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Phase partitioning and source apportionment of polycyclic aromatic hydrocarbons in the surface water and Sediments: A case of the Vietnamese Mekong Delta

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ABSTRACT

This study investigates the occurrence, phase partitioning, and source apportionment of sixteen priority polycyclic aromatic hydrocarbons (PAHs) across the surface water and sediment interface of the Can Tho River network, a rapidly urbanizing hub in the Vietnamese Mekong Delta. The methodology employed a strategic urban-rural gradient sampling design, followed by liquid-liquid extraction (LLE) for aqueous samples and ultrasonic-assisted extraction (UAE) for sedimentary matrices. Quantification was achieved using gas chromatography-tandem mass spectrometry (GC-MS/MS) with multiple reaction monitoring (MRM) for enhanced selectivity. Analysis of samples from nineteen sites revealed a distinct phase fractionation mechanism. The aqueous compartment was dominated by low-molecular-weight (LMW) congeners, specifically acenaphthylene and acenaphthene, which exhibited significant positive correlations with biodegradable organic matter (BOD_5, COD). Conversely, bottom sediments functioned as a preferential sink for high-molecular-weight (HMW) and carcinogenic compounds (e.g., benzo[b]fluoranthene, indeno[1,2,3-cd]pyrene). Spatial analysis delineated a clear urban-rural dichotomy: urban zones were characterized by pyrogenic signatures linked to vehicular emissions, while agricultural areas displayed a stable petrogenic background. These findings underscore the critical role of urbanization in modulating pollutant fate, providing an essential baseline for environmental management in tropical deltaic systems.

Keywords: polycyclic aromatic hydrocarbons, phase partitioning, source apportionment, urban rivers, sediment quality, Mekong Delta.

INTRODUCTION

Polycyclic aromatic hydrocarbons (PAHs) constitute a ubiquitous class of persistent organic pollutants (POPs) characterized by two or more fused aromatic rings, originating primarily from incomplete combustion processes, industrial discharges, and petroleum releases (Akhtar et al., 2021; Najam and Alam, 2023; Ruan et al., 2023). Owing to their carcinogenic, mutagenic, and teratogenic properties, PAHs have been prioritized as critical contaminants by environmental agencies worldwide, including the United States Environmental Protection Agency (US EPA) and the European Union (Abdel-Shafy and Mansour, 2016; Honda and Suzuki, 2020; Mai et al., 2024). In aquatic ecosystems, the environmental fate and transport of these compounds are governed by their physicochemical properties, particularly their high hydrophobicity and octanol – water partition coefficients (K_{ow}). Upon entering riverine systems via wastewater discharge, surface runoff, and atmospheric deposition, PAHs tend to partition rapidly from the dissolved phase onto suspended particulate matter and organic colloids (Sun et al., 2018; Yuan et al., 2021; Phung et al., 2019; Rong et al., 2025). Consequently, bottom sediments serve as

the ultimate geochronological sink for these recalcitrant compounds, integrating contamination signals over extended periods (Yang et al., 2013; Wu et al., 2023). However, under changing hydrodynamic conditions or physicochemical perturbations such as resuspension events or alterations in redox potential sediments can function as secondary sources, remobilizing PAHs into the overlying water column and posing long-term risks to aquatic biota and human health (Shi et al., 2024; Berríos-Rolón et al., 2025).

While the occurrence and distribution of PAHs have been extensively documented in temperate regions and major industrial basins, the dynamics of these pollutants in tropical riverine networks, particularly in rapidly developing economies, remain under-represented in the literature. Tropical deltas are complex hydro-geochemical interfaces where intense anthropogenic pressures intersect with unique hydrological regimes. In these systems, the interplay between rapid urbanization, intensive agriculture, and hydrological variability creates distinct pathways for pollutant transport and transformation (Pohl and Bodzek, 2022; Zhao, 2023). Vietnam, an emerging economy in Southeast Asia, exemplifies this environmental challenge. The Vietnamese government has recently strengthened its regulatory framework, incorporating PAHs into the national technical regulation on sediment quality (QCVN 43:2025/BTNMT), establishing maximum permissible concentrations for priority PAHs to safeguard ecological health (MONRE, 2025). Despite these legislative advances, routine monitoring and systematic source apportionment in Vietnam remain fragmented due to financial constraints and analytical limitations, leading to a critical paucity of data regarding the baseline levels and partitioning behavior of PAHs in key economic zones (MONRE, 2025).

The Mekong Delta, one of the world's largest and most productive river deltas, is currently facing unprecedented environmental stress driven by industrialization and urban expansion. Can Tho City, the socio-economic epicenter of the Vietnamese Mekong Delta, represents a quintessential model of these emerging pressures. The city is characterized by a dense network of rivers and canals that receive a complex mixture of inputs from agricultural runoff, untreated domestic wastewater, industrial effluents, and intensive inland waterway traffic (Thuan et al., 2024; Wilbers et al., 2014; Sudaryanto et al., 2011). Unlike static lacustrine systems, the open hydrological network of Can Tho facilitates the dispersion of contaminants, yet the specific mechanisms governing the distribution of PAHs between surface water and sediments in this region remain poorly understood. Previous studies have primarily focused on localized points or different contaminant classes, leaving a significant gap in understanding how urban and rural gradients influence PAH accumulation and source signatures in this specific deltaic environment (Cai et al., 2023; Fang et al., 2016; Chen et al., 2012; Song et al., 2014).

Understanding the source-sink dynamics of PAHs in the Mekong Delta is of global relevance, offering insights into the behavior of hydrophobic organic contaminants in tropical waters heavily impacted by anthropogenic activities (Liu et al., 2025). Addressing the current knowledge gap is essential not only for local environmental management but also for contributing to the broader scientific understanding of pollutant cycling in large tropical river systems. Therefore, this study was designed to provide a comprehensive assessment of PAHs in the aquatic environment of Can Tho City. The primary objectives of this research were: (1) to determine the occurrence and spatial distribution of sixteen priority PAHs in both surface water and bottom sediments across a gradient of land-use types; (2) to elucidate the partitioning behavior of PAHs and their relationships with organic matter characteristics (TOC, BOD_5, COD); and (3) to apply multivariate statistical techniques and diagnostic ratios for precise source apportionment and predicted ecological risk assessment. This work establishes one of the first comprehensive baselines for PAHs in the lower Mekong River, providing critical data to support evidence-based policy making and environmental risk mitigation in the region.

METHODS

Study area and sampling strategy

To capture the spatial heterogeneity of polycyclic aromatic hydrocarbon (PAH) contamination across the urban-rural gradient, a comprehensive sampling campaign was conducted in Can Tho City, a central hub of the Vietnamese Mekong Delta. The study area encompasses a diverse range of land-use types, including the densely populated urban core (Ninh Kieu, Cai Rang districts),

industrial zones, and peri-urban agricultural areas (Phong Dien, Co Do, Vinh Thanh districts). Nineteen sampling sites (Table 1 and Figure 1) were strategically selected to represent major hydrological inputs, including urban canals receiving untreated domestic wastewater, river sections impacted by intensive inland waterway traffic, and channels influenced by agricultural runoff.

Sample collection was synchronized to occur in February 2024, corresponding to the dry season when river discharge is minimal. Sampling was specifically timed to coincide with the low-tide period to capture worst-case scenarios, as reduced dilution capacity and weakened hydrodynamic flushing typically lead to peak pollutant concentrations during this phase (Zhang et al., 2009; Wang et al., 2013). At each site, paired samples of surface water and bottom sediment were collected. Surface water samples were taken at a depth of 0–25 cm below the air-water interface, while bottom surface sediments (top 0–20 cm layer) were retrieved using a grab sampler. All samples were immediately stored in pre-cleaned amber glass containers at 4 °C and transported to the laboratory for analysis.

Reagents and standards

All solvents, including dichloromethane (DCM), n-hexane, and isooctane, were of HPLC grade (purity ≥ 99.8%, Merck, Germany).

A mixture of sixteen priority PAH standards and a cocktail of deuterated internal standards (acenaphthene-d_{10}, phenanthrene-d_{10}, chrysene-d_{12}, and perylene-d_{12}) were sourced from Agilent Technologies (USA) to ensure metrological traceability. Stock solutions (10 mg/L) were prepared in isooctane and stored at -20 °C in the dark to prevent photodegradation.

Sample preparation and extraction

General water quality parameters (TSS, BOD_5, COD, TOC) and sediment organic carbon (%C) were determined according to standard methods (SMEWW 6440B:2017). For PAH quantification, water samples (300 mL) underwent liquid-liquid extraction (LLE) using DCM in triplicate with vigorous agitation. The extracts were concentrated to 1 mL via rotary evaporation at 40 °C. Sediment samples were air-dried at <100 °C, and 0.15 g aliquots were subjected to ultrasonic-assisted solvent extraction using a DCM/ultrapure water mixture. All final extracts were spiked with internal standards to correct for matrix effects, evaporated to dryness under nitrogen, and reconstituted in isooctane.

Instrumental analysis (GC-MS/MS)

The identification and quantification of target PAHs were performed using an Agilent 7890B Gas Chromatograph coupled with a 7000D Triple

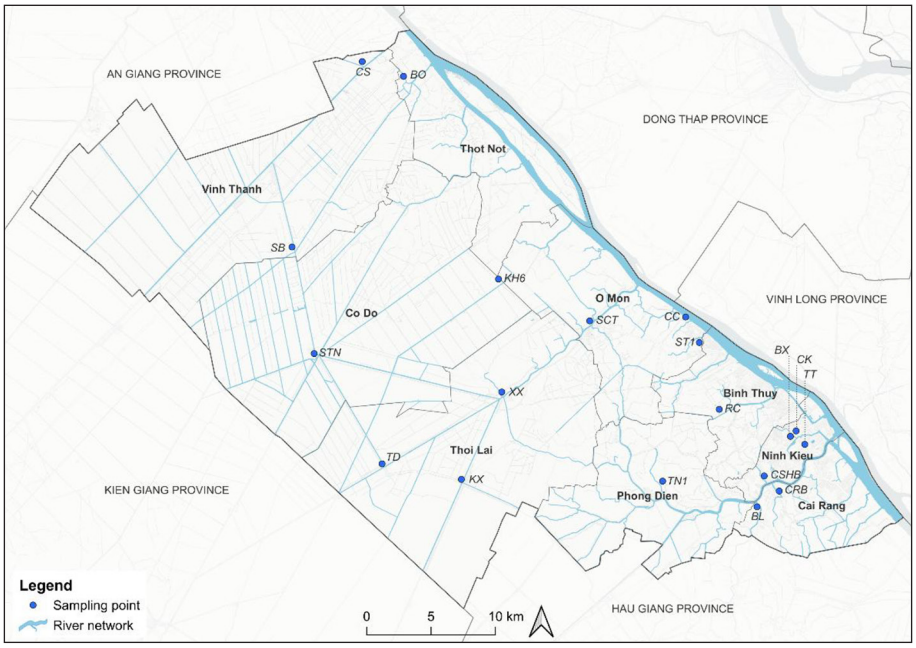

Figure 1. The map indicating the sampling points in this study

Table 1. Sampling sites and potential sources of PAHs in surface waters of Can Tho City

No.	Code	Sampling sites	Area type	Potential PAHs sources
1	TT	Tham Tuong Canal	Urban	UW, RSR, VE
2	CK	Cai Khe Canal	Urban	UW, RSR, VE, MR
3	BX	Bun Xang Canal	Urban	UW, RSR, VE
4	CSHB	Cai Son-Hang Bang Canal	Urban	UW, RSR, VE
5	BL	Ba Lang Canal	Sub-urban	DW, WT, AW, BC
6	CRB	Cai Rang Be River	Sub-urban	DW, WT, AW, BC, MR
7	ST	Sang Trang Canal	Sub-urban and industrial	IW. DW, WT
8	RC	Cam Canal	Agricultural	DW, AW, BC
9	SCT	Can Tho River	Sub-urban	DW, AW, BC
10	CC	Cai Chom Canal	Agricultural	DW, AW, BC
11	BO	Bo Ot Canal	Agricultural	DW, AW, BC
12	TN	Tra Nien Canal	Agricultural	DW, AW, BC
13	KX	Xang Canal	Agricultural	DW, AW, BC
14	XX	Xeo Xao Canal	Agricultural	DW, AW, BC
15	TD	Thi Doi Canal	Agricultural	DW, AW, BC
16	KH	KH Canal	Agricultural	DW, AW, BC
17	STN	Thot Not River	Agricultural	DW, AW, BC
18	CS	Cai San Canal	Agricultural	DW, AW, BC
19	SB	Sau Bong Canal	Agricultural	DW, AW, BC

Note: UW – Urban wastewater; DW – Domestic wastewater; AW – Agricultural wastewater; RSR – Road surface runoff; VE – Vehicle exhaust; WT – Waterway traffic; IW – Industrial wastewater; BC – Biomass combustion; MR – Market runoff.

Quadrupole Mass Spectrometer (Agilent Technologies, USA). Chromatographic separation was achieved on an HP-5MS UI capillary column (30 m × 0.25 mm i.d. × 0.25 µm film thickness). The oven program started at 60 °C (1 min), ramped at 20 °C/min to 120 °C, then 6 °C/min to 300 °C (held for 10 min). The injector was operated in splitless mode at 280 °C with an injection volume of 1 µL. Helium served as the carrier gas (1.2 mL/min). The mass spectrometer utilized Electron Ionization (EI) at 70 eV and operated in Multiple Reaction Monitoring (MRM) mode for high selectivity.

QA/QC and data treatment

Strict quality control included 7-point calibration curves ($R^2 > 0.995$), with recovery rates for internal standards ranging from 78% to 112%. Limits of detection (LOD) were 0.5 ng/L for water and 1.0 µg/kg for sediment. Concentrations below LOD were treated as non-detects. Spatial distribution and source signatures were further evaluated using cluster analysis (CA), Pearson correlation, and principal component analysis (PCA) via SPSS version 20.0.

RESULTS AND DISCUSSION

Accumulation of PAHs in surface water

Occurrence and compositional profiles

The compositional profile of polycyclic aromatic hydrocarbons in the surface waters of Can Tho City (Figure 2) was unequivocally dominated by low-molecular-weight (LMW, 2–3 rings) homologues, reflecting the distinct physicochemical partitioning behavior of these compounds in tropical lotic systems. Among the sixteen priority PAHs targeted, acenaphthylene (Acy) and acenaphthene (Ace) were ubiquitous, being detected at 100% of sampling sites with concentrations ranging from 96 to 150 ng/L and 56.5 to 88.5 ng/L, respectively. Fluorene was also frequently observed (6.0–17.0 ng/L), whereas naphthalene and fluoranthene appeared sporadically. In sharp contrast, high-molecular-weight (HMW, ≥4 rings) compounds, such as benzo[a]pyrene (BaP) and benzo[a]anthracene (BaA), were largely absent or detected at negligible frequencies in the dissolved phase. This distribution pattern is consistent with the fundamental solubility differences

governed by octanol–water partition coefficients (K_{ow}) (Jiang et al., 2022; Liu et al., 2024; Roszko et al., 2020); LMW PAHs exhibit higher aqueous solubility and are thus more persistent in the water column, while HMW PAHs possess strong hydrophobic characteristics, leading to their rapid adsorption onto suspended particulates and subsequent settling into bottom sediments (Li et al., 2019; Suresh et al., 2025; Zhao et al., 2025). The measured concentrations of Acy and Ace in this study were notably higher than those reported in other Vietnamese water bodies (Phung et al., 2019; Quang et al., 2017) suggesting that the dense river network in Can Tho receives continuous diffuse inputs from urban activities, although the rapid degradation or partitioning of toxic HMW congeners limits the immediate ecological risk in the aqueous phase.

Spatial distribution and source identification

Spatial analysis revealed a relatively high degree of homogeneity in PAH distribution across the study area, punctuated by localized elevations at specific hotspots. The highest aggregate concentrations were recorded at site CC near an industrial zone and site TT in the urban center, where a concurrence of peak LMW concentrations (e.g., Nap reaching 37.0 ng/L) and trace detections of combustion markers like indeno[1,2,3-cd]pyrene (4.0–7.0 ng/L) were observed (Figure 2). These hotspots likely reflect direct inputs from untreated domestic wastewater and localized industrial discharges. To further elucidate the underlying factors controlling these spatial patterns, Principal Component Analysis (PCA) was applied to the dataset. A single principal component (PC1) was extracted, explaining 72.8% of the total variance, with moderate loadings for Ace (0.645) and Acy (0.620) (Figure. 4). This statistical output suggests that the presence of LMW PAHs in the surface water is not driven by isolated point sources but rather by a regional background gradient of diffuse pollution. This pattern is characteristic of atmospheric deposition and regional dispersion processes, where lighter PAHs are transported over longer distances before partitioning into the water column (Berríos-Rolón et al., 2025; Semenov et al., 2023; Arzayus et al., 2001; Wang et al., 2026).

Factors influencing phase partitioning

The environmental behavior of dissolved PAHs was further clarified through Pearson correlation analysis with water quality parameters. Significant positive correlations were established between predominant LMW PAHs (Ace, Acy) and indicators of organic pollution, specifically COD ($r = 0.46$ - 0.55, $p < 0.05$) and BOD_5 ($r = 0.55$, $p < 0.05$). This association implies a co-transport mechanism where LMW PAHs enter the aquatic system alongside biodegradable organic matter typical of domestic sewage and urban runoff. Conversely, a strong inverse relationship was observed between these PAHs and Total Organic Carbon (TOC) ($r \approx - 0.60$, $p < 0.01$). This negative correlation highlights a critical attenuation mechanism: as the content of dissolved or colloidal organic carbon increases, hydrophobic organic contaminants tend to partition out of

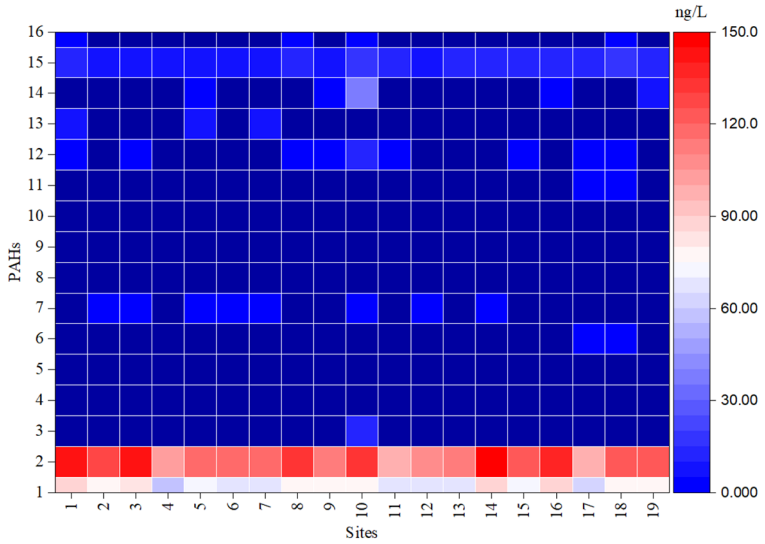

Figure 2. Heatmap illustrating the spatial distribution of PAH concentrations in surface water

the freely dissolved phase and adsorb onto organic matrices, thereby reducing their measurable concentration in the filtered water fraction (Grmasha et al., 2023; Li et al., 2010; Li et al., 2019; Chen et al., 2020; Wernicke et al., 2022). Furthermore, the absence of correlation with total suspended solids (TSS) reinforces the conclusion that the detected PAHs are primarily in the dissolved form, governed by solubility equilibria rather than particle-bound transport (Montuori et al., 2022; Spence et al., 2023). Finally, it is noteworthy that all recorded concentrations remained well within the safety thresholds established by the European Union Drinking Water Directive (2020/2184) (EU, 2020), indicating that while the river network acts as a transport vector for urban pollutants, the direct toxicity risk to surface water users remains low.

Accumulation of PAHs in bottom sediments

Sedimentary profiles and phase fractionation

In distinct contrast to the aqueous phase, the sedimentary compartment of the Can Tho River system functioned as a preferential sink for high-molecular-weight (HMW) PAHs (Figure 3), exhibiting a compositional profile strongly skewed towards hydrophobic congeners. While low-molecular-weight compounds such as naphthalene, fluorene, and phenanthrene were ubiquitously detected across all sampling sites (100% detection frequency), the total PAH burden in sediments was disproportionately governed by 4–6 ring compounds, particularly fluoranthene, pyrene, and benzo[b]fluoranthene. This pronounced fractionation between surface water and sediment is consistent with the canonical theory of hydrophobic partitioning, where HMW PAHs, characterized by high octanol water partition coefficients (K_{ow}) and low aqueous solubility rapidly adsorb onto particulate organic matter and settle out of the water column (Srogi, 2007; Hussain et al., 2015; Sheng et al., 2021; Patel et al., 2020; Wang et al., 2024). Consequently, the sediment matrix effectively integrates temporal contamination signals, revealing a chronic accumulation pattern that is not discernible in the transient surface water profile (Li et al., 2006; Rong et al., 2025; Suresh et al., 2025).

Spatial heterogeneity and urban footprints

The spatial distribution of sedimentary PAHs revealed a stark urban-rural dichotomy, reflecting the intensity of anthropogenic pressures. The highest aggregate concentrations were pinpointed at sites situated within the densely urbanized core (e.g., sites TT and BX) and specific traffic-impacted zones (site KX), with peak loads reaching up to 235 μg kg^{-1} (Figure 3). These hotspots were characterized by complex mixtures of pyrogenic PAHs, correlating spatially with zones of intensive residential activity, commercial operations, and inland waterway transport. In comparison, agricultural and peri-urban sites (e.g., BL, SB, STN) exhibited significantly lower and more homogenous background levels (Figure 3). Despite these elevated concentrations in urban zones, the absolute PAH levels generally remained below

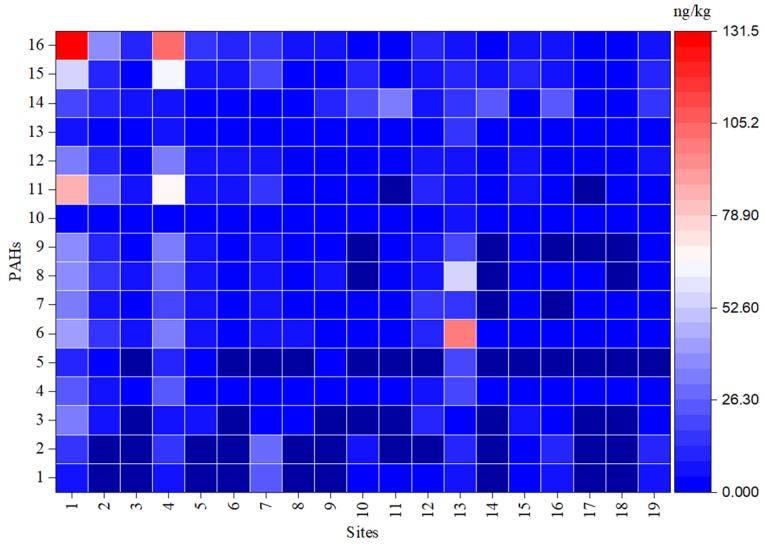

Figure 3. Heatmap illustrating the spatial distribution of individual PAH concentrations in bottom sediment

the threshold limits stipulated in the Vietnamese National Technical Regulation on Sediment Quality (QCVN 43:2025/BTNMT) (MONRE, 2025), indicating that while the system is under clear anthropogenic stress, it has not yet exceeded regulatory safety ceilings. However, the prevalent occurrence of carcinogenic HMW congeners, such as benzo[a]pyrene and indeno[1,2,3-cd]pyrene, warrants continued vigilance regarding long-term ecological risks (Grmasha et al., 2023; Berríos-Rolón et al., 2025; Mai et al., 2024; Ruan et al., 2023; Wernicke et al., 2022).

Source identification and transport mechanisms

To definitively apportion the origins of these sedimentary residues, a combination of molecular diagnostic ratios and multivariate statistical analysis was employed (Figure 4 and Figure 5). The calculated isomeric ratios, specifically Ant/(Ant+Phe) and IcdP/(IcdP+BghiP), predominantly fell within the ranges indicative of pyrogenic sources, pointing to biomass and petroleum combustion as the primary drivers of contamination (Yunker and Macdonald, 2003; Xiong et al., 2025; Szramowiat-Sala et al., 2025; Wang et al., 2026; Zeng et al., 2019). This interpretation was robustly corroborated by principal component analysis (PCA), which extracted distinct component loadings grouping the HMW-enriched urban sites (TT, BX, KX) separately from the LMW-dominated background sites (Figure 5). The strong association of these urban sediments with combustion markers (BaA, BbF, IcdP) provides compelling evidence that vehicular emissions and waterway traffic are the dominant vectors supplying PAHs to the riverbed (Zhang et al., 2015; Li et al., 2009; Yuan et al., 2021; Huang, Xu, et al., 2025). Furthermore, the statistically significant correlation between naphthalene and sediment organic carbon (OC) ($r = 0.464$, $p < 0.05$), contrasted with the lack of such correlation for HMW PAHs, suggests a dual-mechanism model: volatile LMW PAHs are governed by equilibrium partitioning with organic matter (diffuse background), whereas HMW PAHs are deposited directly from soot and combustion particles (direct source inputs), decoupling them from the natural OC content of the sediment (Ukalska-Jaruga and Smreczak, 2020; Lawal, 2017; Yin et al., 2022; Yang et al., 2021; Montuori et al., 2022).

Ecological and health risk potential

The assessment of ecological risks associated with sedimentary polycyclic aromatic

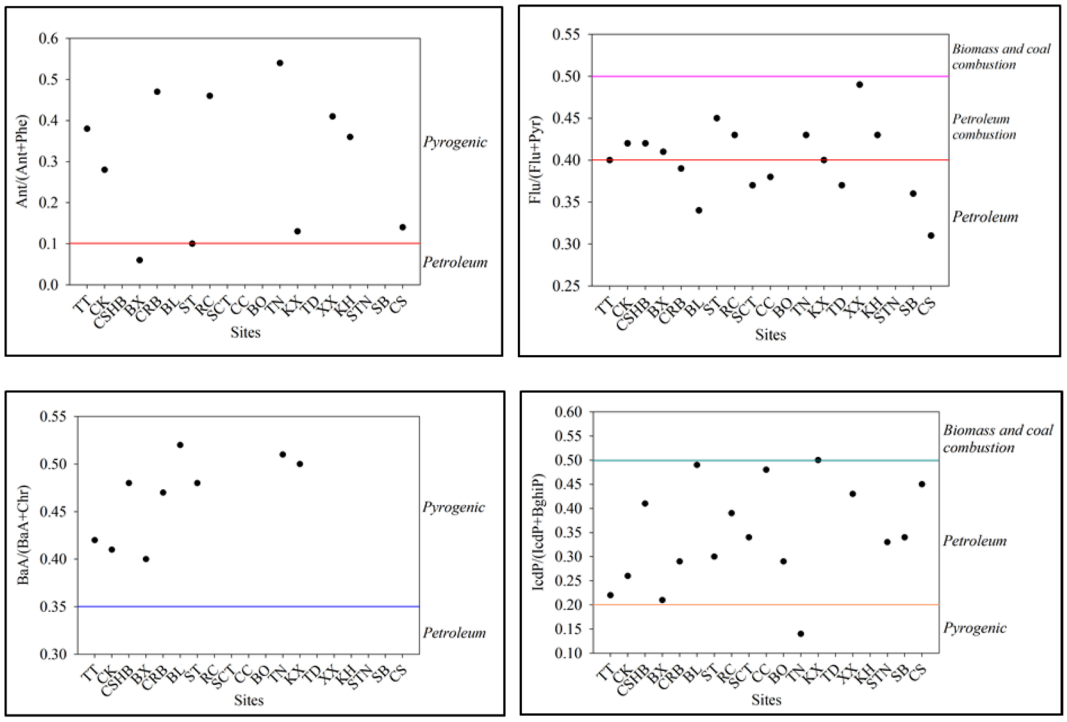

Figure 4. Diagnostic ratio of Ant/(Ant+Phe), Flu/(Flu+Pyr), BaA/(BaA+Chr), and IcdP/(IcdP+BghiP) for PAH source identification across sampling sites

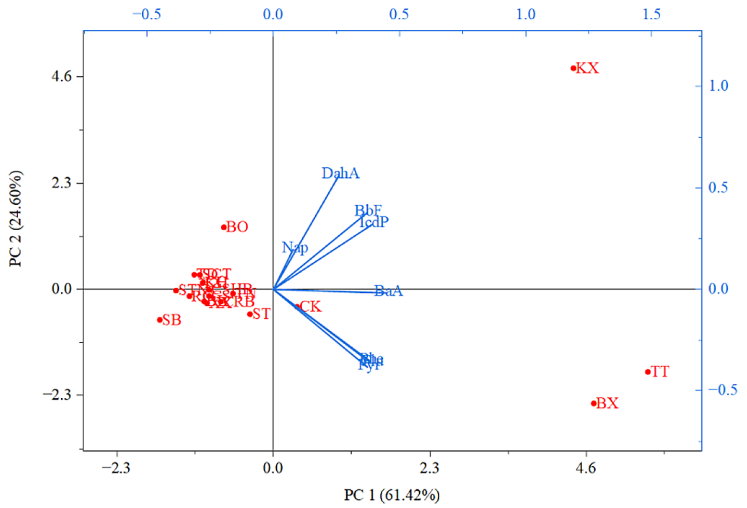

Figure 5. PCA-Biplot showing the spatial distribution of sampling sites and PAH loadings in sediments

hydrocarbons in the Can Tho River system reveals a complex scenario driven by the heterogeneous distribution of contamination hotspots. Although the aggregate concentrations of the sixteen priority PAHs at most sampling stations generally remained below the threshold values stipulated in the Vietnamese National Technical Regulation on Sediment Quality (QCVN 43:2025/BTNMT) (MONRE, 2025) and were largely compliant with international consensus-based sediment quality guidelines (SQGs), the specific compositional profiles in urbanized zones necessitate a more nuanced toxicological evaluation. The preferential accumulation of high-molecular-weight (HMW) congeners, particularly benzo[b]fluoranthene, indeno[1,2,3-cd]pyrene, and fluoranthene, at sites influenced by intense anthropogenic activities (e.g., sites TT, BX, and KX) suggests a localized potential for adverse biological effects (Abdel-Shafy and Mansour, 2016; Berríos-Rolón et al., 2025; Grmasha et al., 2023; Mai et al., 2024; Patel et al., 2020). These 4–6 ring compounds are characterized by high hydrophobicity and environmental persistence, which significantly increases their bioavailability to benthic invertebrates through pore-water exposure and direct sediment ingestion. While acute toxicity events are unlikely given the current contamination magnitude, the chronic exposure of benthic communities to these carcinogenic agents raises concerns regarding sublethal effects, including genotoxicity and mutagenicity, which may propagate through higher trophic levels via biomagnification mechanisms (Suresh et al., 2025; Zhao, 2023; Zhao et al., 2025; Berríos-Rolón et al., 2025). The frequent detection of these priority pollutants serves as an ecological signal that the assimilative capacity of the riverbed in urban core areas is approaching a critical tipping point.

Regarding human health risks, the assessment focused primarily on potential exposure pathways via surface water ingestion and dermal contact, given the extensive use of the river network for domestic and livelihood activities in the Mekong Delta. The dissolved PAH profile was dominated by low-molecular-weight compounds such as acenaphthylene and acenaphthene, while highly potent carcinogenic species, most notably benzo[a]pyrene (BaP), were consistently absent or below analytical detection limits. Consequently, the water quality at all sampling stations complied with the stringent safety benchmarks of the European Union Drinking Water Directive (2020/2184) (EU, 2020). This compliance indicates that the immediate carcinogenic risk posed to local residents utilizing the river water is currently negligible (Wang et al., 2026; Liu et al., 2024; Grmasha et al., 2023). However, the sporadic detection of indeno[1,2,3-cd]pyrene at specific urban locations signifies a latent hazard. It is crucial to acknowledge that standard regulatory comparisons often overlook the synergistic toxicity of PAH mixtures and the potential for cumulative burden (Saraga et al., 2024). Furthermore, the significant correlation observed between dissolved PAHs and organic pollution indicators (BOD_5, COD) implies that these pollutants are co-transported

with untreated wastewater. Therefore, while the individual compound analysis suggests a safe environment, the continued discharge of urban effluents warrants a precautionary management approach to prevent the long-term degradation of water quality and to safeguard public health against future accumulation scenarios (Zhang et al., 2009; Abdel-Shafy and Mansour, 2016; Berríos-Rolón et al., 2025).

CONCLUSIONS

This research provides a pioneering integrated assessment of polycyclic aromatic hydrocarbon dynamics within the rapid urbanization context of the Vietnamese Mekong Delta. A distinct phase fractionation mechanism was evident, where the aqueous compartment was dominated by soluble low-molecular-weight species, particularly acenaphthylene and acenaphthene. This distribution was strongly governed by their physicochemical affinity for biodegradable organic matter, identifying domestic effluents and urban runoff as the primary dissemination vectors in the water column. Conversely, the benthic zone acted as the ultimate geochronological sink for hydrophobic, high-molecular-weight carcinogenic congeners, specifically in high-density urban and traffic-impacted locations. Source apportionment techniques definitively linked these sedimentary burdens to pyrogenic emissions from vehicular and waterway transport, contrasting sharply with the stable petrogenic background observed in agricultural areas. Although current aggregate concentrations comply with regulatory safety limits, the specific enrichment of persistent toxins in the urban core signals an emerging ecological threat driven by anthropogenic encroachment. Consequently, these findings advocate for the urgent integration of sediment quality monitoring into regional management frameworks to preemptively address the environmental footprints of intensifying economic development in this vulnerable tropical delta.

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