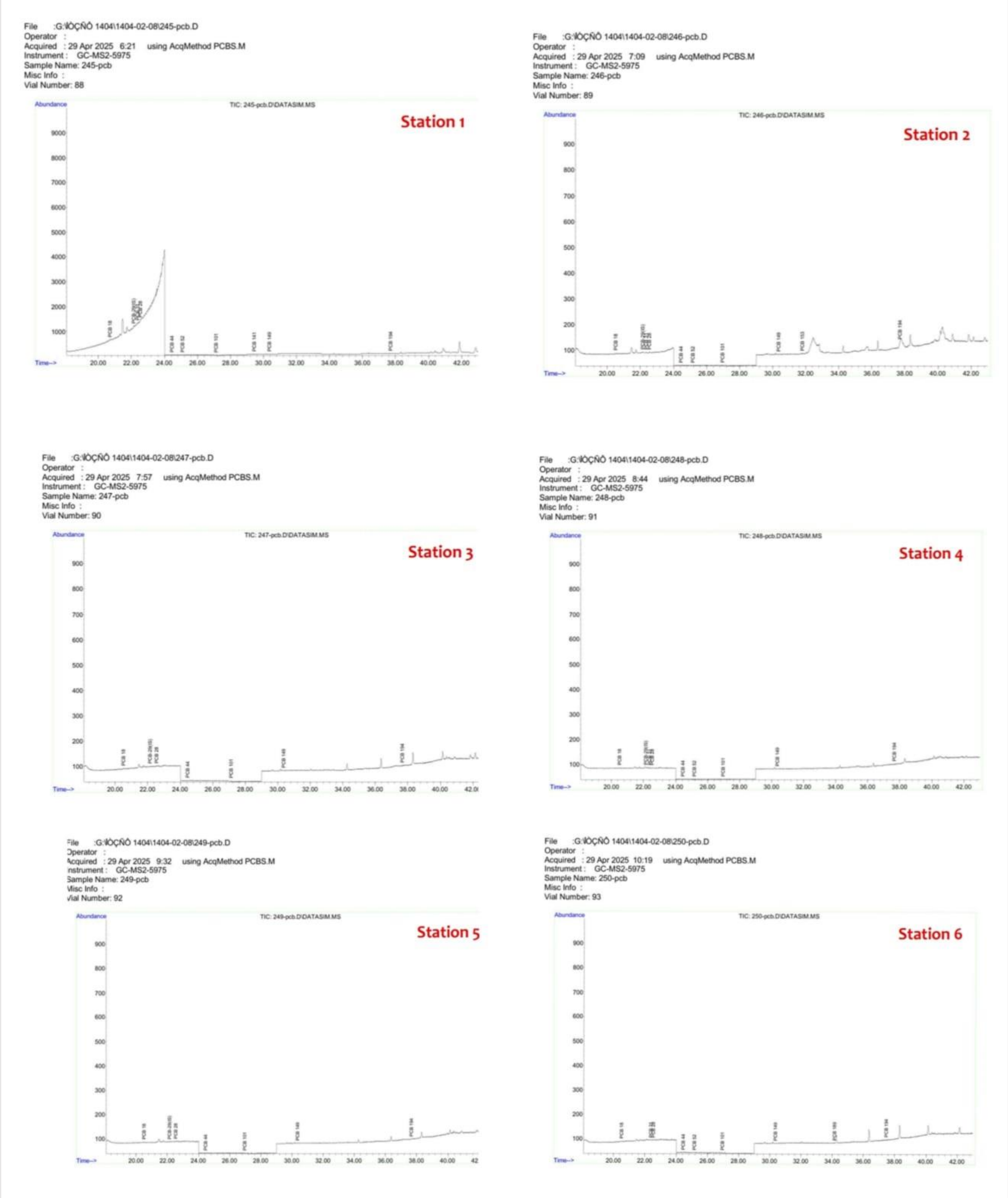
Table 2. Concentrations and types of PCBs (ng/g dw) during the winter season.

Compound Name	St1	St2	St3	St4	St5	St6
PCB 18	0.60	1.09	1.56	1.34	1.51	1.02
PCB 31	0.01	0.01	0.15	0.03	0.04	0.01
PCB 28	1.24	0.27	0.14	0.19	0.15	0.38
PCB 44	0.53	0.04	0.04	0.04	0.03	0.04
PCB 52	0.77	0.59	0.31	0.73	0.01	0.35
PCB 101	0.52	0.53	0.04	0.25	0.10	0.34
PCB 141	0.65	0.72	0.56	0.09	0.00	0.10
PCB 149	0.07	0.13	0.06	0.04	0.03	0.09
PCB 138	0.79	0.36	0.15	0.01	0.00	0.10
PCB 153	0.91	0.02	0.18	0.28	0.20	0.10
PCB 189	0.96	0.90	0.03	0.03	0.00	0.46
PCB 194	0.32	0.49	0.15	0.04	0.11	0.04
Total	7.37	5.13	3.37	3.08	2.18	3.05
Mean	0.61	0.43	0.28	0.26	0.18	0.25
±SD	0.35942	0.35605	0.42738	0.39620	0.42351	0.28766

0=Not detected

Winters Concentrations

The highest total PCB concentration recorded was (7.37 ng/g dw at Station 1 during the winter season. The lowest total PCB concentration during the winter season was (2.18 ng/g dw), at Station 5. These ranges were specifically noticed between Station 1 and Station 5, respectively, showing significant spatial variability in PCB distribution



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Instrument : GC-MS2-5975
Sample Name: 245-pcb
Misc Info :
Vial Number: 88

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Instrument : GC-MS2-5975
Sample Name: 250-pcb
Misc Info :
Vial Number: 93

Figure 3. GC-Mass chromatography of PCBs at stations during the winter

Environmental Variables:

The study provides comprehensive environmental data for summer season as shown in (Table 3) and (Table 4) in winter along study area. These variables offer essential sight about the environmental conditions that may influence the distribution and behavior of PCBs in Khor Al-Zubair.

Table 3. Environmental variables during the summer.

Environmental Variables	station 1	station 2	station 3	station 4	station 5	station 6
PH	7.6	7.7	7.7	7.5	7.6	7.6
Salinity (ppt)	42.2	49.1	47.7	46	41.9	42.2
TDS (ppm)	53.1	63.1	61.1	58.7	53	53.1
DO (mg/L)	2	2.6	2	2.8	7.8	5.8
water temp C°	34	34.4	35	36	36	36
air temp C°	39	42.3	44	46.2	48	48
TOC %	0.334	0.342	0.323	0.235	0.35	0.091

Table 4. Environmental variables during the winter.

Environmental Variable	station 1	station 2	station 3	station 4	station 5	station 6
PH	8.1	7.95	8.06	8	7.86	7.92
Salinity (ppt)	38.7	39.7	44.2	43.6	43.9	43.2
TDS (ppm)	28.6	32.3	35.7	35.6	43.9	35
DO (mg/L)	11.6	11	12.6	10.4	12.8	12.6
water temp C°	15.7	13.8	11.5	12.6	13.6	12.8
air temp C°	24	17	18.4	19.8	21	22.5
TOC %	0.373	0.41	0.114	0.343	0.104	0.097

Discussion

The results showed a clear spatial pattern of PCB distribution in Khor Al Zubair sediments, indicating significant variation in contamination levels between the sites. Station 1 recorded the highest concentrations during winter (7.37 ng/g dw) and summer (6.02 ng/g dw) seasons, indicating its proximity to a potential major contamination source, possibly resulting from industrial discharges, urban runoff, or remnants of previous contamination in the area. This pattern is similar to what has been observed in other coastal areas (de Mora *et al.*, 2010). In contrast, Station 5 showed the lowest concentrations in both seasons (0.23 ng/g dw) in summer and (2.18 ng/g dw) in winter), due to its distance from contamination sources or the influence of hydrodynamic factors such as strong currents or low sedimentation.

The data also showed a seasonal effect on PCB concentrations, with levels being higher during the winter as shown in (Figure 4). This may be attributed to increased runoff from rainfall, as well as lower temperatures, which reduce the volatility of these compounds and increase their deposition in sediments. Conversely, high summer temperatures contribute to increased volatility and reduced sediment accumulation. Seasonal changes in water flow and tides may play a role in the redistribution and accumulation of pollutants. These observations support the scientific literature on the behavior of hydrophobic organic compounds, such as PCBs, and their influence on seasonal environmental factors (Li *et al*., 2023).

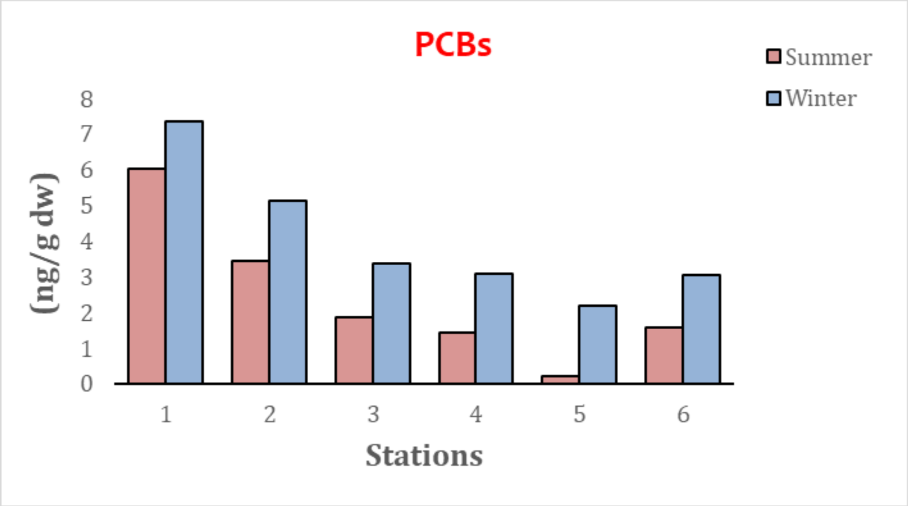

Figure 4. Mean seasonal variations in PCBs (ng/g dw) during summer 2024 and winter 2025.

Air temperature measurements across the six stations showed a consistent and statistically significant difference between summer and winter. Summer temperatures ranged from approximately (40°C - 49°C), whereas winter values were much lower, ranging between (17°C - 24°C), as shown in (Figure 5). The differences at all stations exceeded the LSD value of 0.2405, confirming the significance of seasonal variation.

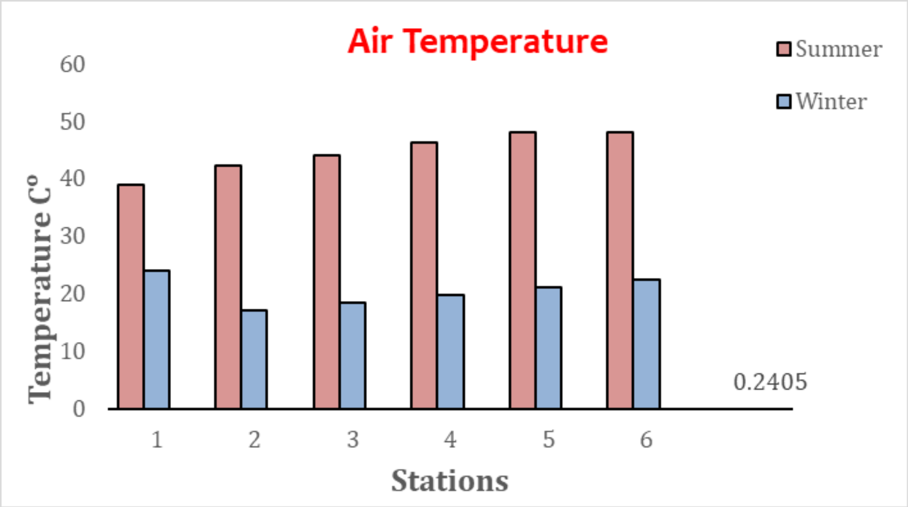

Figure 5. Mean seasonal variations in air temperature (C°) during summer 2024 and winter 2025.

Differences in air temperature are expected in the region and have important implications for environmental processes. Increasing of temperatures in summer may enhance volatilization and photodegradation of PCBs, whereas lower winter temperatures may promote their persistence and accumulation in sediment. This seasonal thermal dynamic helps to explain some of the observed variations in PCB concentrations.

Water temperature exhibited significant seasonal differences along study area stations, with summer temperatures ranging from approximately (34°C - 36°C), and winter between (12°C - 16°C), as shown in (Figure 6). The differences between the two seasons at all stations exceeded the LSD value of 0.2277, indicating statistically significant seasonal variation.

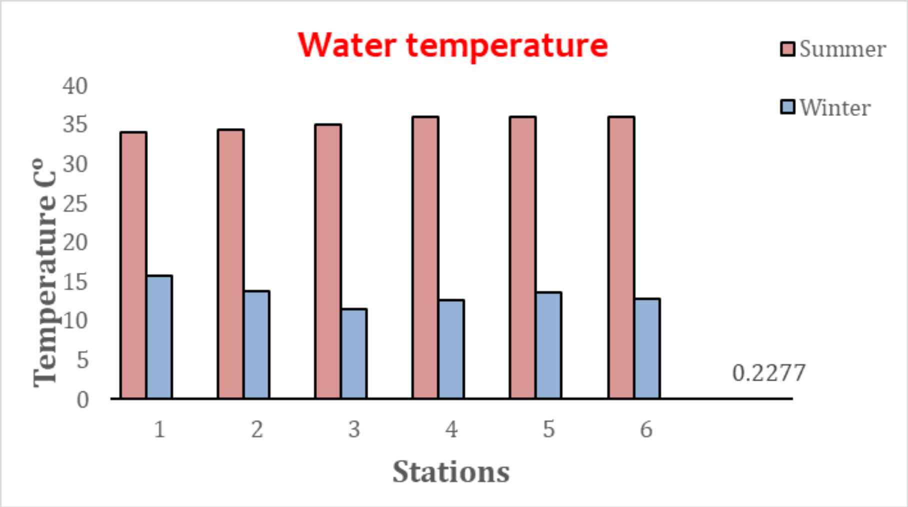

Figure 6. Mean seasonal variations in water temperature (C°) during summer 2024 and winter 2025

Thus, such thermal shifts influence various physicochemical processes in aquatic environments, including the solubility, mobility, and degradation rates of pollutants. In particular, elevated water temperatures during summer may accelerate the volatilization or microbial breakdown of PCBs, while colder winter conditions may reduce such processes and lead to greater pollutant retention in sediments.

Dissolved oxygen (DO) concentrations showed a strong and consistent seasonal pattern, with significantly higher levels in winter across all stations. Winter DO values ranged from approximately (11 - 13 mg/L), while summer values were considerably lower, falling between (2 - 8 mg/L), as shown in (Figure 7). These differences clearly exceeded the LSD value of 0.1141, indicating statistically significant seasonal variation.

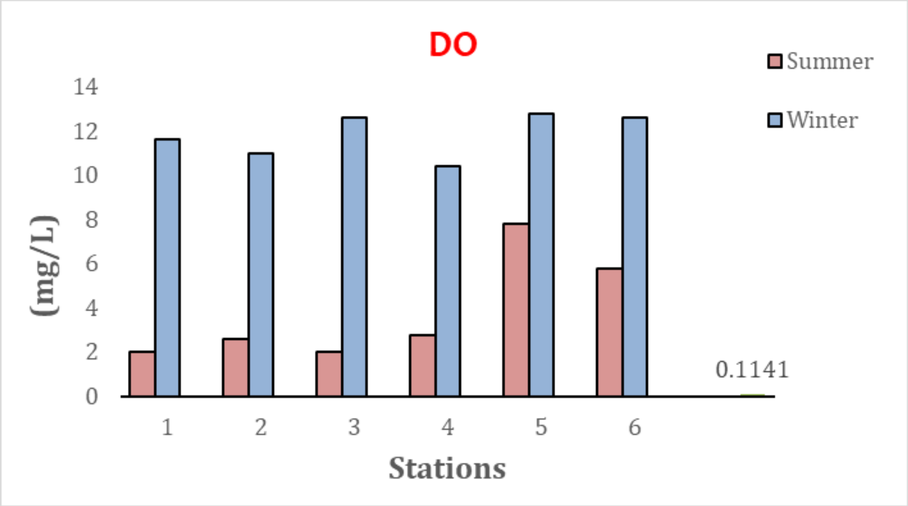

Figure 7. Mean seasonal variations in DO (mg/L) during summer 2024 and winter 2025.

The higher winter DO levels can be attributed to lower water temperatures, which enhance oxygen solubility, as well as reduced microbial activity that consumes oxygen. In contrast, the lower summer concentrations likely result from increased temperatures and higher biological oxygen demand. This seasonal fluctuation in DO is ecologically important and may influence the degradation and mobility of organic pollutants, including PCBs.

PH values across the sampling stations showed slight seasonal variation, with winter values being marginally higher than those in summer. The pH ranged between (7.5 - 8.2), indicating neutral to mildly alkaline conditions throughout the year, as show in (Figure 8). Some differences between seasons exceeded the LSD value of 0.06931, suggesting statistically significant variation at select stations.

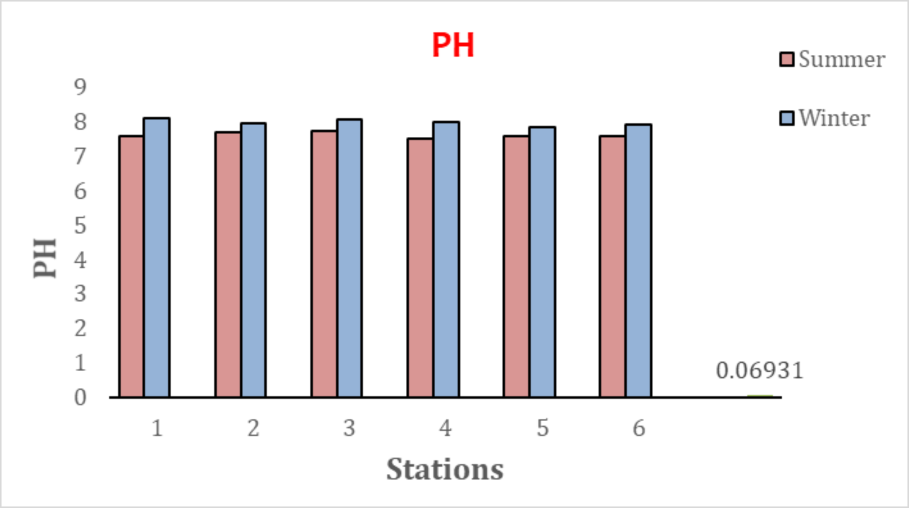

Figure 8. Mean seasonal variations in PH during summer 2024 and winter 2025

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However, the overall stability of pH reflects a relatively buffered aquatic environment. Such mildly alkaline conditions are typical of estuarine and coastal systems and may influence the speciation, solubility, and degradation rates of various pollutants, including PCBs. Nevertheless, pH appears to have played a minimal role in controlling seasonal PCB variability compared to other factors like temperature and dissolved oxygen.

Salinity levels displayed moderate seasonal variation across the six stations. Summer values were generally higher, particularly at stations 2 and 3 where salinity reached approximately (49 ppt). In contrast, winter salinity values ranged between (39 - 45 ppt), as shown in (Figure 9). At certain stations, the differences exceeded the LSD value of 0.219, indicating statistically significant variation, while in others the differences were minimal.

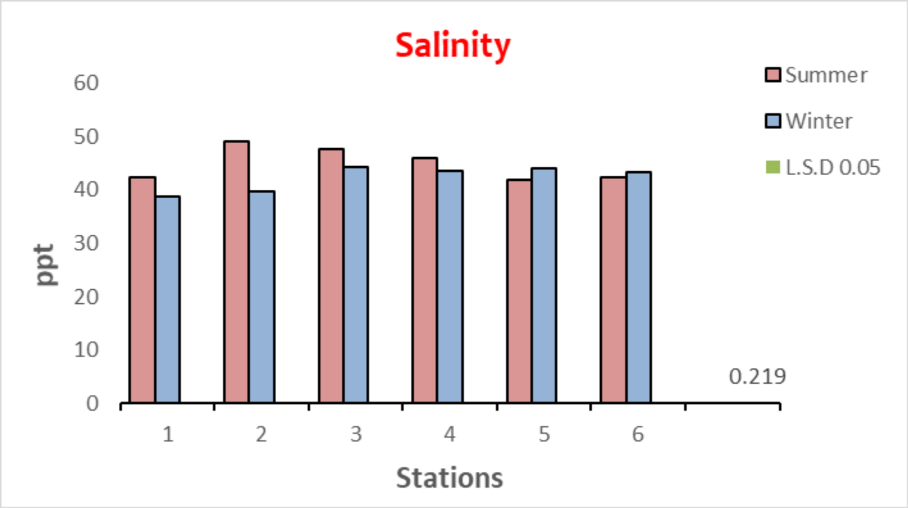

Figure 9. Mean seasonal variations in salinity (mg/L) during summer 2024 and winter 2025.

These seasonal shifts in salinity may be attributed to the increased evaporation during summer and freshwater influx or rainfall during winter. Although the variation is not extreme, it can still influence the behavior of hydrophobic contaminants like PCBs, potentially affecting their partitioning between water and sediments.

Total dissolved solids (TDS) levels showed a distinct seasonal trend, with significantly higher values recorded in summer across all stations. Summer concentrations ranged from approximately (53 - 63 ppm), while winter values were considerably lower, ranging from (28 - 45 ppm), as shown in (Figure 10.) These seasonal differences exceeded the LSD value of 0.2026 at all stations, indicating statistically significant variation.

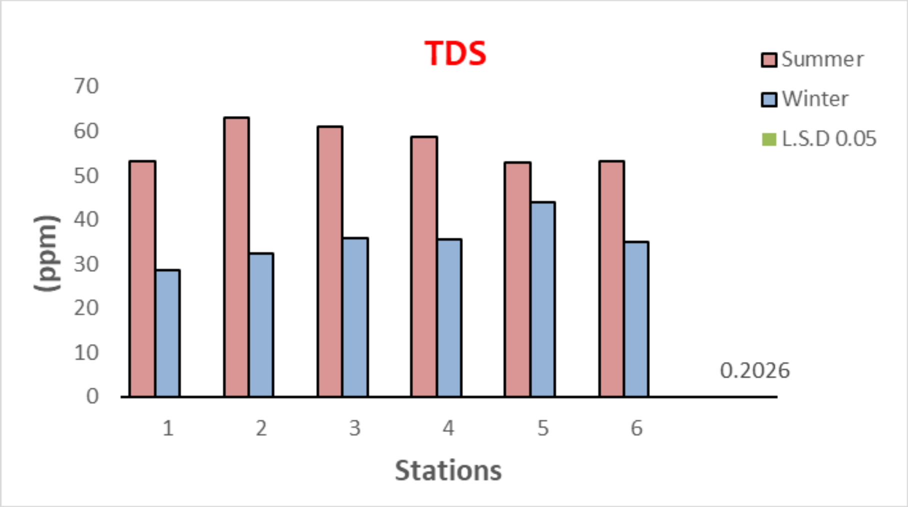

Figure 10. Mean seasonal variations in TDS (mg/L) during summer 2024 and winter 2025.

The elevated summer TDS levels may be attributed to increased evaporation and reduced freshwater input, resulting in the concentration of dissolved ions. In contrast, winter conditions likely led to dilution effects. TDS influences water conductivity and the transport behavior of hydrophobic compounds, including PCBs, thereby playing a role in contaminant dynamics.

Total organic carbon (TOC) levels showed station-dependent seasonal variation. In stations 1, 2, and 4, winter concentrations were notably higher than those in summer, while the opposite trend was observed at stations 3 and 5. At station 6, TOC levels remained consistently low across both seasons, as shown in (Figure 11). In most stations, the differences between seasons exceeded the LSD value of 0.01246, indicating statistically significant seasonal variation.

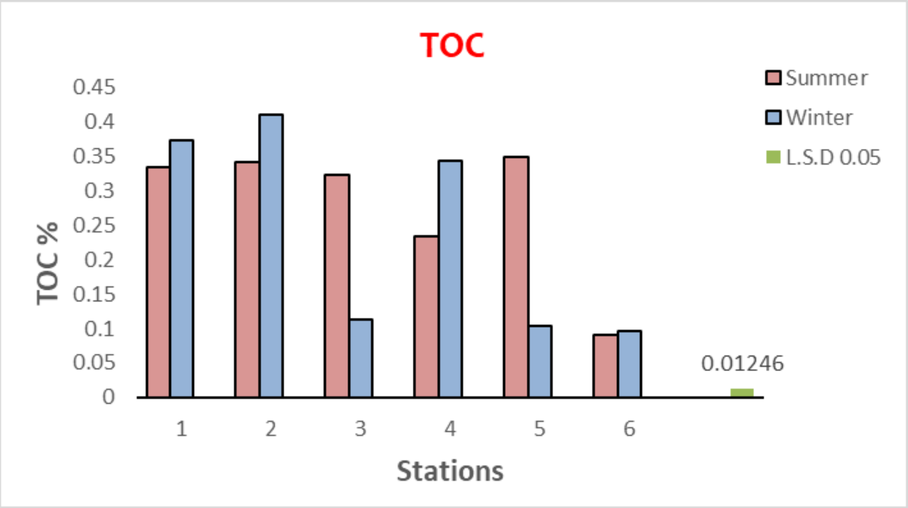

Figure 11. Mean seasonal variations in TOC (%) during summer 2024 and winter 2025.

The fluctuations in TOC may be linked to seasonal changes in primary productivity, organic matter input, and sedimentation rates. Elevated TOC in winter at certain stations might be due to the increased deposition of organic material or reduced microbial degradation under lower temperatures. Since organic carbon can influence the adsorption and retention of hydrophobic pollutants such as PCBs, these variations may contribute to the seasonal distribution patterns observed for PCB congeners.

The sedimentary texture in the study area showed significant spatial variation. Sand predominated at Station 1, accounting for approximately 74% of the sediment, indicating a high-energy environment where coarse sediments are deposited. Stations 2 through 6 were characterized by finer sediments, with clay content ranging from 48% to 72%, while silt contributed between 2% and 32% of the sedimentary composition, as shown in (Figure 12).

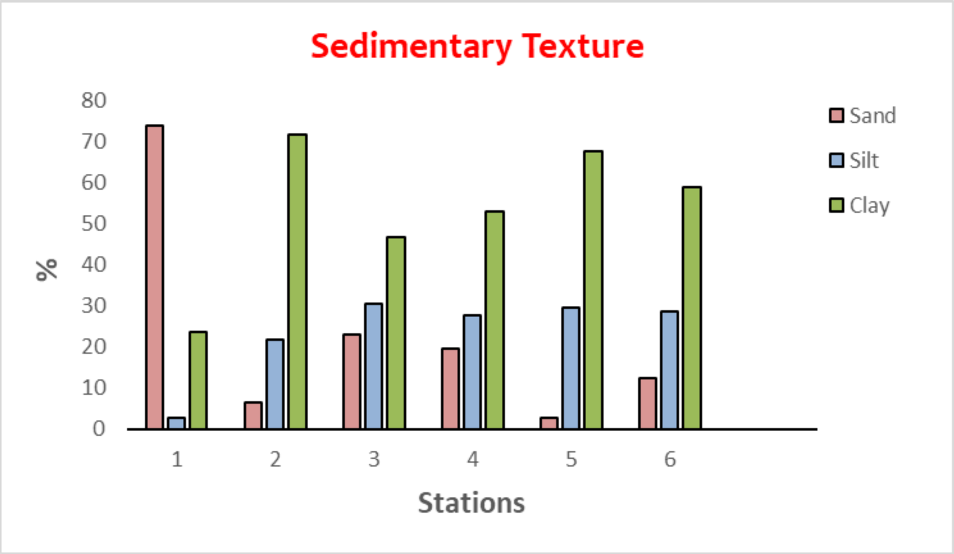

Figure 12. The percentage composition of sediment texture components at the study stations.

This distribution is significant, as the high proportions of clay and silt at most stations reflect the ability of fine particles to adsorb hydrophobic contaminants such as PCBs, due to their large surface area and association with organic matter. Therefore, sedimentary texture appears to play a key role in determining the distribution and accumulation patterns of these compounds in the surface sediments of Khor Al Zubair.

Contextualizing PCB Concentrations and Broader Implications

The contribution of individual PCB congeners to the total PCB concentration was assessed and is illustrated in (Figure 13). PCB 18 accounted for the largest proportion of the total PCBs, contributing 24% (9.34 ng/g DW), followed by PCB 101 and PCB 44, each contributing 10%. Other congeners such as PCB 52 (9%), PCB 153 (8%), and PCB 189 (8%) also showed substantial contributions.

Conversely, PCB 31 contributed only 3%, indicating its relatively minor presence in the studied sediments. The variation in contributions suggests differential sources, environmental behaviors, and degradation patterns of the individual congeners. The dominance of PCB 18 may be linked to its historical usage and environmental stability, while the lower percentages of compounds like PCB 31 may reflect faster degradation or lower input.

These proportions underline the necessity of congener-specific monitoring and risk assessment, as not all PCBs contribute equally to the total load or potential toxicity.

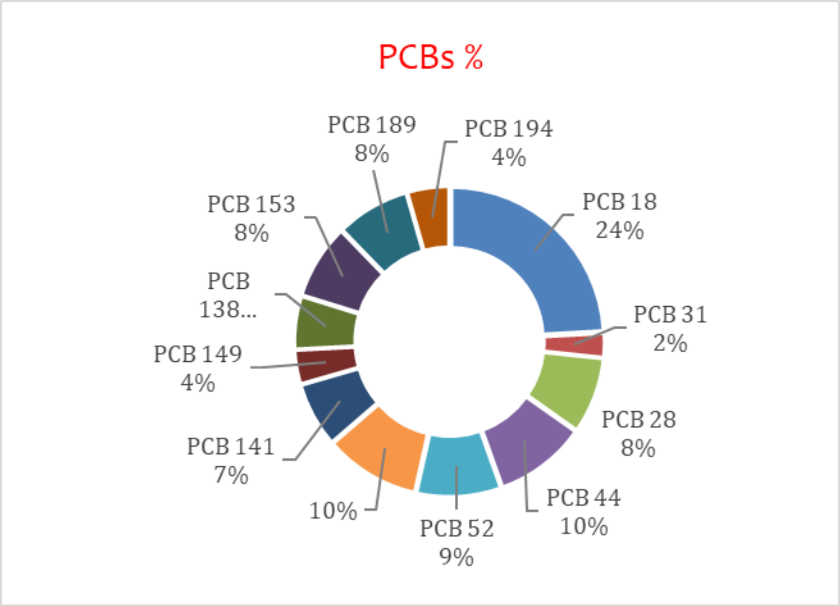

Figure 13. Percentage of PCBs present during the study period

This study reveals a clear pattern of PCB contamination distribution in Khor Al Zubair, shedding light on the ecological status of this vital waterway. Station 1 consistently recorded the highest concentrations during winter (7.37 ng/g dw) and summer (6.02 ng/g dw), indicating its proximity to an active and possibly ongoing source of contamination, such as industrial discharges, urban runoff, or even historical spills patterns previously documented in other coastal areas within the region (de Mora *et al.*, 2010). Station 5 consistently showed the lowest concentrations, likely due to its remote location from pollution sources or to hydrological conditions such as strong currents or low sedimentation, which may reduce contaminant accumulation. Identifying "hotspots" and "cold spots" of contamination is important. This knowledge will guide future monitoring and investigation efforts toward the most affected stations such as Station 1 to identify and address pollution sources, while also enabling the use of relatively cleaner areas such as Station 5 as reference sites for assessing the overall environmental status of the estuary.

A clear seasonal effect on contamination levels is observed. PCB concentrations at Station 1 were higher during winter than summer, indicating the sensitivity of these hydrophobic organic compounds to seasonal environmental changes, such as temperature, rainfall, and water flow (Li *et al.*, 2023). Rainfall in winter promotes surface runoff carrying contaminants, while lower temperatures reduce the volatilization of PCBs and increase their stability in sediments. In summer, higher temperatures accelerate the volatilization of these compounds and reduce their accumulation. In addition, varying river flow and tidal mixing can affect the deposition and redistribution of pollutants.

The study also highlights the importance of other environmental factors such as pH, salinity, total dissolved solids, dissolved oxygen, biochemical oxygen demand, water and air temperatures, and total organic carbon (TOC). Detailed data for these variables were provided at all stations during both summer and winter. Although the study did not explicitly link these factors to PCB concentrations, their inclusion highlights their importance in explaining pollutant behavior. For example, TOC is a key factor in the adsorption of hydrophobic compounds such as PCBs, and its increase is often associated with increased concentrations of these compounds, as documented in the adjacent Shatt al-Arab River (Farid et *al.*, 2016). Notably, Station 5 showed a consistent decrease in TOC across both seasons, which may explain its lower PCB concentrations. The significant variation in water temperatures between summer (34-36°C) and winter (11.5-15.7°C) also affects degradation and volatilization rates (Al-Daraji *et al.*, 2024). The data indicate an inverse relationship between temperature and dissolved oxygen levels, with colder waters retaining more oxygen, potentially affecting aerobic biodegradation processes.

To estimate potential environmental risks, the study compared the results with the National Oceanic and Atmospheric Administration (NOAA) sediment quality guidelines, which specify two impact values: the Environmental Impact Limit (ERL) at (22.7 ng/g) and the Environmental Impact Moderate (ERM) at 180 ng/g (Buchman, 2008). The results indicate that the highest recorded concentration (7.37 ng/g) at Station 1 remains below the ERL, suggesting that adverse environmental effects on aquatic organisms are not expected frequently at these levels. However, the bioaccumulative and persistent nature of these compounds, along with the classification of some as carcinogenic (IARC, 2016; Jones and Li *et al*., 2023), makes even low levels of concern in the long term, both environmentally and health-wise. The presence of 12 similar compounds in the analyses, including highly chlorinated compounds such as PCB-194, suggests a complex mix of potential sources, possibly involving historical uses or multiple industries.

Regional comparisons have shown that PCB concentrations in Khor Al-Zubair fall within the range of values recorded in studies conducted on the Egyptian Mediterranean coast (Aly Salem *et al.,* 2013), as well as in other areas within the scope of the Organization for the Protection of the Marine Environment (ROPME) (de Mora *et al.,* 2010), but remain lower than some highly polluted areas.

This study is considered the first baseline study of its kind in the region, providing important reference data for future environmental monitoring, trend analysis, and the development of effective pollution management strategies in Khor Al-Zubair. The importance of these results lies in their relevance to an estuary that is a major waterway for maritime transport and a natural environment rich in biodiversity (Sultan *et al.,* 2022). The data provided by the study also allows for comparison with results from other estuaries around the world, contributing to a broader understanding of the distribution of persistent organic pollutants in aquatic environments globally.

Conclusions:

This study successfully confirmed the presence and determined the concentration ranges of 12 specific polychlorinated biphenyl (PCB) congeners in the surficial sediments of Khor Al-Zubair, South of Iraq.1 Significant spatial variability in PCB concentrations was observed, with Station 1 consistently exhibiting the highest levels in both winter and summer, strongly suggesting a localized source of contamination. Conversely, Station 5 showed the lowest concentrations, indicating a relatively cleaner area. Seasonal variations were evident in both PCB concentrations and key environmental parameters, with higher peak PCB levels observed in winter at the most contaminated station, likely influenced by factors such as temperature, precipitation, and hydrological dynamics.

This research serves as a crucial baseline study, providing the first comprehensive dataset on organochlorine compound contamination in Khor Al-Zubair. This foundational information is invaluable for establishing long-term environmental monitoring programs, assessing pollution trends, identifying potential risks to the ecosystem and human health, and informing the development of effective environmental protection and management strategies for this ecologically and economically vital waterway. The study data also offers a basis for comparative analyses with similar estuarine systems globally.

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