Egyptian Journal of Soil Science
http://ejss.journals.ekb.eg/

Sediment Quality Assessment of Polycyclic Aromatic Hydrocarbons in Lake Edku, Egypt

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CONTAMINATION of coastal lakes in Egypt is of great public concern due to its potential risk to ecosystem and human health. Lake Edku is one of the most significant lakes in northern Egypt that serving various purposes, including water supply, food security, recreational activities, and industrial applications. Contamination of lakes sediments with polycyclic aromatic hydrocarbons (PAHs) degrades water quality and affects the aquatic organisms, which in turn impacts human and the health of the whole aquatic ecosystem in the long term. Therefore, sixteen sediment samples were collected from Lake Edku through the spring and summer seasons of year 2022 and investigated to ascertain the concentrations, sources, toxicity, and ecological risk of polycyclic aromatic hydrocarbons. The results revealed insignificant difference between the total concentrations of PAHs during spring and summer seasons, as ranged between 211.80 and 363.10 µg kg^{-1} with an average 273.08±62.10 µg kg^{-1} in spring, and 135.50 to 345.40 µg kg^{-1} with an average 271.80±64.14 µg kg^{-1} in summer. In addition, the high molecular weight (HMW) PAHs (with a percentage of 70% and 67%) and PAHs with 3 and 4 rings were predominance in the collected samples through the spring and summer. Moreover, Ant/ (Ant + Phe) ratio ranged between 0.38 to 1 and 0.34 to 0.95 during spring and summer, respectively which showed that the source of PAHs in sediment was related to petroleum sources. While, BaA/BaA/ (BaA + Chry) ratio reached to 1 which revealed the sources of burning coal, grass, and wood. For the majority of stations, InP/ (InP + BgP) and Flu/ (Flu + Pyr) ratios reached to 1 indicated fuel combustion sources. The ratio of high molecular weight (HMW) to low molecular weight (LMW) PAHs ranged between 0.2 and 1 which suggested a petrogenic input. The results indicated a diversity of pollution sources of PAHs, and according to toxicity and ecological risk assessment, the recorded concentrations of PAHs in the sediment samples from all stations do not pose a potential carcinogenic risk or environmental harm as the toxic equivalent concentrations (TEQBaP) values were below 100 µg kg^{-1}. The results of the present study can pave the way for managing, reducing pollution levels, and preventing environmental deterioration in Lake Edku.

Keywords: Polycyclic aromatic hydrocarbons, Lake Edku, Petrogenic source, Food security, Ecological risk.

1. Introduction

With the rapid industrialization, urbanization and economic growth, the environmental concentrations of persistent organic pollutants (POPs) have increased significantly posing a serious threat to human health and ecosystems (Abd El-Hamid *et al*., 2021; Hussein et al., 2022; Gyanwali *et al*., 2024). Polycyclic aromatic hydrocarbons (PAHs) are one of these pollutants which found and persist everywhere in the natural environment. PAHs which also known as polycyclic organic matters (POM) are organic compounds consisting of two or more unsubstituted fused benzene rings (Zhang et al., 2024). PAHs can result from one of three sources: petrogenic (fossil fuels), pyrogenic (decomposition and burning of organic matter), or biogenic (conversion of natural organics in the environment by relatively rapid chemical or biological microbial activity through diagenetic processes) (Osman *et al*., 2024). Due to their high toxicity, bioaccumulation, mutagenicity, and carcinogenicity, the US Environmental Protection Agency (US EPA) listed sixteen PAHs compounds as priority pollutants (Shi et al., 2024; Zhang *et al*., 2025). The danger of PAH compounds to the ecosystem in general and to living organisms in particular lies in the fact that PAHs are insoluble, which makes them bind to or be adsorbed with dissolved organic matter in natural waters, especially those substances with high molecular weights (Okbah *et al*., 2024a). PAHs have environmental properties defined by the number of benzene rings and their molecular weight. PAH compounds that have four or more bonded rings of benzene are known as high molecular weight (HMW) PAHs, while low molecular weight (LMW) PAHs compounds consist of two to three bonded rings of

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Received:26/01/2025; Accepted: 05/04/2025
DOI: 10.21608/ejss.2025.355665.1977

benzene. Naphthalene, phenanthrene, anthracene, and fluorene are examples of (LMW) PAHs; pyrene, benz[a]anthracene, benzo[a]pyrene, chrysene, and indeno [1, 2, 3-cd] pyrene are some examples of an HMW PAH (Venkatraman *et al*., 2024).

The anthropogenic sources of PAHs vary vastly, including gas and coal plants, oil and fuel spills, and industrial incinerators. Therefore, they are widely spread in the aquatic environment (water and sediment). Physiochemical properties such as solubility rate and PAHs hydrophobicity control the fate and transport of PAHs in the aquatic environment (El Kafrawy *et al*., 2020). PAHs could be transported into aquatic environments via various processes including surface water runoff, either through natural processes (e.g., rainfalls, floods, and snowmelt) or human direct/indirect actions, such as oil spills and atmospheric dispersions, e.g., through Aeolian processes (Suresh *et al*., 2024). After entering the aquatic environment, PAHs could accumulate in sediments, and then might be released back into the water or accumulated in organisms. This makes sediments as an important reservoir for PAHs where they can easily combine with organic matter and adsorbed by sediment particles (due to their lipophilicity and hydrophobicity) and an indicator for environmental change (Zhang *et al*., 2025; Huang *et al*., 2023). Thus, PAH concentrations in the sediments potentially reflect the degree of regional pollution and biological safety to a certain extent (Sun *et al*., 2022, Badr ElDin *et al*., 2022). Currently, pollution of the coastal lakes in Egypt is one of the significant environmental problems, as it affecting the whole aquatic system of the Mediterranean Sea basin (El-Gammal *et al*., 2023; Abd El-Aziz *et al*., 2025). Lake Edku is one of the most important lakes situated on the northern coast of Egypt, near the Mediterranean Sea (Okbah *et al*., 2024b). It plays a vital role in the ecosystem and serves as an essential habitat for various bird species (especially during migration season), supporting biodiversity and maintaining the ecological balance in the area (Shaheen *et al*., 2024).

Lake Edku faces various environmental problems due to its geographical location within fish farms, urban areas (Behaira Governorate), factories (e.g., El-Tapia pumping station) and agricultural lands, which resulting in the discharge of huge quantities of untreated or partially treated wastes in to the lake (Emam *et al*., 2021; Moneer *et al*., 2023). Thus, the continuous monitoring of environmental changes in Lake Edku is required to reduce water & sediment pollution, as well as the negative socio-economic consequences on fisheries and maritime activities. As our previous study focused on studying the spatial & seasonal distribution, sources, toxicity, and ecological risk of PAHs in the water of Lake Edku through the spring and summer seasons of year 2022 (Okbah *et al*., 2024b), there is a must to determine PAHs concentrations in the sediments of Lake Edku (as one of the major sinks for PAHs in the aquatic environment) to present a complete environmental study about PAHs through this period of year 2022.

Therefore, the main aim of the current study is to: 1) investigate the PAH concentrations in the sediments of Lake Edku, 2) identify the possible sources of this pollutant in an attempt to reduce or treat them, and 3) evaluate the potential toxic effects of PAHs bound to bottom sediments through the spring and summer seasons of year 2022. The present study demonstrated a new avenue to achieve efficient management of the coastal lakes of Egypt.

2. Materials and Methods

2.1. Study area and sampling

Lake Edku, the third largest Egyptian northern lake, lies in the west of the Rosetta Branch of the Nile Delta, approximately 36 km east of Alexandria between latitudes 31◦ 12′ and 31◦ 16′ N and longitudes ◦30◦ 8′ and 30◦ 18′ E (Shaheen *et al*., 2024). It is a brackish and shallow coastal lagoon with a depth varies between 0.1 and 1.4 m (Okbah *et al*., 2024b). It is united by a coastal road and a railroad to Alexandria, about 42 km along the west-southwest side, and a railroad to Rosetta, about 19 km to the northeast (Moneer *et al*., 2023). Lake Edku receives various industrial, domestic and agricultural wastewater, as well as the drainage water of fish farms from four main drains; Edku, El-Bousily, El-Khairy and Barsik. The maximum inflow from all drains occurs during summer, with total annual discharges exceeding 4×10^8 m^3 (BadrElDin et al., 2022). The surface area of the lake has shrunk from approximately 205 km^2 in 1957 to 56 km^2 in 2021 due to the development of drainage and irrigation schemes in the area (Shaheen *et al*., 2024). Sixteen sediment samples were collected to a depth of 5:10 cm using a stainless-steel grab sampler from eight sampling sites in Lake Edku during the spring and summer seasons of 2022 and examined for sixteen priority PAHs, including seven carcinogenic PAHs: Chr, BaA, BkF, BbF, DahA, and InP (Astolfi *et al*., 2024). The labeled samples (500gm) from each station were placed in clean zip-locked bags, and kept at 4 °C in an ice pack before extraction and analysis. GPS device (DGPS Hemisphere R131-Canada) was used with the Google Earth program to locate the stations under study on the map (Fig.1 and Table 1). Based on the intensified anthropogenic activities surrounding the lake, eight representative stations were selected for collecting sediment samples from Lake Edku: stations I, II, and III cover the middle and northern regions; station IV covers the eastern region; stations V, VI, and VII cover the northern region; and station VIII covers the inlet (Fig. 1). Station I cover the drainage resulting from fish farms, station II cover the western Edku drain, station III cover the eastern Edku drain, station IV cover the Edku Elkhiry drain, station V cover the middle of the lake, station VI cover Bosiliy drain, station VII covers the area of the international road's connection with the lake, and finally station VIII cover Bogas area, which is the area of the lake's connection with Mediterranean Sea.

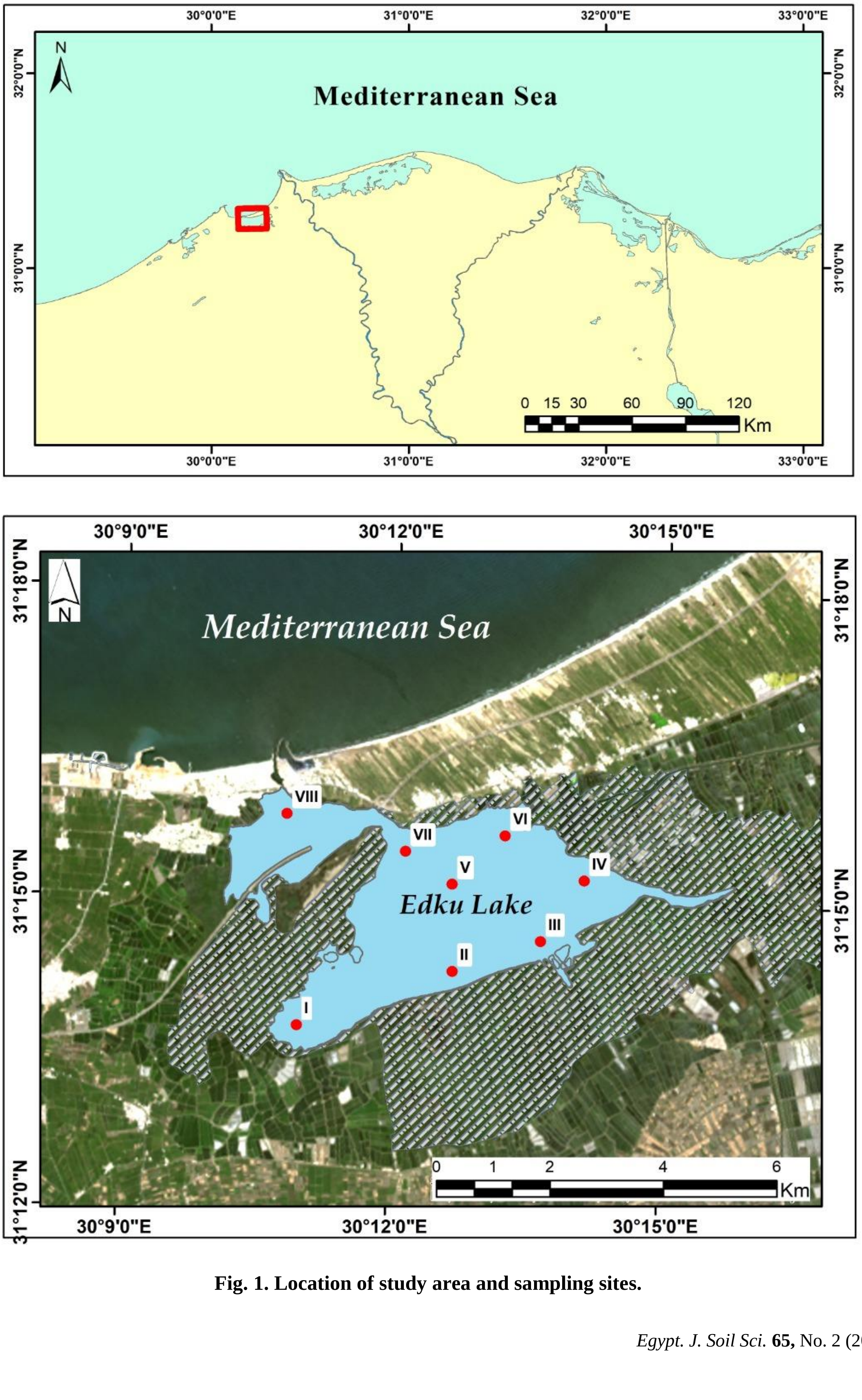


Fig. 1. Location of study area and sampling sites.

Table 1. Latitude and Longitude of the sampling sites, Lake Edku.

Sampling Sites	Latitude	Longitude
I	31.22960860140	30.18282187300
II	31.23882319440	30.21139137330
III	31.24396506060	30.22758567000
IV	31.25388091050	30.23537318970
VI	31.26083073490	30.22055302880
V	31.25285787250	30.21097861350
VII	31.25795338210	30.20217395440
VIII	31.26358323550	30.18008125810

2.2. Sample extraction and analysis

All sediment samples were dried using a vacuum freeze-dryer (Virtis 2K Benchtop Freeze Dryer, USA); homogenized and then extracted (50 g) for 72 hours using 200 mL of dichloromethane and acetone (1:1, v/v) and soxhlet extraction apparatus (EXTRACTORS, SOXHLET, MICRO-Chemglass Life Sciences LLC- Canada). Both of drying and extraction processes were performed in the National Institute of Oceanography, Egypt. Afterward, the extracted sample were concentrated to a volume around 2 ml using a rotary evaporator device. An alumina/silica gel glass column containing 1 cm of anhydrous sodium sulfate was used to clean up the hexane extract. The fractions containing PAHs were eluted and collected using dichloromethane/hexane (3:7, v/v, Sigma-Aldrich Chemie GmbH, USA); then evaporated to 5 mL under a moderate nitrogen stream and finally dissolved in 1 mL hexane (Sigma-Aldrich Chemie GmbH, USA) and corked for gas chromatography analysis (Han *et al*., 2020).

2.3. Instrumental analysis and Quality Assurance/Quality Control

All of the extracted sediment samples were analyzed using gas chromatography (Hewlett-Packard 6890, Agilent Technologies Inc. USA) coupled with a flame ionization detector (Hewlett-Packard 5973) to determine the concentrations of PAHs. Samples were analyzed on a fused silica capillary column HP-1, with 100% dimethyl polysiloxane (30 m length, 0.32 mm i.d., and 0.17 mm film thickness). The gas chromatography instrument was programmed as follows: initial temperature of 60 °C for 2 min, increased to 120 °C with a rate of 10 °C/min, allowed to stay for 5 min, then increased to 290 °C with a rate of 4 °C/min, and to 300 °C at 25 °C/min for 5 min, and held for 15 min, giving a total run time of 22 min. The injector and detector temperatures were 270 and 280 °C, respectively. The carrier gas was nitrogen flowing at 1.2 ml/min. A stock solution containing the following PAHs: naphthalene, acenaphthylene, fluorene, phenanthrene, anthracene, fluoranthene, benzo(a)anthracene, chrysene, benzo(b)fluoranthene, benzo(k)fluoranthene, pyrene, benzo(a)pyrene, dibenzo (a, h) anthracene, benzo(ghi)perylene, and indeno (1,2,3- cd) pyrene was used to prepare a series of calibration standards 0.1, 0.25, 0.5, 0.75, 1.0, 2.0, 5.0, and 10 µg/ml of PAHs (Han et al., 2020). All the reagents used throughout the current study were analytically pure and the glassware were cleaned, dried at 120 ˚C and rinsed with hexane. In order to control any contamination or mix-up during chemical analysis, all analytical procedures were performed under quality control (QC) and quality assurance (QA) procedures. The methods of full procedure blank, blank spike recovery, clean soil matrix spike recovery, and comparison with reference materials were used to ensure the quality of the assay results. Three blanked samples were analyzed and treated in the same manner as the samples; all recorded values were lower than the detection limit. Certified methods were used for the analysis process. All reference materials' validity has been verified by the International Atomic Energy Agency (IAEA), and the results of analyzing reference materials were within the range.

2.4. Source of PAHs in sediment samples

Flu/ (Flu + Pyr), Ant/ (Ant + Phen), BaA/ (BaA + Chry), InP/ (InP + BgP), and LMW/ΣHMW ratios are used to determine the source and origin of polycyclic aromatic hydrocarbons in sediment samples. Flu/ (Flu + Pyr) between 0.4 and 0.4: 0.5 refers to fuel combustion, more than 0.5 refers to coal, grass, and wood burning, while less than 0.4 refers to petrogenic source. Ant/ (Ant + Phe) more than 0.1 refers to petroleum and petrogenic sources, and less than 0.1 refers to combustion sources. BaA/ (BaA + Chry) more than 0.3 refers to coal, grass, and wood burning; less than 0.2 refers to petroleum sources; and between 0.2 and 0.3 indicates mixed sources. InP/ (InP + BghiP) more than 0.5 indicates coal, grass, and wood burning sources; a range between 0.2 and 0.5 refers to fuel combustion sources; and less than 0.2 indicates petroleum input (Zhang et al., 2025; Huang et al., 2023). The ratio ΣLMW/ΣHMW more than 1 refers to a petrogenic source, and less than 1 refers to pyrogenic input (Hassaan *et al*., 2024; Potapowicz *et al*., 2025).

2.5. Statistical analysis

In the current study, multivariate statistics including cluster analysis, principal component analysis (PCA), hierarchical cluster analysis (HCA), and Pearson's correlation coefficients were employed using SPSS 20 (SPSS Inc., USA) program to quantitatively investigate relationships among the dataset of the investigated sediment samples (Abdelrhman *et al*., 2024; Mohamed *et al*., 2023) and the value of $p < 0.05$ was considered statistically significant. These types of analyses have been widely applied to evaluate complex data in a wide variety of samples, including pollutants in environmental samples as soil (El-Gammal *et al*., 2023). Excel 2010 software and Origin 8.5 (Origin Lab Inc., USA) were used for data plotting. The map in the current study (Fig. 1) was derived from a Landsat 9 satellite image acquired in 2022 and overlaid with two polygons delineating the lake boundaries and surrounding areas. It was produced using ArcGIS 10.8 software with a UTM projection (WGS 1984 datum). The spatial analyses were performed using OriginLab2019 following the Inverse Distance Weighting (IDW) geostatistical method. This method was used for mapping the sediment quality parameters in the whole lake including the non-surveyed sites.

3. Results

3.1. Seasonal and spatial Levels distribution of PAHs in sediment samples

Table 2 illustrated the levels, threshold effect concentration (TEC), and probable effect concentration (PEC) of the different PAHs measured in the sediment's samples. The results showed that the average concentration of 16 PAHs in the samples from the selected sites was 273.08 µg kg^{-1} in the spring and 271.80 µg kg^{-1} in the summer season. The average concentrations of Ant, Pyr and BbP were higher than those of other PAHs through both seasons, while the compound with the lowest average concentrations was Ace (5.74 and 7.70 µg kg^{-1}) in the spring and summer season, respectively. As shown in Fig 2, the total PAH concentrations were generally lower in the northern region than in the southern region, which indicated the limited sources of urban pollution discharge. Stations I, II, II, and V recorded the highest values throughout the summer, with levels of 363.10, 345.90, 326.70, and 260.00 µg kg^{-1}, respectively. The lowest levels were reported in the spring at stations III, VII, VIII, and VI, with respective values of 228.7, 224.40, 223.50, and 211.80 µg kg^{-1}. Stations III, VII, VIII, and VI recorded the lowest levels, while stations I (345.40 µg kg^{-1}), II (321.920 µg kg^{-1}), VI (306.4 µg kg^{-1}), and V (285.50 µg kg^{-1}) recorded the highest levels; stations III (277.70 µg kg^{-1}), VII (252.40 µg kg^{-1}), IV (249.6 µg kg^{-1}), and VIII (135.50 µg/ kg^{-1}) recorded the highest levels, providing more detailed information on the sources of PAH pollution.

Table 2. Seasonal distribution (Min., Max., and average), TEC, and PEC for different PAHs measured in the sediment's samples (µg kg^{-1} dw) form Lake Edku through the spring and summer of year 2022.

Compund	Ring	H/L	Spring				Summer				Consensus-Based		
			Min.	Max.	Ave.	SD.	Min	Max	Ave.	SD	*TEC	**PEC	
Nap	2	L	3.80	12.30	8.24	2.75	4.40	13.10	9.56	3.17	176	561	Rare adverse ecological effects
Acy	3	L	7.60	18.10	11.65	3.34	8.10	16.60	11.86	3.12	-	-	
Ace	3	L	0.00	11.80	5.74	4.04	0.00	13.30	7.70	4.56	-	-	
Flu	3	L	7.40	18.80	11.86	4.32	5.90	15.60	11.15	3.02	77.4	536	
Phe	3	L	0.00	31.50	19.88	9.60	5.60	33.20	23.14	9.02	904	1170	
Ant	3	L	14.60	45.10	25.06	10.27	19.70	34.90	26.55	5.73	57.2	845	
Flua	4	H	0.00	36.30	18.75	11.63	0.00	37.10	21.09	10.46	423	2230	
Pyr	4	H	0.00	42.20	25.04	13.36	0.00	39.80	26.89	12.64	195	1520	
BaA	4	H	0.00	30.40	17.99	8.99	9.70	21.90	17.55	4.33	108	1050	
Chr	4	H	0.00	33.70	19.20	10.81	0.00	26.90	15.23	9.19	166	1290	
BbF	4	H	0.00	22.40	13.88	6.93	0.00	22.50	15.78	7.11	-	-	
BkF	5	H	13.60	21.00	17.85	2.80	0.00	17.90	11.86	5.73	-	-	
BbP	5	H	0.00	41.50	26.23	13.21	0.00	39.20	28.60	12.61	150	1450	
DBA	5	H	0.00	20.40	16.39	6.75	0.00	15.50	11.71	5.18	33	2230	
BghiP	6	H	0.00	34.20	19.49	9.88	0.00	30.40	18.93	10.33	-	-	
InP	6	H	0.00	23.90	15.85	7.32	5.90	22.10	14.21	6.12	-	-	
∑			211.80	363.10	273.08	62.10	135.50	345.40	271.80	64.14	1610	22800	

*TEC: Threshold effect concentration
**PEC: Probable effect concentration

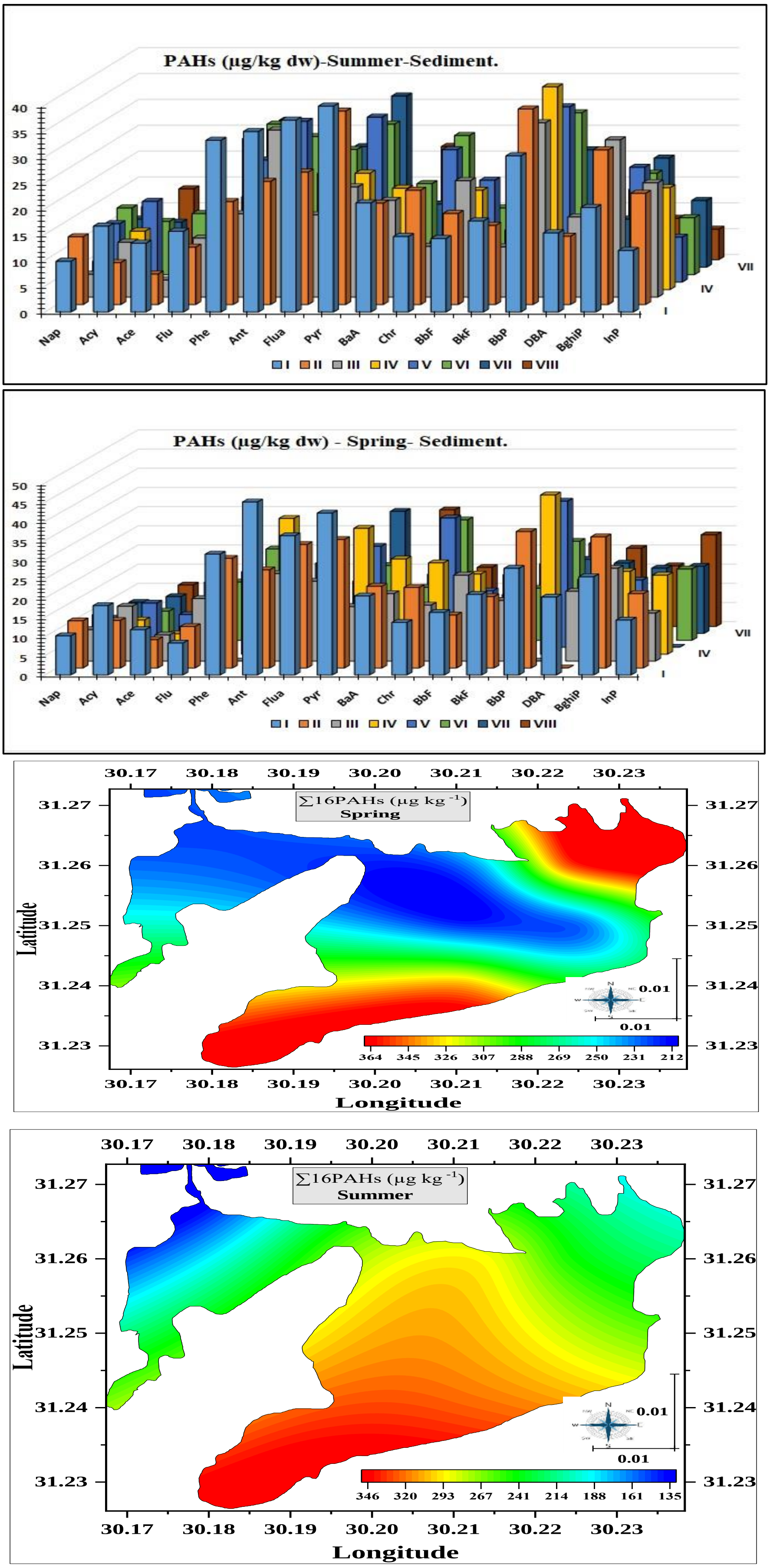


Fig. 2. Seasonal and regional distribution of PAHs in the sediment samples from Lake Edku through the spring and summer of year 2022.3.2. Principal component analysis (PCA).

Principal component analysis (PCA) is a versatile widespread statistical technique used for analyzing datasets and reducing dimensionality (Osman *et al.*, 2024). Fig. 3 show the number and percentage eigenvalues in a downward curve, from highest to lowest. The first two components can be considered to be the most significant since they contain almost all of the total information in the data. Considering the dominant two PCA axes, the first principal component has high positive values for both PAH (Nap, Acy, Ace, Phe, Ant, Flua, Pyr, BbF, BkF, BaP, and Bghi) at stations I, II, IV, and V; PC2 was composed of remaining pollutants (BaA, InP, Flu, DBA, and Chr) and stations (III, VI, VII, and VIII) during spring. While, through summer (PC1) recorded positive values for all pollutants at stations III, IV, and VIII except BbF, BaA, and DBA at stations III, IV, and VIII.

First component (PC1)

As shown in Fig. 3, the first factor represented 39.06% during the spring and 39.97% during the summer of the total variance. During spring, all stations recorded a strong positive loading, reaching 0.38 and 0.39 during spring and summer, respectively except for Flu, BaA, Chr, DBA, and InP during spring and Acy, BaA, BbF, and DBA during summer, which recorded a negative loading. The first component may be suggested due to anthropogenic activities such as domestic activities and wastewater discharging.

Second component (PC2)

The second factor that can be suggested is that these compounds could be transferred to the lake from the drains that are led to cumulate and deposit them in the lake, which is considered the same factor for water. The second factor recorded 18.43% and 18.88% during spring and summer, respectively, of total variance, which owned a positive loading with Nap (0.20), Acy (0.20), Flu (0.14), Ant (0.10), Flua (0.15), BaA (0.43), BbF (0.32), DBA (0.08), Bghi (0.25), and InP (0.30) during spring; Phe (0.02), Flua (0.07), Pyr (0.02), BaA (0.2), BkF (0.21), BaP (0.07), DBA (0.34), Bghi (0.22), and InP (0.01) during summer, as illustrated in Fig.3.

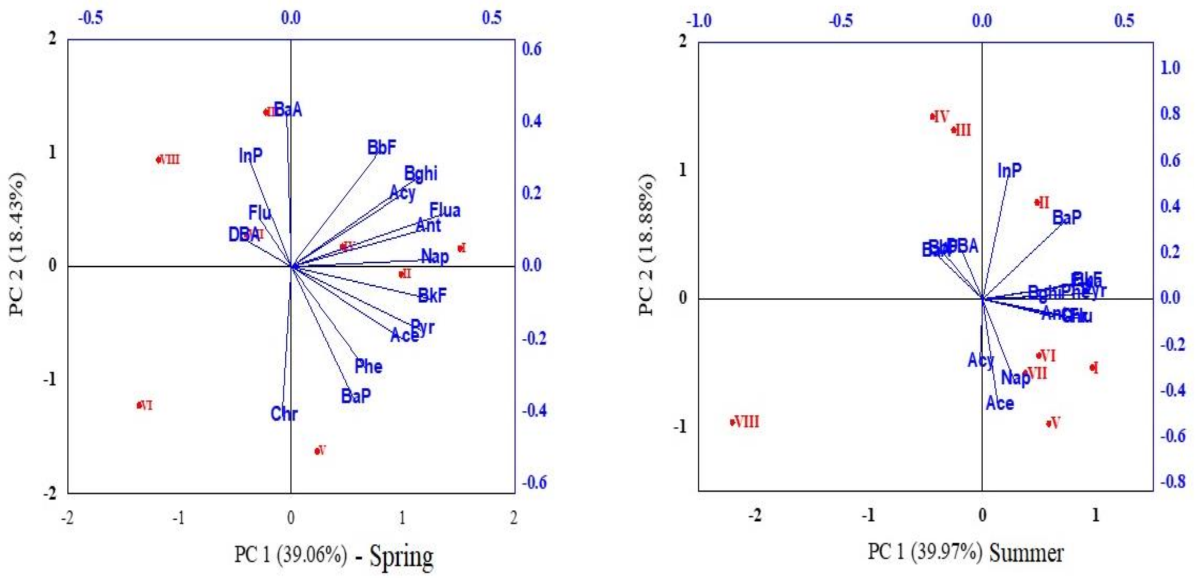


Fig. 3. Loading matrix of the first two principal components of PAHs in the sediment of Lake Edku during the spring and summer of year 2022.

3.3. Hierarchical cluster analysis (HCA)

Single linkages

Grouping of sampling stations based on regional similarities/dissimilarities and differences among 16 PAHs in surface sediment was conducted using hierarchical cluster analysis (HCA). The resultant dendrograms during spring and summer (Fig. 4) confirm the results obtained with PCA. Single linkage (for stations) presented similarity between stations I, II, and IV (group A) and V, VI (group B) with 73.96 and 33.88, respectively during spring; while in summer, stations I, II, and VI (group A) recorded similarity of 62.20, and stations IV, VIII (group B) recorded similarity of 62.07. In detail, stage (1) contains stations (II and IV) at a distance of 32.30, stage (2) stations (I and II) at a distance of 34.42, stage (3) stations (VII and VIII) at a distance of 32.30, stage (4) stations (III and VII) at a distance of 40.87, stage (5) stations (V and VI) at a distance of 41.93, stage (6) stations (III and V) at a distance of 49.63, and stage (7) stations (I and III) at a distance of 52.06.

Complete linkage

On the other hand, in complete linkage hierarchical cluster analysis (HCA), the results showed a correlation between three groups: group (A) between both Ace and Acy with a similarity of 72.38, group (B) between DBA and BaA with a similarity of 7.23, and group (C) between Chr and Ant with a similarity of 68.32 during spring; while on summer, a correlation was recorded between Ace and Acy as a group (A) with a similarity of 76.79, DBA and InP as a group (B) with a similarity of 75.76, and Phe and Flua with a similarity of 69.75, as shown in Fig. 5.

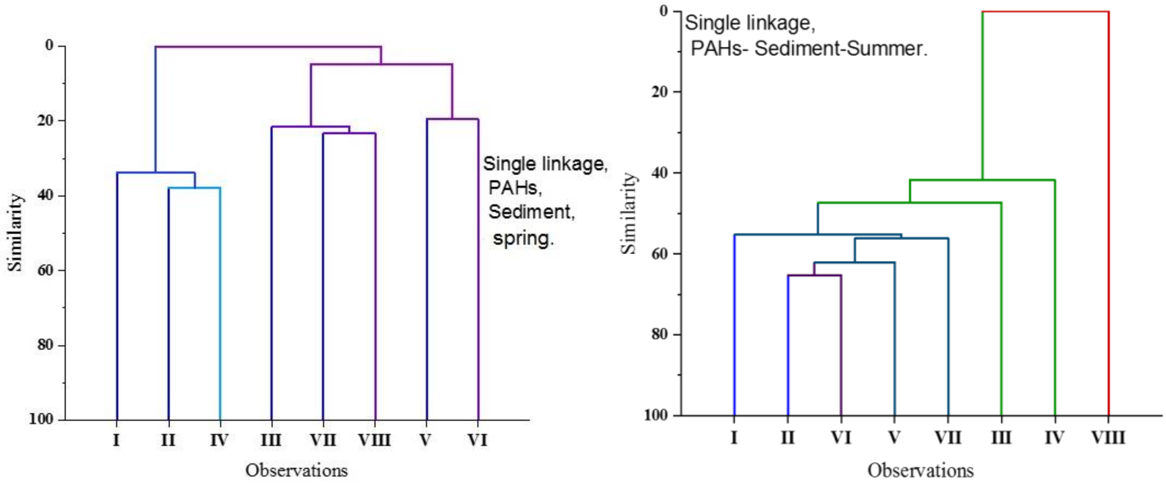


Fig. 4. Single linkage Dendrogram for hierarchical cluster analysis of sampling site of Lake Edku during spring and summer.

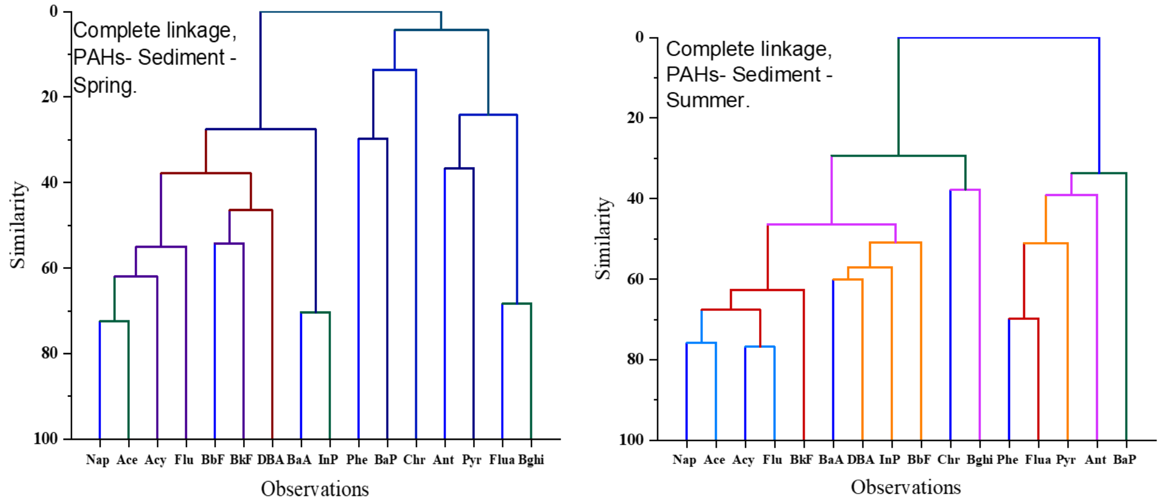


Fig. 5. Complete linkage Dendrogram for hierarchical cluster analysis of PAHs concentrations in the sediment samples, Lake Edku during spring and summer.

3.4. Pearson's correlation coefficients

Pearson correlation coefficient (PCC)[a] assesses the linear correlation between two sets of data. The ratio of two variables' covariance and standard deviations yields a number between -1 and 1, that determines the degree and direction of the relationship between two variables (Jebarathinam et al., 2020; Cooksey, 2020). As illustrated in Tables 3, PAHs during spring recorded a strong direct correlation: Nap with (Flu, Pyr, BKF, and Bghi) (r -0.55:0.82); Acy with Flua (r -0.34:0.81); Phe and BaP (R-0.38: 0.74); Ant with (Flua, and BKF) (r-0.11: 0.79); Flua (BKF, and Bghi) (r-0.33: 0.91); Pyr with BKF (r-0.24:0.79); BaA with Inp (r -0.42:0.89); BbF with Bghi (r -0.18:0.73). While, PAHs during summer recorded a strong direct correlation as: Flu with (Ant, Flua, and Pyr) (r-0.43:0.86); Phe with (Flua, Pyr, and BKF) (r- 0.50:0.90); Flua with (Pyr, BKF, and BaP (r-0.36:0.93); Pyr with (Chr, BKF, and BaP) (r-0.40:0.89); BaA with DBA (r-0.52:0.85); Chr with BKF (r-0.36:0.80); BKF with BaP (r-0.05:0.78)

Table 3. Pearson's correlation coefficients and relationships amongst studied PAHs in the sediment samples of Lake Edku during the spring of year 2022.

Corr.	Nap	Acy	Ace	Flu	Phe	Ant	Flua	Pyr	BaA	Chr	BbF	BkF	BaP	DBA	Bghi	InP
Nap	1.00															
Acy	0.40*	1.00														
Ace	0.53**	0.63**	1.00													
Flu	0.05*	-0.34	0.00	1.00												
Phe	0.39*	0.06*	0.33*	-0.34	1.00											
Ant	0.65**	0.66**	0.62**	0.04*	0.43**	1.00										
Flua	0.82***	0.81***	0.60**	-0.24	0.32*	0.79***	1.00									
Pyr	0.82***	0.31*	0.55**	-0.17	0.65**	0.67**	0.63**	1.00								
BaA	0.01*	0.07*	-0.35	0.32*	0.04*	0.27*	0.14*	-0.24	1.00							
Chr	-0.09	-0.27	0.45**	0.26*	0.15*	-0.11	-0.22	-0.08	-0.42	1.00						
BbF	0.47**	0.52**	0.23*	0.21*	-0.38	0.56**	0.62**	0.13*	0.21*	-0.19	1.00					
BkF	0.72***	0.41**	0.47**	-0.25	0.44**	0.76***	0.72***	0.79***	-0.16	-0.03	0.54**	1.00				
BaP	0.35*	-0.25	0.24*	-0.11	0.74***	0.30*	0.17*	0.48**	-0.12	0.52**	-0.10	0.58**	1.00			
DBA	-0.55	0.01*	-0.17	0.06*	-0.33	0.10*	-0.35	-0.24	-0.02	-0.14	0.11*	-0.02	-0.26	1.00		
Bghi	0.79***	0.63**	0.32*	-0.14	0.08*	0.56**	0.91***	0.41**	0.25*	-0.30	0.73***	0.60**	0.08*	-0.48	1.00	
InP	-0.09	-0.28	-0.52	0.36*	0.16*	0.00	-0.15	-0.22	0.89***	-0.37	-0.18	-0.37	-0.07	-0.13	-0.04	1.00

Table 4. Pearson's correlation coefficients and relationships amongst studied PAHs in the sediment samples of Lake Edku during the summer of year 2022.

	Nap	Acy	Ace	Flu	Phe	Ant	Flua	Pyr	BaA	Chr	BbF	BkF	BaP	DBA	Bghi	InP
Nap	1.00															
Acy	0.00	1.00														
Ace	0.61**	0.31*	1.00													
Flu	0.07*	0.20*	0.26*	1.00												
Phe	0.05*	0.04*	0.10*	0.67**	1.00											
Ant	-0.04	0.47**	0.26*	0.77***	0.33*	1.00										
Flua	0.15*	0.05*	0.14*	0.80***	0.90***	0.51**	1.00									
Pyr	0.30*	-0.08	0.11*	0.86***	0.79***	0.53**	0.93***	1.00								
BaA	-0.16	0.02*	0.04*	-0.42	-0.27	-0.20	-0.10	-0.36	1.00							
Chr	0.61**	-0.10	0.13*	0.47**	0.53**	0.38*	0.57**	0.73***	-0.52	1.00						
BbF	-0.24	0.34*	-0.46	-0.43	-0.50	0.08*	-0.36	-0.40	0.39*	-0.16	1.00					
BkF	0.32*	-0.05	0.12*	0.65**	0.82***	0.51**	0.91***	0.89***	-0.14	0.80***	-0.21	1.00				
BaP	-0.12	-0.21	-0.52	0.46**	0.63**	0.35*	0.70***	0.72***	-0.21	0.62**	0.11*	0.78***	1.00			
DBA	-0.18	-0.28	0.17*	-0.21	-0.08	-0.06	0.06*	-0.17	0.85***	-0.36	0.05*	0.05*	-0.12	1.00	0.01	
Bghi	0.25*	-0.24	0.16*	0.56**	-0.01	0.63**	0.29*	0.52**	-0.27	0.50**	-0.08	0.39*	0.31*	0.01*	1.00	
InP	-0.46	-0.58	-0.71	0.10*	0.12*	0.01*	0.29*	0.29*	0.22*	0.03*	0.20*	0.28*	0.68**	0.33*	0.30*	1.00

*** (0.7:1): Strong direct correlation
(-0.7: -1): Strong reverse correlation

** (0.4:0.7): average direct correlation
(-0.4: -0.7): average reverse correlation

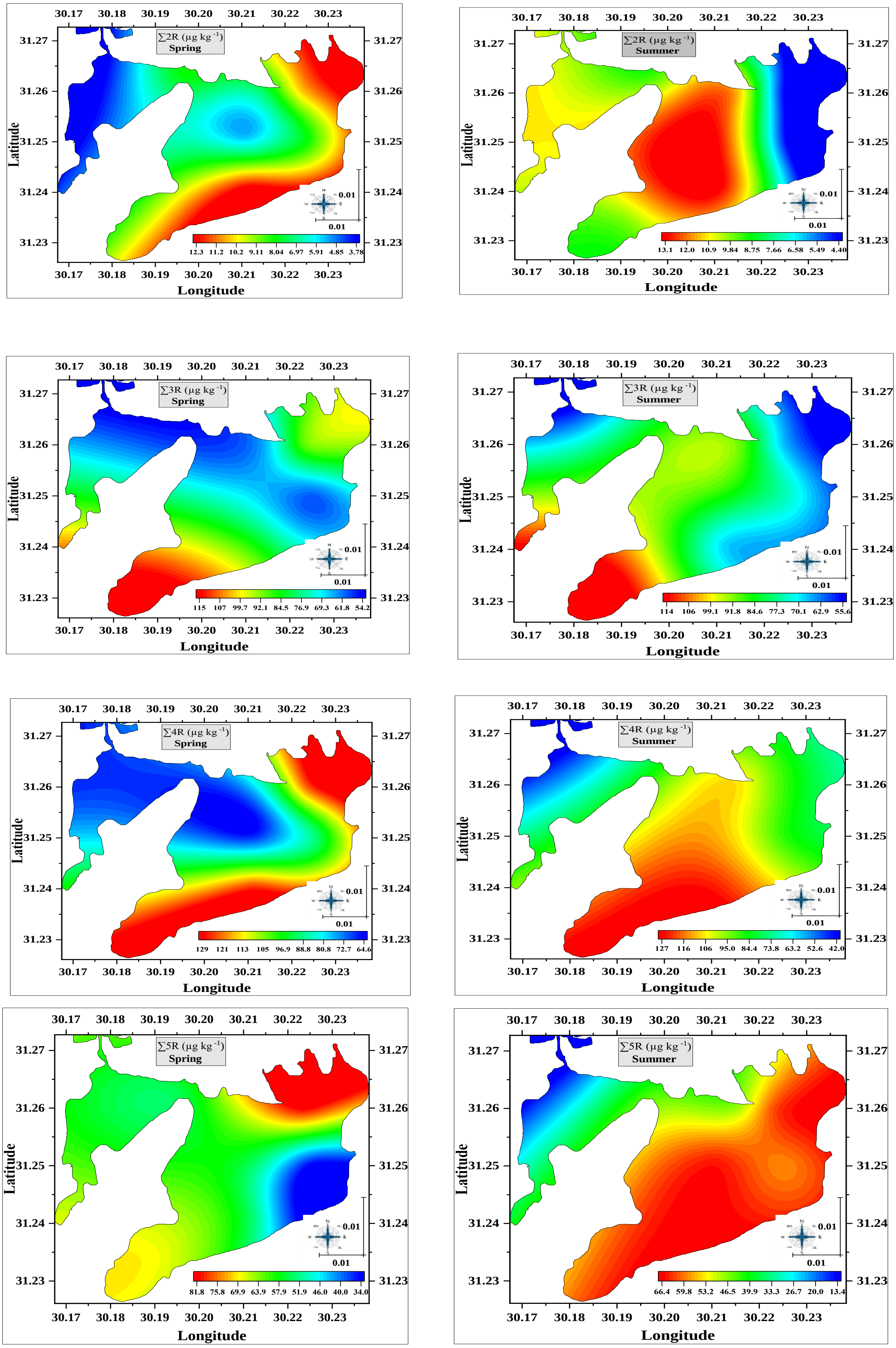
* (0: 0.4) weak direct correlation
(0: - 0.4) weak reverse correlation

4. Discussion

4.1. Composition, and sources of PAHs in sediment

4.1.1. Composition of PAHs in sediment

Determination and identification of PAHs sources is crucial for studying the fate of PAHs contaminants and their way to environmental pollutants. There are five categories for PAHs: Nap makes up two rings (2R); Acy, Ace, Flu, Phe, and Ant make up three rings (3R); Flua, Pyr, BaA, Chr, and BbF make up four rings (4R); Acy, BkF, BbP, and DBA make up five rings (5R); and BghiP and InP make up six rings (6R) (Table 1), which are used to determine the composition pattern of PAHs (Li *et al*., 2024; Gundlapalli *et al*., 2024). In the current study, the concentrations of (2R) PAHs ranged from 3.80 µg kg^{-1} to 12.30 µg kg^{-1}, 3R PAHs from 54.2 µg kg^{-1} to 114.80 µg kg^{-1}, 4R PAHs from 64.70 µg kg^{-1} to 129.10 µg kg^{-1}, 5R PAHs from 34.00 µg kg^{-1} to 81.70 µg kg^{-1}, and 6R PAHs from 17.50 µg kg^{-1} to 153.60 µg kg^{-1} (Fig. 6). Predominance of 3 and 4 PAHs rings in the sediment sample, as illustrated in Fig. 7 and 8 attributed to heavy traffic nearing this area, especially the international road that connects the coastal cities and passes through the lake. PAHs with low molecular weights, such as acenaphthylene, and fluorene do not easily biodegrade in water, while naphthalene and phenanthrene biodegraded in water. Anthracene, benz[a]anthracene, chrysene, and fluorene did not easily decompose in water but decompose easily in sediment. PAHs with five or more rings (benzo[a]pyrene, dibenz[a,h]anthracene, and benzo[g,h,i]perylene) may not decompose easily in water and sediment (Gundlapalli *et al*., 2024). Generally, PAHs are dominated by HML with a percentage of 70% and 67% compared to ∑LMW with a percentage of 30% and 33% during spring and summer, respectively. the rings of PAHs can be arranged as 4R> 3R >5R> 6R> 2R during spring and summer with a percentage of 35%, 27%, 22%, 13%, and 3% during spring and 35%, 30%, 19%, 12%, and 4% during summer, respectively (Fig. 7). HMW PAHs are considered to originate from pyrolytic sources, whereas LMW PAHs originate from petrogenic and combustion sources. Because it influences their behaviors in the environment, including their solubility, bioavailability, and stability, the difference between LMW and HMW PAHs is significant. Polycyclic aromatic hydrocarbons (HMW) are a class of chemicals that are refractory because they tend to adsorb onto soil and sediments and are less soluble in water. Conversely, lower-weight PAHs dissolve better in water and are present in the water column in larger quantities (Venkatraman *et al*., 2024). The annual ring number for PAHs in sediment is distributed descending as 4, 3, 5, 6 and 2 during spring and summer. On another hand, the ring number was arranged according to spatial distribution as 4,3,5,6, and 2 rings at stations I, II, and VI; 4,3,6,5,2 at station III; 4,5,3,6,2 at stations V, VII, and VIII; 3,4,5,6,2 at station VI during spring. The rings were distributed through summer as 4,3,5,6 and 1 at all stations except station VII arranged as 3,4,5,6,2 and station VIII arranged as 3, 4, 6, 5 and 2 as illustrated in Fig.7. The distribution of high molecular weight PAHs, sum (four: six) ring PAHs to the sum of (two: three) ring PAHs are displayed in Fig. 8.


∑2R (µg kg⁻¹) Spring
12.3 11.2 10.2 9.11 8.04 6.97 5.91 4.85 3.78
∑2R (µg kg⁻¹) Summer
13.1 12.0 10.9 9.84 8.75 7.66 6.58 5.49 4.40
∑3R (µg kg⁻¹) Spring
115 107 99.7 92.1 84.5 76.9 69.3 61.8 54.2
∑3R (µg kg⁻¹) Summer
114 106 99.1 91.8 84.6 77.3 70.1 62.9 55.6
∑4R (µg kg⁻¹) Spring
129 121 113 105 96.9 88.8 80.8 72.7 64.6
∑4R (µg kg⁻¹) Summer
127 116 106 95.0 84.4 73.8 63.2 52.6 42.0
∑5R (µg kg⁻¹) Spring
81.8 75.8 69.9 63.9 57.9 51.9 46.0 40.0 34.0
∑5R (µg kg⁻¹) Summer
66.4 59.8 53.2 46.5 39.9 33.3 26.7 20.0 13.4
0.01
Latitude
Longitude
31.27 31.26 31.25 31.24 31.23
30.17 30.18 30.19 30.20 30.21 30.22 30.23

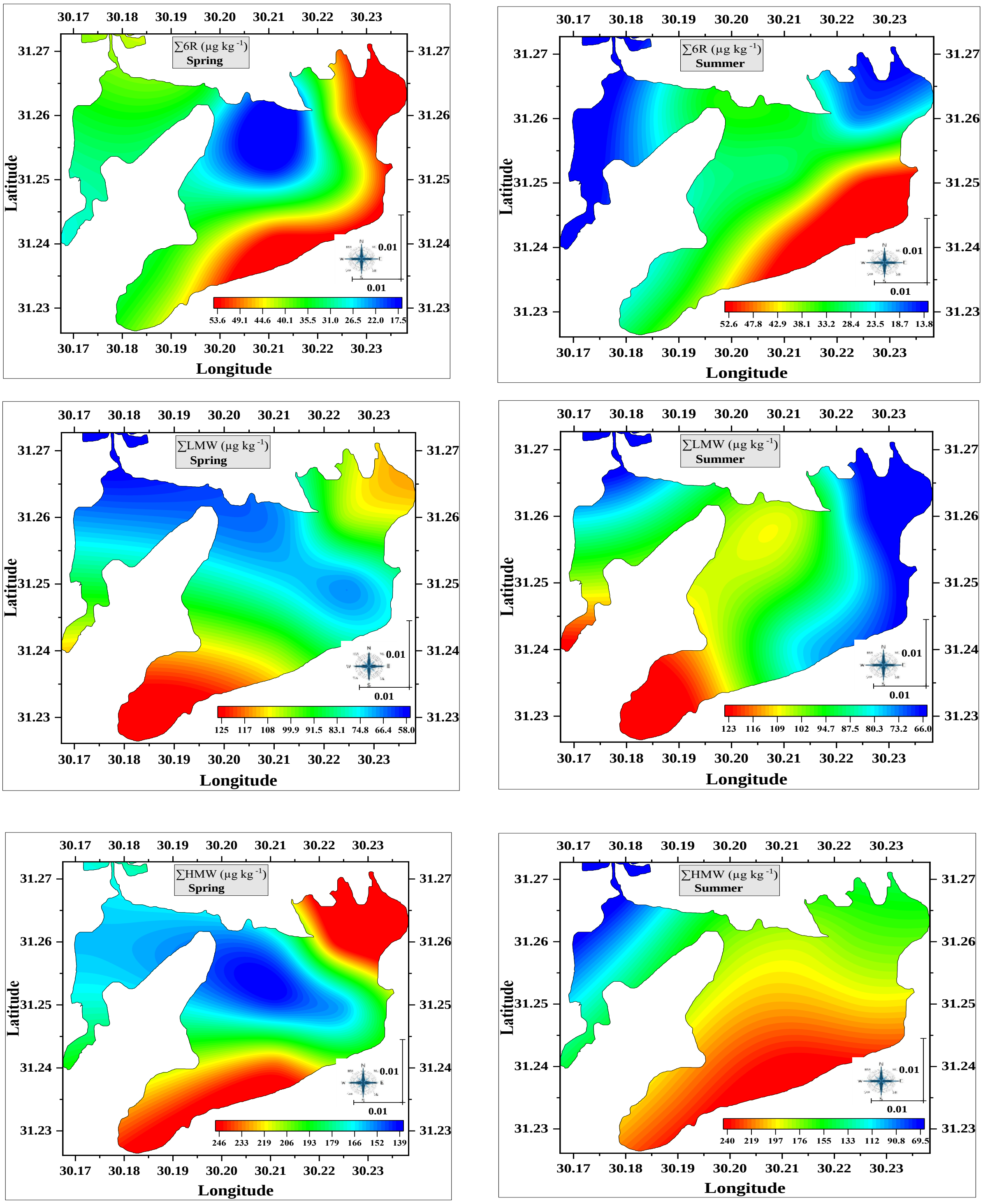


Fig. 6. Horizontal contours for Edku Lake simulated different PAHs rings, ∑LMW, and ∑HMW distribution through spring and summer of year 2022.

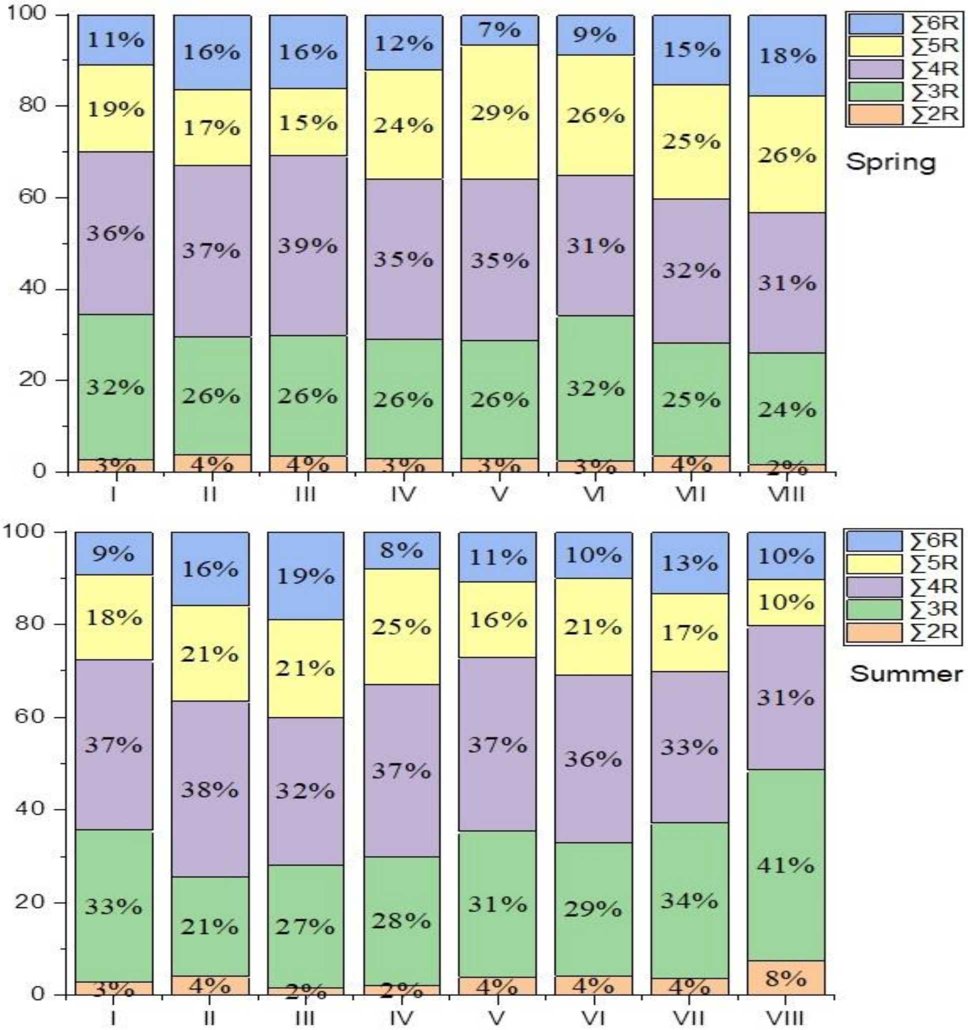


Fig. 7. Distribution and percentage of PAHs surface sediment rings during the spring and summer of year 2022.

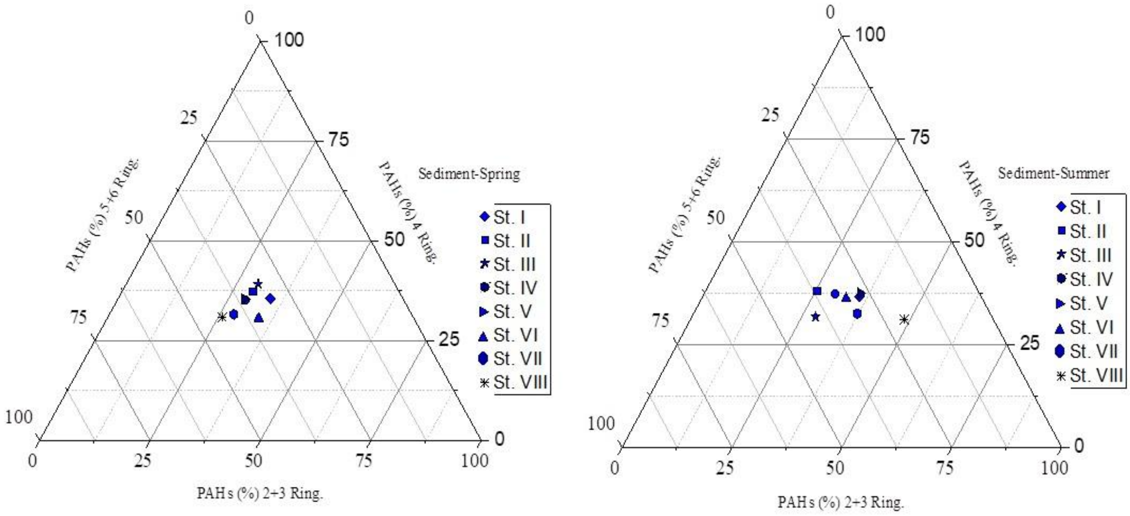


Fig. 8. PAHs ternary distribution plots (%) for Edku Lake considering the congeners containing 2 + 3, 4, 5 + 6 cyclic rings in sediment samples during the spring and summer of year 2022.

4.2. Source of PAHs in sediment samples

PAHs in the environment may come from one of three sources: petrogenic, pyrogenic or biogenic and these sources can be analyzed with the characteristic ratio method (Osman *et al*., 2024; Li *et al*., 2024). As shown in Fig. 9, Ant/ (Ant + Phe) results indicated petroleum source during spring and summer seasons, while, BaA/ (BaA + Chry) ratio for PAHs in all stations revealed coal, grass, and wood burning source except stations V during spring (petrogenic) and station V (mixed source) during summer. The results of Flu/ (Flu + Pyr) indicated fuel combustion for most stations except stations III and VIII during spring, which recorded coal, grass, and wood burning sources, stations VI and VII during spring (Hassaan *et al*., 2024; Potapowicz *et al*., 2025). InP/ (InP + BgP) results showed that fuel combustion dominated at most stations except stations VI, VIII during spring, and station IV during summer, which recorded coal, grass, and wood burning sources. ∑HMW/∑LMW ratio results are not less than 1 during spring and summer at all stations, which indicates that the source of PAHs in sediment is petrogenic input (Fig. 9). Petrogenic and combustion sources are the most common sources of LMW PAHs. In contrast, pyrolytics are the most common sources of HMW PAHs (Gundlapalli *et al*., 2024). Soliman *et al*. (2023) conducted an ecological assessment of PAHs in water, sediment, and fish in the Suez Bay, Egypt and found that Pyrene (Pyr) was the dominant PAH in water, sediment, and edible parts of fish species. Low ratio PAHs were observed in all samples, suggesting pyrogenic sources, however the other indexes that depend on the component's ratios of the same molecular weight suggested petrogenic sources. Li et al., (2024) examined the contents, compositions and sources of PAHs in the sediment of Caohai Lake in China and found that the PAHs were predominantly HML compounds (mean 57.5 %), and the diagnostic ratios revealed that coal, biomass burning, and traffic were the sources of PAHs. Pohl and Bodzek (2022) investigated the level of PAHs in Lake Manzalah via determining the concentrations of 16 PAHs present in sediment samples collected from eight locations from the lake and concluded that the major source of PAH pollution in the lake was the pyrogenic with a minimum petrogenic contribution. The obtained results indicate that PAHs that had a strong correlation (PCC) may have originated from the same source, while low correlation may be attributed to the degradation by some physicochemical or biological processes such as volatilization, leaching, degradation, and binding with soil particles. HMW-PAHs have a high rate of PCC values that mean a lower rate of degradation in sediment. PAHs with 2 to 3 LMW rings are recognized as the most sensitive to degradation, which likely explains the low concentration of LMW-PAHs, the low values of correlation coefficients between PAHs compounds (Gundlapalli *et al*., 2024).

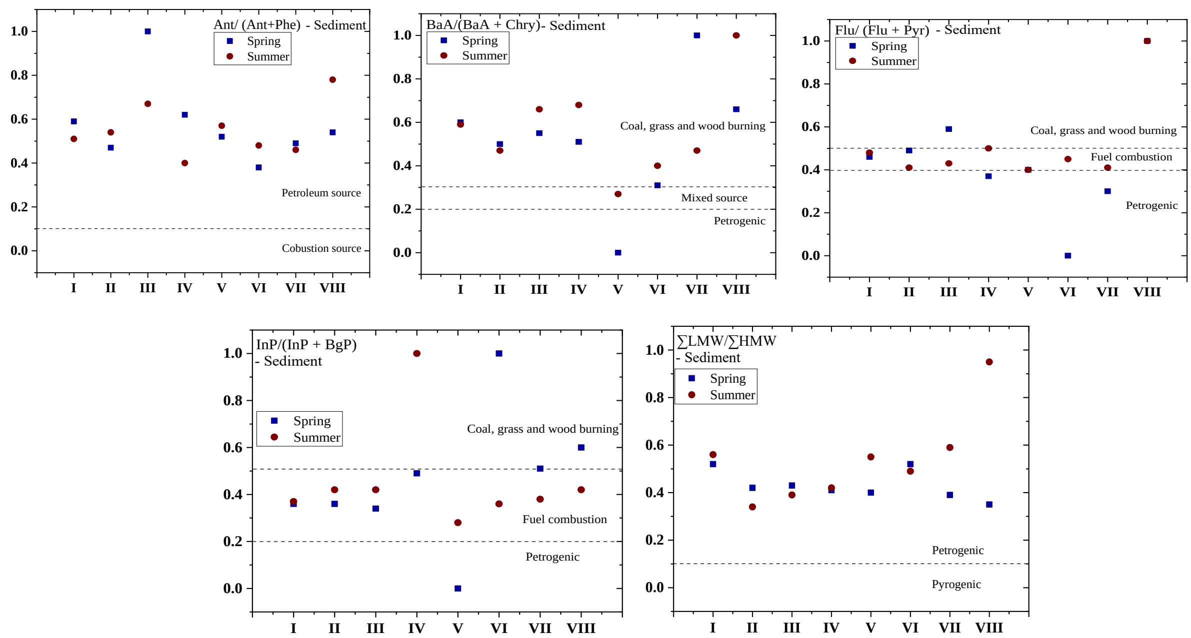


Fig. 9. Levels and Guidelines, for determining the sources of PAHs in sediment samples from Lake Edku during the spring and summer seasons of year 2022.

4.3. Toxicity and ecological risk assessment

The ecological risk of PAHs in the sediments samples was evaluated using the sediment quality guidelines (SQG) (Okbah *et al*., 2024a). The observed results of PAHs were compared with Effect Range Low (ERL) and Effect Range Median (ERM) values, concentration values less than ERL values are considered relatively rarely harmful, concentrations between ERL and ERM values are considered to be harmful occasionally, and concentrations higher than ERM values are considered relatively harmful to organisms and ecosystems (Dib *et al*., 2024). Among SQGs categories, ERM and ERL are widely applied for sediment quality assessment, especially in aquatic environments. Other different categories include lowest effect level (LEL), severe effect level (SEL), threshold effect level (TEL), chronic equilibrium partitioning threshold (SQAL), probable effect level (PEL), minimal effect threshold (MET) and toxic effect threshold (TEF) (Okbah *et al*., 2024a, Dib *et al*., 2024; *Rotondo et al*., 2021). Table 5 shows the quality guidelines (SQGs) values that are used for sediment quality and ecological risk assessments.

Table 5. Sediment quality guidelines for PAHs in freshwater ecosystems (μg kg^{-1} DW).

Material	TEL	LEL	MET	ERL	SQAL	TEC	PEL	SEL	TET	ERM	PEC
Ant	-	220.00	-	85.00	-	57.20	-	3700.00	-	960.00	845.00
Flu	-	190.00	-	35.00	540.00	77.40	-	1600.00	-	640.00	536.00
Nap	-	-	400.00	340.00	470.00	176.00	-	-	600.00	2100.00	561.00
Phe	41.90	560.00	400.00	225.00	1800.00	204.00	515.00	9500.00	800.00	1380.00	1170.00
BaA	31.70	320.00	400.00	230.00	-	108.00	385.00	14800.00	500.00	1600.00	1050.00
BaP	31.90	370.00	500.00	400.00	-	150.00	782.00	14400.00	700.00	2500.00	1450.00
Chr	57.10	340.00	600.00	400.00	-	166.00	862.00	4600.00	800.00	2800.00	1290.00
DBA	-	60.00	-	60.00	-	33.00	-	-	-	-	-
Flua	111.00	750.00	600.00	600.00	6200.00	423.00	2355.00	10200.00	2000.00	3600.00	2230.00
Pyr	53.00	490.00	700.00	350.00	-	195.00	875.00	8500.00	1000.00	2200.00	1520.00
Total PAHs	-	4000.00	-	4000.00	-	1610.00	-	100000.00	-	35000.00	22800.00

TEL: Threshold effect level, LEL: Lowest effect level, MET: Minimal effect threshold, ERL: Effect range—low, SQAL: Chronic equilibrium partitioning threshold, TEC: Threshold effect concentration, PEL: Probable effect level, SEL: Severe effect level, TET: Toxic effect threshold, ERM: Effect range—median, PEC: probable effect concentration.

4.3.1 Toxicity equivalent concentration (TEQ)

Generally, PAHs with low molecular weight (LMW, 2–3 rings) do not represent any observable toxicity or hazard, while PAHs with high molecular weight (HMW, 4–6 rings) may present a potential toxicity hazard (Wang *et al*., 2022). Toxic equivalent is used to calculate the health risk from exposure to the carcinogen in several compounds. The toxic equivalency factor (TEF) is used to compare the toxicity of each PAH relative to B[a]P. TEFs value for PAHs which are illustrated in Table 6.

$$TEQ= \sum(C\times TEFs) \quad (1)$$

where C is the level of PAH and TEFs is the toxic equivalency factor. To assess the potential toxicity of PAHs, the toxic equivalent concentrations (TEQ_{BaP}) of 16 PAHs in sediments were calculated, as shown in Table 5. TEQ_{BaP} of the 16 PAHs ranged between 211.80 TEQ g^{-1} at station VI and 363.10 TEQ g^{-1} at station I with an average of 273.08 ±62.10 ng TEQ g^{-1} during spring and between 135.50 TEQ g^{-1} at station VIII and 345.40 TEQ g^{-1} at station I with an average of 271.80 ±64.14 ng TEQ g^{-1} during summer. TEQ_{BaP} of the seven carcinogenic PAHs fluctuated between 98.70 ng TEQ g^{-1} at station VIII and 171.80 TEQ g^{-1} at station IV with an average of 127.38 ±23.15 TEQ g^{-1}, while during spring and summer fluctuated between 61.50 TEQ g^{-1} at station VIII and 147.10 TEQ g^{-1} at station II with an average of 114.94 ±29.30 ng TEQ g^{-1}. The most dominant PAHs in the seven carcinogenic PAHs (Table 3) are according to IARC, 2007, and BaP, which recorded 18%, followed by Chr and BghiP with 13% of TEQ_{BaP} of ∑7CPAHs. In the present study, all stations had TEQBaP values below 100 μg kg^{-1} which indicated that all stations had lower carcinogenic potency (Wick *et al*., 2011). The total TEQ_{BaP} for 16 PAHs and C-PAHs of these sediment samples during spring and summer does not exceed the Method B cleanup level (the levels of hazardous substances in the environment that are considered sufficient to protect the environment and human health) for benzo(a)pyrene (0.137 mg kg^{-1}). Therefore, these sediment samples have met the cleanup level for benzo(a)pyrene (Younis *et al*., 2018).

Table 6. Seasonal Toxic equivalent factor of different PAHs in surface sediments from the Lake Edku.

PAHs	Study-Average				Aver. ×TEF	
	IARC	Spring	Summer	TEFs	Spring	Summer
Nap	2B	8.24	9.56	0.001	0.01	0.01
Acy	3	11.65	11.86	0.001	0.01	0.01
Ace	3	5.74	7.7	0.001	0.01	0.01
Flu	3	11.86	11.15	0.001	0.01	0.01
Phe	3	19.88	23.14	0.001	0.02	0.02
Ant	3	25.06	26.55	0.01	0.25	0.27
Flua	3	18.75	21.09	0.001	0.02	0.02
Pyr	3	25.04	26.89	0.001	0.03	0.03
BaA	3	17.99	17.55	0.1	1.8	1.76
Chr	2B	19.2	15.23	0.01	0.19	0.15
BbF	2B	13.88	15.78	0.1	1.39	1.58
BkF	1	17.85	11.86	0.1	1.79	1.19
BaP	2A	26.23	28.6	1	26.23	28.6
DBA	3	16.39	11.71	1	16.39	11.71
BghiP	2B	19.49	18.93	0.01	0.19	0.19
InP	2B	15.85	14.21	0.1	1.59	1.42
∑16PAHs		273.1	271.81	2.437	49.93	46.98
∑7PAHs		120.74	114.17	1.321	31.39	33.14

(1) carcinogens, (2A) probable carcinogens, (2B) possible carcinogens, and (3) not possible carcinogenic.

5. Conclusion

In recent years, Egyptian coastal lakes have become repositories for a variety of pollutants discharged from domestic, agricultural and industrial activities. Lake Edku, the third largest coastal lake in Egypt, is drastically affected by man-made activities due to its proximity to fish farms, urban areas, factories and agricultural lands. The current study provides critical data on PAHs contamination in the sediments of Lake Edku, helping to identify pollution sources and assess potential ecological risks. The findings emphasize the need for pollution management strategies to mitigate contamination levels and prevent environmental degradation in the Edku lake. To protect the lake’s ecosystem, future efforts should prioritize: controlling industrial discharges to reduce pollutant influx, improving wastewater treatment to minimize contamination, and promoting sustainable environmental practices to ensure long-term ecological balance.

List of abbreviations:

PAHs: Polycyclic Aromatic Hydrocarbons

Nap: Naphthalene

Acy: Acenaphthylene

Ace: Acenaphthene

Flu: Fluorene

Phe: Phenanthrene

Ant: Anthracene

Flua: Fluoranthene

Pyr: Pyrene

BaA: Benzo(a)anthracene

Chr: Chrysene

BbF: Benzo(b)Fluoranthene

BkF: Benzo(k)Fluoranthene

BbP: Benzo(a) Pyrene

DBA: Dibenz(a,h)anthracene

BghiP Benzo(g,h,i) perylene

InP: Indeno(1,2,cd)pyrene

TEF: Toxicity Equivalence Factor

SQGs Sediment Quality Guidelines

ILCR: Incremental Lifetime Cancer Risk

PCA: Principal Component Analysis

HCA: Hierarchical Cluster Analysis

LEL: Lowest effect level

TEL: Threshold effect level

MET: Minimal effect threshold

ERL: Effect range low

TEC: Threshold effect concentration

SEL: Severe Effect Level

PEL: Probable Effect Level

ERM: Effect range median

PEC: Probable Effect Concentration

Declarations

Ethics approval and consent to participate

Consent for publication: The article contains no such material that may be unlawful, defamatory, or which would, if published, in any way whatsoever, violate the terms and conditions as laid down in the agreement.

Availability of data and material: Not applicable.

Competing interests: The authors declare that they have no conflict of interest in the publication.

Funding: Not applicable.

Authors' contributions: Basma Mohamed Omar: reviewing and editing the manuscript, Mohammed El Sayed Nassar: performed the experiments, data interpretation, writing and editing the manuscript, Mohamed Abdel-Aziz Okbah, and Maie Ibrahim El-Gammal: Resources, conceptualization, supervision, reviewing and editing the manuscript.

Acknowledgments: Not applicable

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