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Which part of an edible clam poses the highest health concern? A tissue-specific assessment of PAH bioaccumulation in *Ruditapes philippinarum*

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ABSTRACT

The growing global emphasis on food safety, coupled with projected increases in seafood consumption, underscores the need for rigorous health risk assessments associated with dietary intake of seafood products. This study investigates the distribution and ecological risk of PAHs in seawater and sediment, and further examines tissue-specific patterns of PAHs bioaccumulation in the clam *Ruditapes philippinarum* from typical bays of the Bohai Sea and the Yellow Sea. PAHs concentrations in environmental media were within globally reported ranges, with elevated ecological risks observed in a semi-enclosed, urban-adjacent bay (Jiaozhou Bay). Among tissues, the digestive gland consistently showed higher PAH accumulation and bioaccumulation factors than other organs. Health risk assessment approaches (ILCR and MOE) indicated generally acceptable risks from whole soft tissue consumption, while tissue-level scenarios identified the digestive gland as a dominant contributor to potential exposure. These findings provide mechanistic insight into tissue-specific PAHs accumulation and support targeted risk-reduction strategies in seafood consumption.

1. Introduction

Seafood derived from fisheries and aquaculture accounts for approximately 17 % of global edible meat production (Costello et al., 2020), underscoring the necessity to comprehensively evaluate its safety for human consumption. The US EPA has established frameworks for assessing pollutant bioavailability and exposure related to human health, including risks from dietary intake (Reiley, 2007; Woodruff et al., 2023). Among the most frequently employed methods for risk characterization are the incremental lifetime cancer risk (ILCR) and the margin of exposure (MOE), which have been widely utilized in seafood safety assessments. For instance, Wang et al. (2021) applied both ILCR and MOE to evaluate fish from Shandong Province, China, and found no toxicological concern based on MOE, whereas ILCR suggested a potential health risk. However, existing studies have largely focused on whole-organism risk assessments, and although recent evidence indicates that tissue-specific bioavailability and health risks offer new perspectives for seafood safety evaluation (Habumugisha et al., 2025), research on tissue-level risk assessment remains limited.

Among the various contaminants in seafood, persistent organic pollutants (POPs) especially polycyclic aromatic hydrocarbons (PAHs) are of particular concern. POPs have garnered increasing attention since the Stockholm Convention. While the convention primarily restricts artificially synthesized POPs, PAHs—mainly derived from incomplete combustion of organic matter, such as traffic emissions, or petroleum sources like oil spills—are not included in the list. Nevertheless, PAHs have long been recognized as typical POPs by environmental scientists (Johansen et al., 2017; Gong et al., 2021; Deng et al., 2023). As ubiquitous environmental contaminants, PAHs pose considerable public health concerns due to their carcinogenic, teratogenic, and mutagenic properties (Montano et al., 2025). Consequently, the US EPA has designated sixteen PAHs as priority pollutants requiring regulatory monitoring and control

Abbreviations: Nap, naphthalene; Acy, acenaphthylene; Ace, acenaphthene; Flu, fluorene; Phe, phenanthrene; Ant, anthracene; Fla, fluoranthene; Pyr, pyrene; BaA, benzo[*a*]anthracene; Chr, chrysene; BbF, benzo[*b*]fluoranthene; BkF, benzo[*k*]fluoranthene; BaP, benzo[*a*]pyrene; Ind, indeno[1,2,3-cd]pyrene; DahA, dibenzo[*a*,*h*]anthracene; BghiP, benzo[*g*,*h*,*i*]perylene.

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(Keith, 2015). Despite this, tissue-specific bioavailability and health risk assessments of POPs, including PAHs, in marine organisms—particularly invertebrates—are scarcely documented. Available studies include tissue-specific bioavailability assessments of mercury in mussels (Kádár et al., 2005) and PCB28 in edible jellyfish (Hu et al., 2023), as well as tissue-specific health risk evaluations of POPs in freshwater crayfish (Wang et al., 2024), or of heavy metals in marine clams (Liu et al., 2020) and scallops (Lin et al., 2021). Given this context, the present study was designed to address this documented research gap by systematically evaluating the tissue-specific bioavailability of PAHs in bivalves and assessing the ensuing health risks to consumers.

Bays hold a unique position in marine environments, functioning as critical ecotones that bridge geological and ecological systems (Zeren et al., 2022). Ecological risk assessment is considered as useful approaches to give toxicological information about pollution in seawater and sediment of bay system, including some most-used methods like risk quotient (RQ) and hazard index (HI) (Li et al., 2023). In typical bays of the Bohai Sea and the Yellow Sea, PAHs have been widely detected, raising concerns over their ecological and health impacts (Zhang et al., 2024; Zheng et al., 2024). Clam *Ruditapes philippinarum* represents an economically important seafood species in this region, widely harvested and consumed (Lu and Wang, 2023). Therefore, this study aimed to (i) characterize the occurrence and ecological risks of PAHs in seawater and sediment from representative bays along the Bohai Sea and the Yellow Sea; (ii) quantify tissue-specific bioaccumulation and bioaccumulation factors of PAHs in the commercially important clam *Ruditapes philippinarum*; and (iii) evaluate dietary exposure risks based on whole edible soft tissue concentrations, while using tissue-level analyses as scenario tools to identify dominant contributors to overall human exposure. By integrating multiple environmental media with tissue-specific bioaccumulation patterns, this work provides complementary evidence for refining seafood safety assessments rather than replacing whole-organism–based risk evaluation.

2. Materials and methods

2.1. Study areas and field sampling

A total of thirteen sampling sites were selected across three typical bays in the Bohai Sea and the Yellow Sea (Fig. 1A). The term "typical" here indicates that these bays are highly representative of bay systems along the Chinese coast. Specifically, Laizhou Bay and Haizhou Bay are open-mouth bays with wide connections to the Bohai Sea and the Yellow Sea, whereas Jiaozhou Bay features a comparatively narrower opening, which may influence its pollutant exchange capacity with the Yellow Sea (Wu et al., 2024; Yan et al., 2024; Li et al., 2025). Detailed site information is provided in Supplementary Table S1.

Surface seawater samples (3 L per site, depth: 0–50 cm) were collected from three nearshore locations at each site using a gourd ladle, with each replicate consisting of 1 L. Water temperature, salinity, and pH were measured in situ using a thermometer, salinometer, and pH meter, respectively (see Supplementary Table S2 for background environmental data). Seawater samples were stored in pre-cleaned, chemically inert polyethylene containers and transported to Ocean University of China, where they were kept in a basement prior to analysis of 16 PAHs.

Surface sediment (300 g; depth: 0–5 cm) and 90 individuals of the clam *R. philippinarum* were collected from low, mid, and high tidal zones

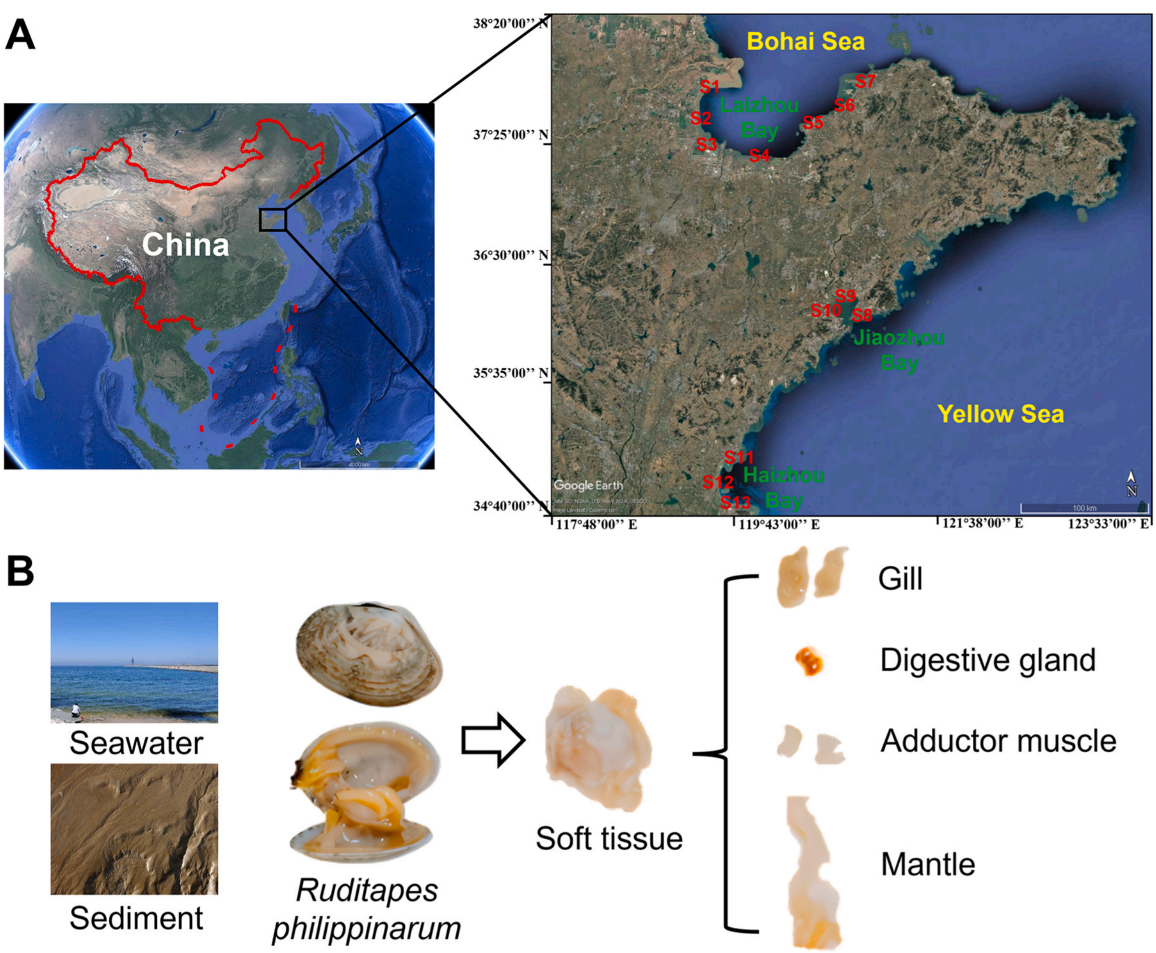

Fig. 1. Sampling sites (A) and samples (B) in three typical bays of the Bohai Sea and the Yellow Sea, China.

at each site using specialized rakes, yielding three replicates per site. Each replicate contained 100 g of sediment and 30 clams. Sediment samples were placed in pre-cleaned, chemically inert polyethylene containers and transported to the laboratory for PAHs analysis. The clams were transported alive under cold conditions (4°C) within 4 h. No significant differences in shell length (3.54 ± 0.32 cm) or weight (8.25 ± 1.47 g) were observed among sites ($P > 0.05$). For each replicate, 20 clams were dissected to obtain gill, digestive gland, adductor muscle, and mantle tissues; the remaining 10 clams were used to obtain whole soft tissue. All five tissue types were stored at −80°C prior to PAHs analysis.

2.2. PAHs extraction and analysis

The 16 US EPA priority PAHs analyzed are presented in the "Abbreviations". Standard solutions for PAHs quantification in seawater, sediment, and clam tissue, along with internal and surrogate standards—including 2,4,5,6-Tetrachloro-m-Xylene (TCMX), Nap-d_8, Ace-d_{10}, Phe-d_{10}, perylene-d_{12}, Chr-d_{12}, 2-fluorobiphenyl, and P-terphenyl-d_{14}—were purchased from J&K Scientific (Beijing, China).

Seawater samples were filtered through a 0.45 μm membrane to separate dissolved and particulate phases. The filtered water was used for dissolved PAH analysis, while the retained suspended particulate matter (SPM) was analyzed for particulate PAHs following the national standard method HJ 805–2016, with adjustments for smaller sample sizes. Particulate PAHs concentrations (ng/mg SPM) were converted to ng/L seawater using the SPM content (mg/L, presented in Supplementary Table S2) (Li et al., 2024).

Sample pretreatment and quantification for seawater, sediment, and clam tissues followed Chinese National Standards GB 26411–2010, HJ 805–2016, and GB 5009.265–2021, respectively. Briefly, filtered seawater was extracted via separatory funnel, concentrated using an automated vacuum parallel evaporator (MPE16, RayKol, China), purified by an automated solid-phase extraction (SPE) system (Fotector02HT, RayKol, China), and reconcentrated to 1 mL for GC-MS analysis. SPM, sediment, and clam samples were freeze-dried (CoolSafe 55–4, SCANVAC, Denmark; −48°C, < 2.0 Pa, 72 h), ground, and sieved (100-mesh). Ultrasonic extraction and centrifugation were performed twice under different solvent conditions. Extracts were concentrated and purified similarly before final GC-MS analysis using an automated vacuum parallel evaporator (MPE16, RayKol, China) and an automated solid-phase extraction (SPE) system (Fotector02HT, RayKol, China).

Quantification of PAHs was conducted using a Shimadzu GCMS-QP2020 NX system equipped with an SH-Rxi-5Sil MS capillary column (30 m × 0.25 mm × 0.25 μm). Operational parameters—including inlet, transfer line, and ion source temperatures—were consistent with previous studies (Li et al., 2024). Samples (1 μL) were injected in splitless mode with helium carrier gas at 1.0 mL/min. Detection employed selected reaction monitoring (SRM) with electron ionization (EI). Retention times and *m/z* values for SIM are listed in Supplementary Tables S3-S5.

2.3. Quality assurance and quality control

Quality assurance and control procedures were strictly implemented for PAHs analysis in clam tissues. Each batch included solvent blanks, procedural blanks, spiked blanks, and triplicate samples. No target compounds were detected in blank samples. As shown in Supplementary Tables S3-S5, method detection limits (MDLs), calculated as three times the signal-to-noise ratio, were 0.017–0.268 ng/L for dissolved PAHs in seawater, 0.015–0.209 ng/g for particulate PAHs in SPM and sediment, and 0.039–1.348 ng/g for PAHs in clam tissue. Spike recoveries ranged from 79 ± 5 % to 104 ± 12 % for dissolved PAHs, 76 ± 7 % to 113 ± 14 % for particulate PAHs, and 83 ± 7 % to 116 ± 12 % for clam PAHs. Concentrations below MDL (Nap in all seawater and sediment samples; Ind and DahA in all seawater samples) were treated as zero.

2.4. Risk assessment approaches

Bioaccumulation factor (BAF) and biota-sediment accumulation factor (BSAF) were used to evaluate PAHs bioaccumulation potential in clams, calculated as:

$$\text{BAF or BASF} = C_c/C_S \tag{1}$$

Where, C_c is the concentration of certain PAHs in clam tissue without lipid normalization and C_S is the concentration of certain PAHs in seawater or sediment (Buckhard et al., 2003; Arnot and Gobas, 2006; Séguin et al., 2022).

Ecological risks in seawater and sediment were assessed using risk quotient (RQ) and hazard index (HI) (Kalf et al., 1997; Cao et al., 2010; Abd Manan et al., 2021). Human health risk assessment was conducted in accordance with U.S. EPA dietary exposure assessment guidelines (US Environmental Protection Agency US EPA, 1992) and Lee et al. (2021). Detailed methodologies were described in Li et al. (2023). Primary exposure estimates were based on PAH concentrations measured in whole soft tissue of *R. philippinarum*, representing the composite edible portion consumed by the general population. Incremental lifetime cancer risk (ILCR) and margin of exposure (MOE) were calculated using standardized exposure parameters, including an adult body weight of 60 kg, a shellfish ingestion rate derived from the Shandong Statistical Yearbook 2025 (21.64 g/day/person for urban citizens and 7.95 g/day/person for rural residents), an exposure frequency of 365 days year^{-1} , an exposure duration of 70 years for both carcinogenic and noncarcinogenic risk, and an average time of 70 years for both cancer and non-cancer risk. Demographic stratification including age groups and genders was not considered in the exposure assessment due to the limitation of data gap. In addition, tissue-specific ILCR and MOE values were calculated as scenario-based indicators to examine the relative contribution of individual tissues to potential dietary exposure. These tissue-level estimates are not intended to represent actual population exposure, but rather to support mechanistic interpretation and evaluate potential risk-reduction strategies, such as selective removal of high-accumulation organs.

2.5. Data analysis

Data normality and homogeneity of variance were assessed using Kolmogorov-Smirnov and Levene's tests, respectively. Non-normal or heteroscedastic data were log-transformed before analysis. Transformed and original data were analyzed by one-way ANOVA followed by Tukey's post-hoc test for multi-site comparisons, with significance levels set at $P < 0.05$ and $P < 0.01$. Analyses were performed using SPSS 30.0. Specifically, for tissue-specific bioaccumulation and health risk analysis, data were expressed as the average of total 16 PAHs, and the variance was calculated based on the data of all replicate per-site.

3. Results and discussion

3.1. Spatial distribution and ecological risk of PAHs in surface seawater and sediment

As shown in Fig. 2, the spatial distribution of the total concentrations of 16 PAHs (A-C) and the concentrations of individual congeners (D-F) revealed that the total dissolved PAHs in seawater ranged from 38.27 to 131.56 ng/L, with BbF being the most abundant congener. These levels are lower than those reported in inshore waters of the East China Sea (235.2 ng/L; Li et al., 2025), comparable to those from Giresun shores in the Southeastern Black Sea (161.5 ng/L; Aydin et al., 2023), and higher than those along the coast of Taiwan Province, China (3.3–25.8 ng/L; Chen et al., 2022). The particulate PAHs ranged from 8.08 to 45.24 ng/L, with BaP as the dominant congener. These values are lower than those reported in the Eastern Mediterranean coastal area

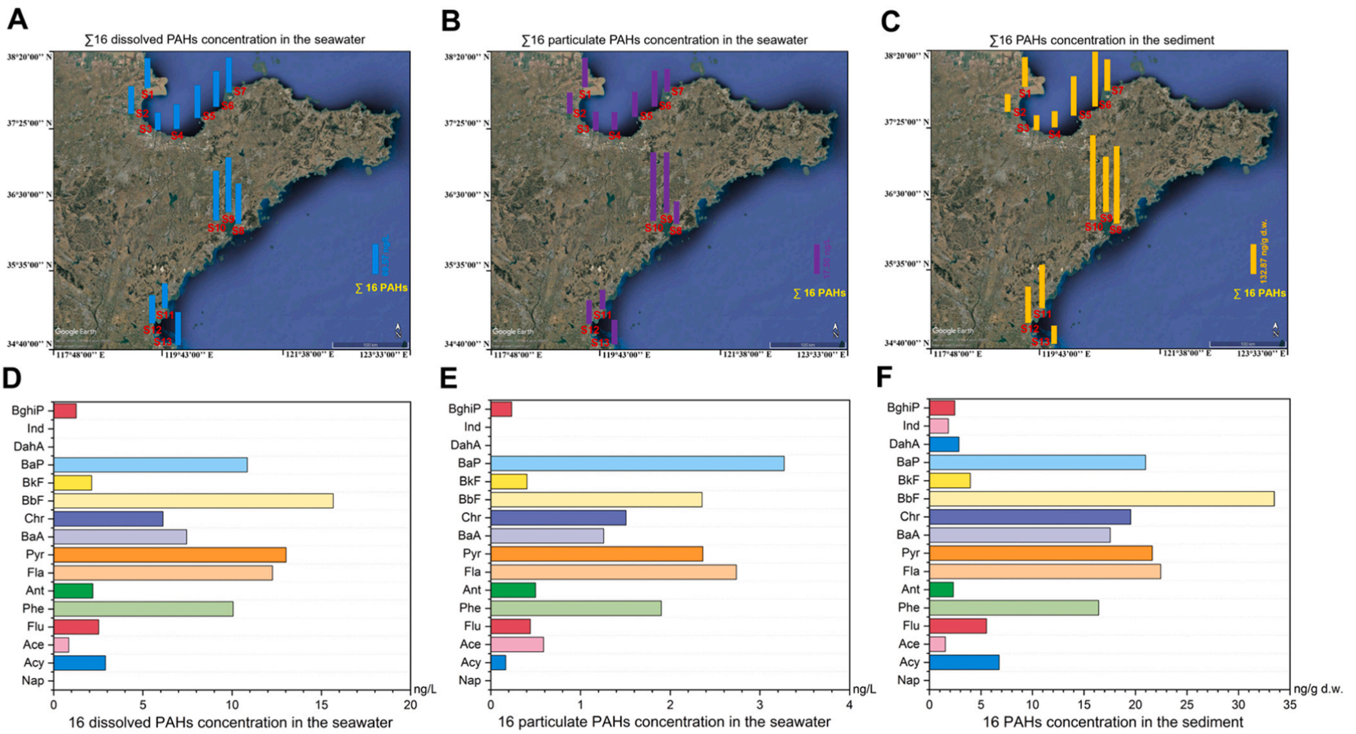

Fig. 2. Total 16 PAHs concentrations (A-C) and 16 individual PAH concentration (D-F) in the seawater and sediment. For A-C, the columns were standardized with the total 16 PAHs concentration in S1, which was marked as the legend in figures. For D-F, the concentrations were expressed as the average of all sampling sites (S1-S13).

(30.8–177 ng/L; Sakellari et al., 2021), similar to those off the coast of Taiwan Province, China (3.3–22.4 ng/L; Chen et al., 2022), and higher than those in surface waters of Kongsfjorden, Arctic (4.4–6.7 ng/L; Li et al., 2020). In sediments, the total PAHs ranged from 66.98 to 365.81 ng/g dry weight (d.w.), with BbF again being the predominant congener. These concentrations are lower than those in surface sediments from Gorgan Bay, Caspian Sea (107.81–516.18 ng/g d.w.; Araghi et al., 2014), comparable to those from the Yangtze River Estuary (13.3–318.9 ng/g d.w.; Zhang et al., 2025), and higher than those in sediments from Daya Bay, South China (42.5–158.2 ng/g d.w.; Yan et al., 2009). Overall, the PAHs levels observed in this study are similar with those reported in other marine systems worldwide, providing

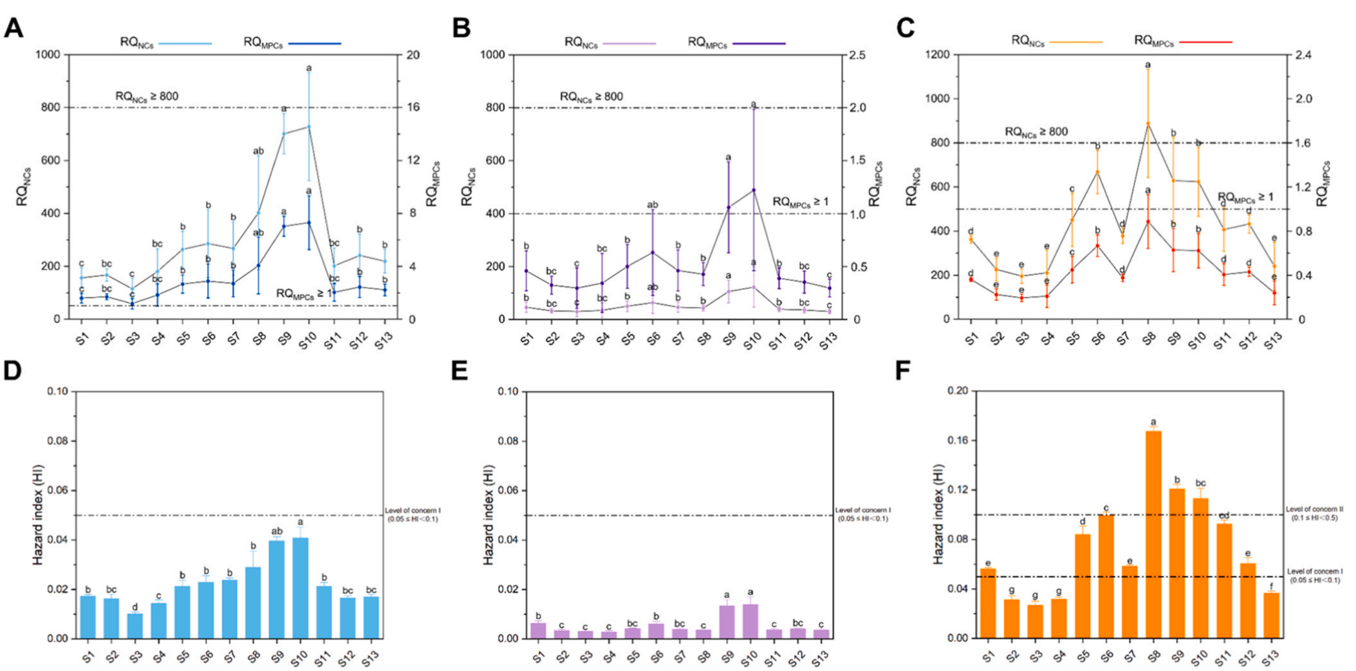

Fig. 3. Ecological risk assessment results of risk quotient (A-C) and hazard index (D-F) in the seawater and sediment, where Figs. A and D are results of dissolved PAHs in seawater, B and E are particulate PAHs in seawater, C and F are PAHs in sediment. Different letters (a, b, and c) represent that differences are significant at $P < 0.05$.

reliable baseline data for environmental monitoring and supporting risk assessment of both dissolved and particulate PAHs.

To systematically evaluate the ecological risks posed by PAHs, RQ and HI are adopted in this study. In principle, RQ compares measured environmental concentrations (MECs) to predicted no-effect concentrations (PNECs) and are typically categorized into different risk levels (e.g., low, medium, high), providing an intuitive indication of the ecological threat for single compounds (El Zokm et al., 2022). While HI is the sum of the hazard quotients of individual PAHs that share a similar mechanism of toxicity, offering a cumulative risk estimate (Hosseini and Bonyadi, 2025). As shown in Fig. 3, the average RQ and HI values for dissolved PAHs across all sites fell into the "Moderate-risk 2" category ($RQ_{\Sigma PAHs(NCs)} < 800$ and $RQ_{\Sigma PAHs(MPCs)} \geq 1$; referring to Supplementary Table S6), while HI values indicated no significant concern based on the criteria in Supplementary Table S7. A similar risk level was observed for particulate PAHs using HI. However, based on RQ, only two sites in Jiaozhou Bay (S9 and S10) were classified as "Moderate-risk 2", while the remaining 11 sites were "Low-risk" ($RQ_{\Sigma PAHs(NCs)} < 800$ and $RQ_{\Sigma PAHs(MPCs)} < 1$). For sediments, all sites except S8 (also in Jiaozhou Bay) were classified as "Low-risk" based on RQ. S8 reached "Moderate-risk 1" ($RQ_{\Sigma PAHs(NCs)} \geq 800$ and $RQ_{\Sigma PAHs(MPCs)} < 1$). Thereinto, "Moderate-risk 1" represents sites where ΣPAHs exceed the low-risk threshold but remain below higher concern levels, indicating moderate contamination with limited potential ecological effects. In contrast, "Moderate-risk 2" refers to sites approaching the upper screening threshold, suggesting elevated contaminant pressure and a higher likelihood of adverse ecological impacts. This subdivision provides a finer resolution for differentiating relative risk levels among moderately impacted sites and is consistent with previous multi-tier ecological risk assessment approaches for PAHs (Kalf et al., 1997; Cao et al., 2010). HI values placed the sites into two levels of concern: three sites in Jiaozhou Bay (S8-S10) reached level II ($0.1 \leq HI < 0.5$), and nearly half of the sites (S1, S5-S7, S11, and S12) reached level I ($0.05 \leq HI < 0.1$), indicating potential ecological risks. These findings align with our previous study (Li et al., 2023), which also identified Jiaozhou Bay as the area with the highest ecological risk, likely due to its proximity to Qingdao—the third-largest city in northern China—where industrial and urban activities are intense. The observed differences in ecological risk between seawater and sediment are consistent with reports from other coastal systems, including Liaodong Bay (Zhang et al., 2016), Hangzhou Bay (Wu et al., 2023), and the Yellow River Estuary (Liu et al., 2024), underscoring the broader relevance of our assessment.

3.2. Tissue-specific bioaccumulation and bioavailability of PAHs in clams

Tissue-specific PAHs concentrations in clams are shown in Fig. 4. Mean concentrations ± standard deviations of the 16 PAHs were 166.17 ± 61.56 ng/g in gill, 215.36 ± 51.03 ng/g in digestive gland, 175.37 ± 52.48 ng/g in adductor muscle, 140.05 ± 46.69 ng/g in mantle, and 176.59 ± 47.57 ng/g in whole soft tissue, yielding the following order: digestive gland > soft tissue > adductor muscle > gill > mantle. The average percentages of bioaccumulated PAHs in each tissue excluding the soft tissue were 24 %, 31 %, 25 %, 20 % for gill, digestive gland, adductor muscle, and mantle, respectively, with a difference higher than 10 % between digestive gland (31 %) and mantle (20 %). To our knowledge, this is the first study to report PAHs (and more broadly, POPs) concentrations across these five tissues in shellfish; previous investigations have focused on trace elements (Kumari et al., 2006; Sepúlveda et al., 2025) and paralytic shellfish toxins (Fast et al., 2006). The elevated accumulation in the digestive gland may be attributed to its role in pollutant metabolism and excretion (Kim et al., 2017), where reactive compounds such as PAHs tend to accumulate (Al-Howiti et al., 2020).

To quantify this transfer of hydrophobic organic contaminants, such as PAHs, PCBs, and pesticides, from the environment into biota, two principal metrics are widely employed: BAF for aqueous exposure and

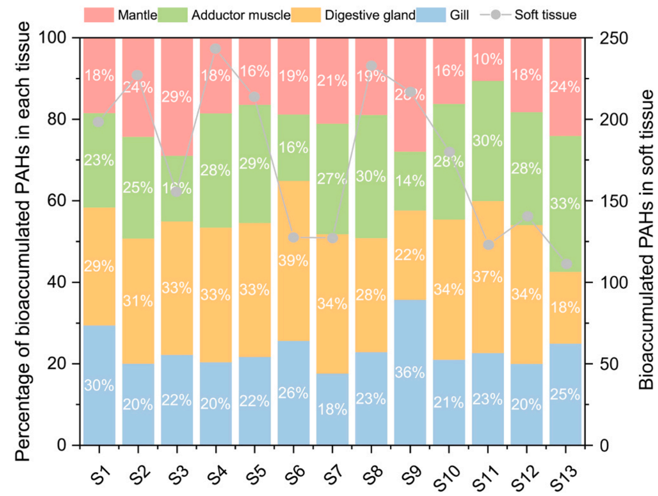

Fig. 4. Tissue-specific bioaccumulation of PAHs in clam. The columns for percentage of bioaccumulated PAHs in each tissue (corresponding to the left y-axis) didn't include the bioaccumulation of PAHs in soft tissue, which was expressed as the grey polyline with concentrations marked in the right y-axis.

BSAF for soil and sediment exposure (Buckhard et al., 2003). Integrating BAF and BSAF values into bioavailability assessments provides a mechanistic understanding of contaminant dynamics, moving beyond total concentrations to predict actual exposure levels in food webs (Wang et al., 2018). As summarized in Table 1, BAF values for dissolved and particulate PAHs in seawater ranged from 1.95 ± 0.93–3.04 ± 1.21 and 9.22 ± 4.23–14.54 ± 6.61, respectively, with significantly higher values in the digestive gland than in other tissues ($P < 0.05$). Similarly, BSAF values for sediment-derived PAHs ranged from 1.12 ± 0.75–1.63 ± 0.98, again with the digestive gland showing significantly higher accumulation ($P < 0.05$). Our results are consistent with a tissue-specific BAF (from seawater to bivalve) study, which found that the digestive gland of *Mytilus galloprovincialis* had higher BAF values of trace metals (Bellante et al., 2016). Meanwhile, according to the bioaccumulation model of Endo et al. (2011), the scatter plot of LogBAF and LogBSAF against LogKow also showed that the digestive gland accumulated most across all PAHs congeners (Fig. S1-S3), and a positive monotonic relationship between BAF and logKow for low- and mid-molecular-weight PAHs was revealed, while high-molecular-weight PAHs exhibited a plateau or slight decline, consistent with biodilution patterns reported previously for PAHs in filter-feeding bivalves (Qadeer et al., 2019; Liu et al., 2023). More importantly, this study is the first to report tissue-specific bioavailability of POPs from multiple environmental media in marine invertebrates. Previous studies focused on single medium, such as inorganic mercury or PCB28 from seawater (only dissolved phase) to mussels (Kádár et al., 2005) and jellyfish (Hu et al., 2023). Our findings provide new insights into the multimedia bioavailability of POPs in marine invertebrates, aiding in understanding their environmental fate. However, its limitation also fell into the

Table 1
Tissue-specific bioavailability (BAF and BSAF) of PAHs in clams collected from typical bays of the Bohai Sea and the Yellow Sea, China. Different letters (a, b, and c) represent that differences are significant at $P < 0.05$.

	Gill	Digestive gland	Adductor muscle	Mantle	Soft tissue
Seawater	2.24 ± 0.82^{bc}	3.04 ± 1.21^{a}	2.42 ± 0.89^{b}	1.95 ± 0.93^{c}	2.45 ± 0.93^{b}
SPM	10.57 ± 3.90^{b}	14.54 ± 6.61^{a}	11.96 ± 5.74^{ab}	9.22 ± 4.23^{b}	11.86 ± 5.56^{ab}
Sediment	1.22 ± 0.65^{b}	1.63 ± 0.98^{a}	1.33 ± 0.78^{ab}	1.12 ± 0.75^{b}	1.37 ± 0.90^{ab}

multimedia, which didn't include other media like sediment core and especially porewater (Endo et al., 2017), which is widely recognized as a more mechanistically relevant metric linking sediment-associated contaminants to benthic organism uptake, and more media will be incorporated into our future studies.

3.3. Tissue-specific health risk assessment of PAHs and dietary suggestion of clams

Human health risk assessment (HHRA) provides critical scientific disciplines for evaluating the adverse impacts of environmental contaminants on human populations (Woodruff et al., 2023). With the

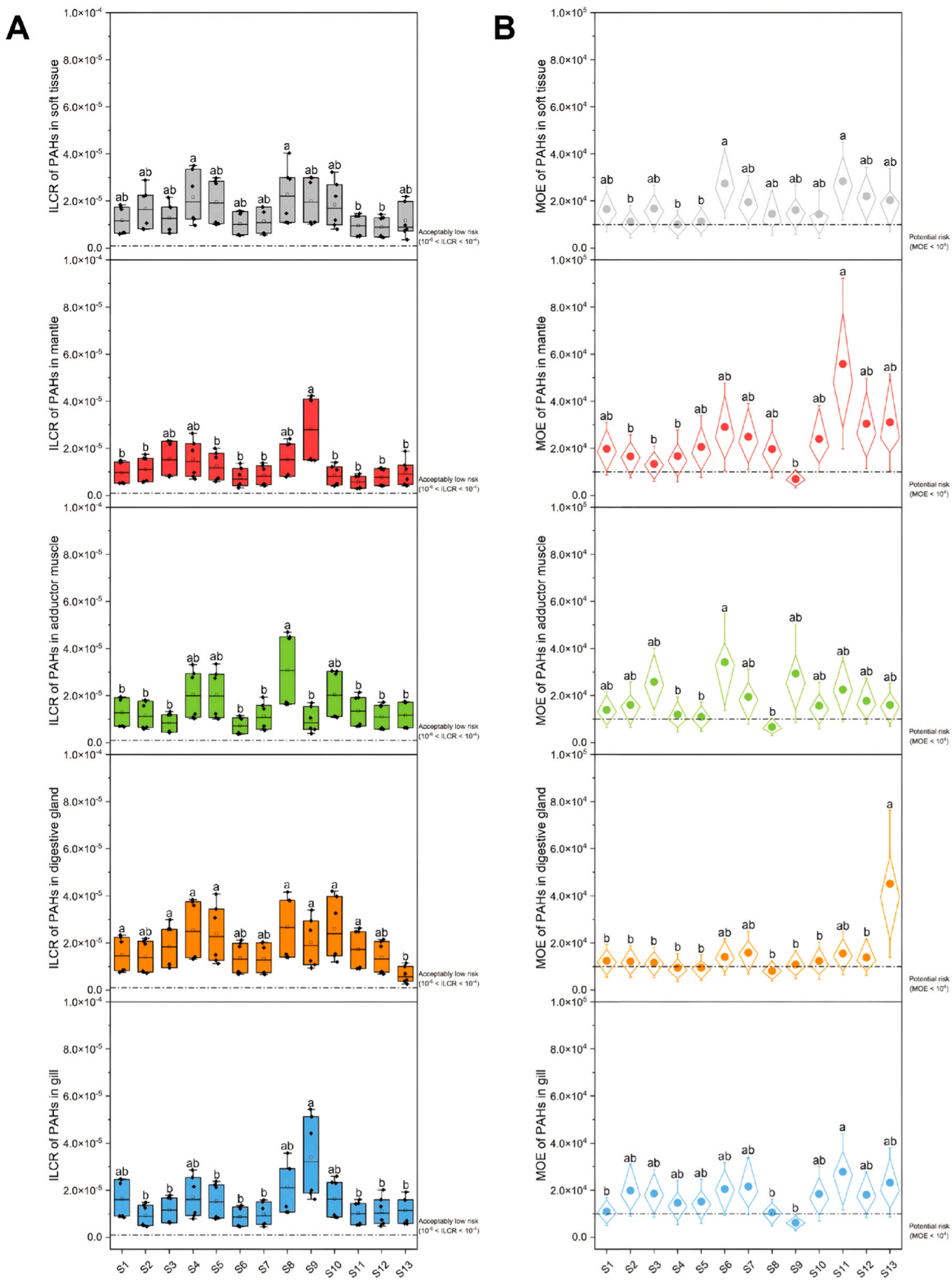

Fig. 5. Tissue-specific health risk assessment results of incremental lifetime cancer risk (A) and margin of exposure (B) in clam, where Figs. A and B both used the common x-axis for their results of five tissues for clarity. Different letters (a and b) represent that differences are significant at $P < 0.05$.

increasing prevalence of chemical pollutants derived from industrial, agricultural, and urban sources into ocean and ultimately polluting seafood, the need for robust and reliable risk quantification methods has never been more pressing (Landrigan et al., 2020). Here, we evaluated tissue-specific health risks of PAHs in clams using ILCR and MOE. It is important to emphasize that the interpretation of these values is inversely related; while a higher ILCR indicates greater cancer risk, a lower MOE signifies higher concern for non-cancer health outcomes. For clarity, it is important to note that the risk classification criteria for ILCR and MOE are inversely related: risk increases with higher ILCR values, whereas for MOE, risk increases with lower values (Lee et al., 2021). As shown in Fig. 5A, ILCR values for all tissues across sites fell within an acceptable range (10^{-6} < ILCR < 10^{-4}), though values from Jiaozhou Bay were significantly higher ($P < 0.05$), consistent with ecological risk trends and suggesting a correlation between ecological and health risks—a pattern also observed in other PAH studies (Sun et al., 2023). In contrast, MOE results indicated potential risk (MOE < 10^4) only in specific tissues at certain sites: gill (S9), digestive gland (S4, S5, S8), adductor muscle (S8), mantle (S9), and soft tissue (S4). Discrepancies between ILCR and MOE outcomes have been previously reported in fish (Wang et al., 2021) and in our earlier work (Li et al., 2023). Based on whole soft tissue concentrations, ILCR values for all sites fell within the range generally considered acceptable for lifetime exposure (10^{-6}-10^{-4}), although higher values were observed in Jiaozhou Bay. Tissue-level scenario analyses revealed pronounced differences among organs, with the digestive gland consistently exhibiting higher ILCR values and lower MOE values than other tissues, indicating a greater contribution to overall exposure when present in the consumed tissue mixture. Notably, this is the first study to assess tissue-specific health risks of POPs in marine invertebrates; previous tissue-specific health risk assessment of POPs focused on freshwater fish and crayfish (Zhang et al., 2012; Wang et al., 2024), while those tissue-specific health risk assessment for marine invertebrates only involved with heavy metals rather than POPs in bivalves like clam (Liu et al., 2020) and scallop (Lin et al., 2021). Together with the tissue-specific bioaccumulation and bioavailability of POPs in shellfish, this work provides a comprehensive tissue-specific assessment framework for future studies.

To formulate dietary advice, we compared PAHs concentrations, ILCR, and MOE across tissues (Fig. 6A-C). While humans typically consume the whole soft tissue of clams, tissue-specific analyses provide useful information for identifying dominant exposure sources within the organism. The elevated PAHs accumulation observed in the digestive gland suggests that this organ disproportionately contributes to total dietary exposure. Meanwhile, the Spearman's correlation analysis between environmental PAHs concentrations and bioaccumulated PAHs concentrations (Fig. S4) showed that bioaccumulated PAHs in digestive gland and adductor muscle had significant correlation with particulate PAHs ($P < 0.05$) and extremely significant correlation with dissolved PAHs and sediment PAHs ($P < 0.01$), which further proved the connection of environmental media to these two tissues and similar correlation was revealed between environmental heavy metals in Mediterranean coastal areas and bioaccumulation of these metals in different tissues of marine bivalves (Sakellari et al., 2013). Therefore, digestive gland consistently showed significantly higher accumulation and risk ($P < 0.05$), identifying it as the tissue of greatest concern for human consumption. While natural predators of clams (e.g., starfish, crabs, fish, and birds) consume the whole organism, humans—as the most selective predator—can avoid high-risk tissues. For instance, in scallops, the adductor muscle is often harvested alone and valued for its nutritional content (Xie et al., 2020); studies suggest consuming only this tissue to minimize exposure to heavy metals (Lin et al., 2021). Similarly, we recommend that consumers remove the digestive gland from clams before cooking to significantly reduce PAHs-related health risks. From a risk-management perspective, selective removal of the digestive gland prior to cooking represents a feasible risk-reduction option rather than an implication of unacceptable consumption risk under typical dietary

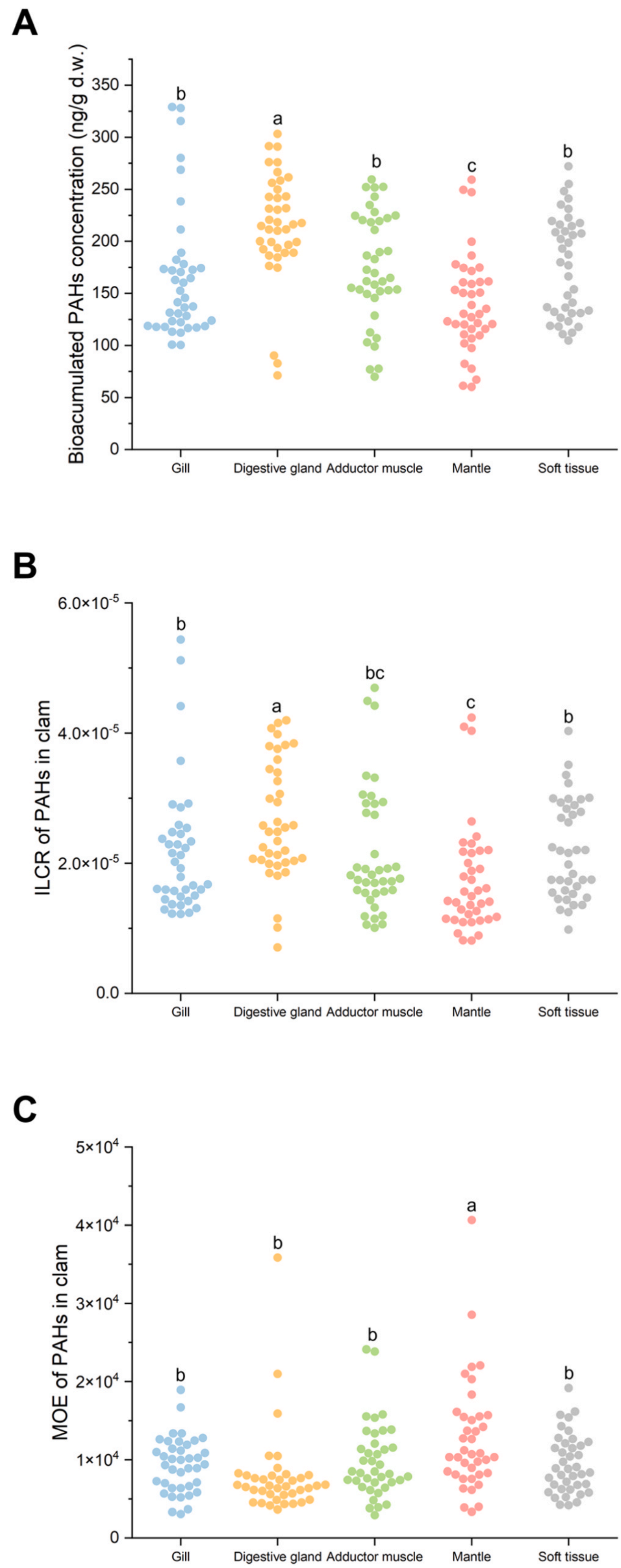

Fig. 6. Comparison of tissue-specific bioaccumulation (A) and health risk assessment (B and C) results. Different letters (a, b, and c) represent that differences are significant at $P < 0.05$.

patterns. However, it must be acknowledged that this study is limited to the detection of only one type of POPs across 13 sampling sites. This constraint is particularly evident when contrasted with a recent large-scale analysis, which examined 64 million surface water monitoring records in the United States spanning 1900 chemicals from 1958 to 2019 at over 310,000 sites. That study revealed that adequate exposure data for retrospective risk assessment are available for less than 1 % of the 297,000 chemicals of potential environmental concern (Bub et al., 2025). Therefore, to develop comprehensive dietary recommendations that effectively and accurately safeguard seafood consumers at national and global levels, it remains imperative to conduct large-scale monitoring efforts along with tissue-specific bioavailability and health risk assessments.

4. Conclusion

Collectively, this study provides a comprehensive assessment of the occurrence, distribution, and multi-media bioavailability of PAHs in three typical bays of the Bohai Sea and the Yellow Sea, with a specific focus on tissue-specific accumulation and associated health risks in the economically important clam *R. philippinarum*. The concentrations of PAHs in seawater (both dissolved and particulate phases) and sediment were found to be within ranges comparable to those reported in other coastal systems globally, affirming the relevance of these bays as critical monitoring zones for POPs. Ecological risk assessments indicated moderate risk levels in certain sites, particularly within Jiaozhou Bay, likely due to proximity to urban and industrial activities. Notably, the digestive gland exhibited significantly higher PAHs accumulation and bioavailability compared to other tissues, highlighting its role as a primary organ for contaminant storage and metabolism. The application of both ILCR and MOE models for health risk evaluation revealed that while cancer risks generally fell within acceptable limits, certain tissues—especially the digestive gland—posed potential health concerns upon consumption. This underscores the importance of tissue-specific risk assessment in refining seafood safety guidelines. Furthermore, our findings support the practical dietary recommendation that removing the digestive gland before consumption can significantly reduce PAH exposure.

Overall, health risk assessment based on whole soft tissue indicated generally acceptable PAH-related risks for consumers. Tissue-level scenario analyses identified the digestive gland as a major contributor to potential exposure, highlighting the value of tissue-specific bioaccumulation data for understanding contaminant dynamics and informing practical risk-reduction strategies. These findings complement, rather than replace, conventional whole-organism seafood safety assessments.

CRediT authorship contribution statement

Zeyuan Li: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ruicheng Qi:** Software, Methodology, Investigation. **Luqing Pan:** Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Songhui Xie:** Investigation. **Rongjun Cai:** Investigation. **Pengfei Li:** Investigation.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT (OpenAI) to improve the readability and language of the manuscript. After using this tool, the authors carefully reviewed and edited the content as needed, and we take full responsibility for the content of the published article.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ecoenv.2025.119644.

Data availability

Data will be made available on request.

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