

Spatiotemporal dynamics of nutrients and eutrophication in Laizhou Bay: implications of long-term phosphorus limitation*

Limei QU¹, Hansen LF², Saipai DUAN², Sujie LIU², Weiyan DUAN^{2, **}

¹ National Marine Environmental Monitoring Center, Dalian 116023, China

² Ocean College of Hebei Agricultural University, Qinhuangdao 066003, China

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Abstract Based on continuous monitoring data from 16 standardized monitoring stations in the coastal waters of Laizhou Bay, Shandong Province, from 2020 to 2024, we investigated the spatiotemporal distribution characteristics of nitrogen and phosphorus nutrients and assessed the eutrophication status. Results indicate that the concentration of dissolved inorganic nitrogen (DIN) in the bay exhibited significant seasonal and spatial variations, and the overall trend was higher in the west and lower in the east, while the concentration of dissolved inorganic phosphorus (DIP) remained relatively stable. Specifically, the DIN concentration in spring was significantly higher than that in summer and autumn. The N/P ratio showed an initial increase followed by a decreasing trend during 2020–2024; however, the overall ratio remained substantially higher than the Redfield ratio, indicating a pronounced phosphorus-limited condition in the bay. Eutrophication assessment revealed that the eutrophication index (EI) in autumn was significantly higher than that in spring and summer. The western coastal area of the bay top was identified as a high-risk zone for eutrophication, while the outer bay maintained an oligotrophic state throughout the year. Complex coupling relationships were observed among pH, dissolved oxygen (DO), chemical oxygen demand (COD_{Mn}), and nutrients. Specifically, pH and DO exhibited weak correlations with nutrient levels, whereas COD_{Mn} showed a significant positive correlation with nutrients. The findings provide a theoretical reference for the construction of the Beautiful Bays Initiative in Shandong Province.

Keyword: Laizhou Bay; nutrient; potential eutrophication; water quality; phosphorus limitation

1 INTRODUCTION

Nitrogen and phosphorus are key biogenic elements driving marine primary production. Their concentrations and stoichiometric ratios (N/P ratio) regulate phytoplankton community composition and productivity, thereby maintaining the stability of ecosystem structure and function (Qu et al., 2025). When excessive dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP) are continuously discharged into coastal waters from rivers, atmospheric deposition, and industrial-agricultural wastewater, deviations from the Redfield ratio (16:1) occur. This can trigger abnormal proliferation of specific phytoplankton groups, leading to eutrophication and even harmful algal blooms, often accompanied by decreased dissolved oxygen (DO), which stresses

fish and benthic communities (Zheng and Zhai, 2023; Hagstrom et al., 2024). In semi-enclosed bays, narrow topography significantly restricts water exchange capacity and prolongs water renewal time, facilitating accumulation of excess nutrients and consequently increasing eutrophication risks (Liang et al., 2024; Sun et al., 2024b).

Laizhou Bay, one of the three major bays in the Bohai Sea, serves as a primary aquaculture area for economically important species including *Fenneropenaeus chinensis* (Chinese white shrimp), *Portunus trituberculatus* (swimming crab), *Argopecten irradians* (bay scallop), and *Stichopus japonicus* (sea cucumber) (Yang et al., 2017; Huang et al.,

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** Corresponding author: duanweiyan@hebau.edu.cn

2018; Ju et al., 2020; Chen et al., 2025). The bay hosts a diverse port system encompassing cargo ports, fishing ports, and small local harbors, supporting industries such as fisheries, energy, chemical engineering, and logistics (Shandong Provincial People's Government, 2008, 2025). More than 10 rivers, including the Xiaoqing River, Bailang River, Weihe River, and Yuhe River, discharge substantial loads of DIN and DIP into the bay. Due to the proximity to Laizhou Bay, the Huanghe (Yellow) River is the main source of materials for the bay (Liang et al., 2022). Previous studies have demonstrated that seasonal N/P ratios in Laizhou Bay far exceed the Redfield ratio, indicating severe nutrient structure imbalance (Liang et al., 2022). Furthermore, severe phosphorus limitation triggers shifts in phytoplankton communities toward undesirable groups, increasing harmful algal bloom risks (Wang et al., 2020; IPCC, 2021). As a semi-enclosed inner bay, Laizhou Bay contributes over 40% of mariculture production in northern Shandong Peninsula and acts as a critical stopover site for more than 120 waterbird species along the East Asian-Australasian Flyway, highlighting its prominent ecological and economic significance (Duan et al., 2023; Shandong Provincial Bureau of Oceanography, 2024). Current research primarily focuses on short-term surveys (e.g., single or multiple seasons within a year). While the spatial pattern of DIN and DIP (higher concentrations in coastal and estuarine areas) has been repeatedly confirmed, long-term trends from 2019 to 2024 remain unquantified, hindering identification of ecological responses to anthropogenic pressures. Additionally, existing eutrophication assessments commonly adopt single-factor threshold methods, lacking a comprehensive multi-indicator framework integrating chlorophyll *a* (Chl *a*), phytoplankton community structure, and bottom water hypoxia frequency—impeding precise management decisions (Luo et al., 2022; Zhang et al., 2022a).

Based on the monitoring data from 16 fixed stations in the coastal waters of Laizhou Bay from 2020 to 2024, this study systematically analyzes the spatiotemporal distribution characteristics of DIN and DIP. Furthermore, by integrating the single-factor pollution index, N/P ratio, and eutrophication index (EI), we assess the eutrophication status and pollution level in Laizhou Bay. This study aims to test three scientific hypotheses: (i) DIN and DIP concentrations exhibit pronounced spatial gradients, decreasing from estuarine and nearshore areas to

offshore waters due to terrestrial runoff and anthropogenic inputs; (ii) nutrient concentrations display significant seasonal dynamics driven by catchment hydrological dynamics and marine biogeochemical cycling; and (iii) the N/P ratio in Laizhou Bay systematically deviates from the Redfield ratio (16:1), manifesting bay-wide phosphorus limitation with distinct spatial variations in limitation intensity.

To test these hypotheses, this study has the following specific objectives: (i) to quantitatively characterize spatiotemporal heterogeneity and interannual trends of DIN and DIP concentrations; (ii) to comprehensively assess eutrophication status and pollution levels through integration of single-factor pollution index, N/P ratio, and EI; and (iii) to identify spatial patterns of high-risk eutrophication zones and their key driving factors.

2 MATERIAL AND METHOD

2.1 Study area

Laizhou Bay, located in the southern Bohai Sea, is one of China's important semi-enclosed bays with a total area of 6 966.93 km². Water depth typically ranges from 10 to 15 m, with a maximum depth of approximately 20 m (Yu et al., 2016). Multiple rivers (Xiaoqing River, Yuhe River, Jiehe River, and other rivers) discharge into Laizhou Bay, carrying substantial loads of DIN and DIP, among which the Xiaoqing River and other coastal rivers contribute considerable nitrogen and phosphorus loads (Zhang et al., 2012). These inputs significantly enhance phytoplankton primary productivity, providing ample food resources for the entire food web. Consequently, Laizhou Bay serves as a primary spawning, feeding, and nursery ground for various commercial fish, shrimp, and crab species in the Yellow Sea and Bohai Sea, and functions as a traditional major fishing ground in northern China.

2.2 Sample collection and analysis

Sampling sites were primarily located in coastal waters of Laizhou Bay (Fig.1), following the *Technical Specifications for Layout of Environmental Monitoring Sites in Coastal Waters* (HJ 730-2014). Water samples were collected three times annually (2020–2024) during spring (April–May), summer (July–August), and autumn (October–November). At each site, 5 L of surface seawater (<1-m depth) was collected using a water sampler. A 500-mL subsample was immediately filtered through a 0.45-μm

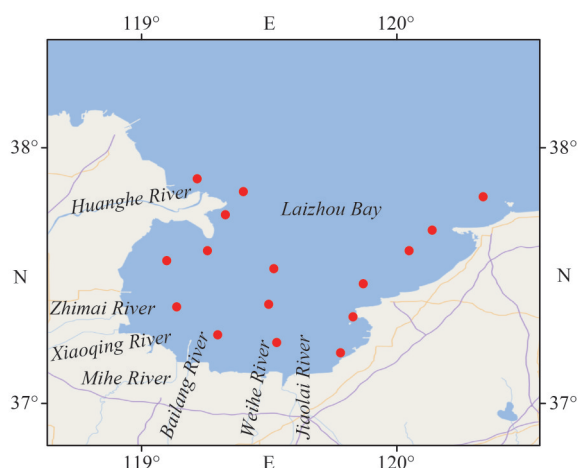


Fig.1 Study area and monitoring stations in Laizhou Bay

glass fiber filter for dissolved component analysis; the remaining sample was frozen at -20°C and transported to the laboratory under low-temperature conditions. The entire process of sample collection, preservation, and transportation strictly adhered to *The Specification for Marine Monitoring-Part 3: Sample collection, Storage and Transportation* (GB 17378.3-2007) (General Administration of Quality Supervision, 2008a). Laboratory analyses followed *The Specification for Marine Monitoring-Part 4: Seawater Analysis* (GB 17378.4-2007) (General Administration of Quality Supervision, 2008b): DO was determined via iodometric titration; pH via pH 910 benchtop pH meter; COD_{Mn} via alkaline potassium permanganate method; $\text{NH}_4^+\text{-N}$ via hypobromite oxidation method; $\text{NO}_2\text{-N}$ via naphthylethylenediamine spectrophotometry; $\text{NO}_3\text{-N}$ via cadmium column reduction method; and $\text{PO}_4^{3-}\text{-P}$ via phosphomolybdenum blue spectrophotometry. DIN was calculated as the sum of $\text{NH}_4^+\text{-N}$, $\text{NO}_2\text{-N}$, and $\text{NO}_3\text{-N}$, while DIP was considered equivalent to $\text{PO}_4^{3-}\text{-P}$. During nutrient sample analysis, national standard reference materials (GBW(E)081696, GBW(E)081697, GBW(E)081698, and GBW(E)081699) were simultaneously analyzed, with relative errors between measured and certified values of less than 3%, all within the uncertainty range. The relative standard deviation (RSD) of parallel samples was less than 5%, and the spiked recovery rates ranged from 90% to 110%.

2.3 Evaluation method

This study employed the single factor index method (SFIM), the N/P ratio, and the EI method to assess the eutrophication level in Laizhou Bay. The standards used in the evaluation process included

the *Seawater Quality Standard* (GB3097-1997) (State Environmental Protection Administration, 1997), *The Technical Specification for Marine Environmental Monitoring-Part 10: Eutrophication Monitoring and Assessment* (HJ 442.10-2020) (Ministry of Ecology and Environment of the People's Republic of China, 2020), and other relevant technical specifications.

2.3.1 SFIM

To assess the seawater quality in Laizhou Bay, the SFIM was applied, referencing the Class II seawater quality standards stipulated in GB3097-1997, which are applicable to aquaculture zones and coastal scenic tourist areas. The single factor index is calculated using Eq.1:

$$P_i = C_i / S_i, \quad (1)$$

where P_i represents the single factor index value for the i^{th} parameter; C_i denotes the measured concentration of the i^{th} parameter (mg/L); S_i represents the corresponding seawater quality standard limit for the i^{th} parameter (mg/L; specific values provided in Supplementary Table S1). S_i uniformly adopted the Class II seawater standard limits specified by GB 3097-1997. According to this method: when $P_i > 1$, it indicates that the parameter's concentration exceeds the water quality standard limit; when $P_i \leq 1$, it indicates that the concentration meets or is below the standard limit.

2.3.2 N/P ratio

The N/P ratio was calculated using the following formula:

$$\text{N/P} = \text{DIN/DIP}, \quad (2)$$

where DIN (mol/L) and DIP (mol/L) are the measured concentrations of DIN and DIP, respectively.

2.3.3 EI method

The EI was calculated using the following formula:

$$\text{EI} = \frac{C_{\text{COD}} \times C_{\text{DIN}} \times C_{\text{DIP}}}{4500} \times 10^6, \quad (3)$$

where C_{COD} (mg/L), C_{DIN} (mg/L), and C_{DIP} (mg/L) are the measured concentrations of COD_{Mn} , DIN, and DIP, respectively.

2.4 Data statistics and processing

Monitoring data were statistically analyzed using Excel 2019. Station distribution maps were created using ArcGIS. Pearson correlation analysis in SPSS 20.0 was used to examine the correlations among

pH, DO, COD_{Mn} , and DIN, DIP, and EI, with statistical significance levels set at $P < 0.05$ and $P < 0.01$ (two-tailed). Additionally, heatmaps for correlation analysis were generated using Origin 2021.

3 RESULT

3.1 Annual-seasonal variation and spatial distribution characteristics of nutrient

The DIN concentration showed considerable fluctuation from 2020 to 2024. It peaked in 2022 (annual average: 0.419 mg/L), the highest level recorded in the five-year period, followed by a notable decrease to 0.253 mg/L in 2023, close to the 2020 level, and a slight rebound to 0.275 mg/L in 2024, indicating a general trend towards stabilization. The five-year average DIP concentration remained within a very low range of 0.003–0.005 mg/L, showing no significant overall variation. It was slightly higher in 2020–2021 (0.005 mg/L), lowest in 2022–2023 (0.003 mg/L), and experienced a minor increase to 0.004 mg/L in 2024, overall maintaining low-level fluctuations.

As shown in Fig.2a, the average DIN concentration exhibited the largest fluctuation in spring: it peaked at 0.558 mg/L in 2022, dropped to the lowest value of 0.281 mg/L in 2021, and recovered to 0.309 mg/L in 2024. The overall concentration of DIN was the lowest in summer. Its peak also occurred in 2022 (0.431 mg/L), with the trough in 2021 (0.166 mg/L), and it rose slightly to 0.232 mg/L in 2024. The fluctuation of DIN was the smallest in autumn: it was relatively higher in 2021 (0.394 mg/L), reached the lowest level in 2023

(0.186 mg/L), and rebounded to 0.284 mg/L in 2024. There was little seasonal difference in DIP concentration. Only a brief and slight increase was observed in the summer of 2020 and the autumn of 2021, after which it returned to a relatively low level, showing a relatively stable overall trend (Fig.2b).

Spatial distribution maps of DIN (Fig.3) reveal that from 2020 to 2024, the high-value DIN areas (annual average > 0.40 mg/L) were concentrated in the western coastal region of the bay top. The five-year spring average at one station in this area reached 0.831 mg/L, with the peak DIN concentration (1.576 mg/L) occurring in 2022, the highest observed across the entire bay. Medium-value DIN areas (annual average 0.25–0.40 mg/L) were located in the central-southern coastal area of the bay top and the western side of the bay mouth, showing relatively obvious interannual fluctuations, with generally high values in 2022 that decreased after 2023. Low-value DIN areas (annual average < 0.25 mg/L) were primarily distributed east of the bay mouth and towards the open sea, where the annual average DIN concentration was only about 0.10 mg/L. DIP in Laizhou Bay showed a weak gradient distribution characterized by “slightly higher concentrations near the coast at the bay top and very low concentrations in the outer bay and open sea”, with relatively small spatial variation (Fig.4). Notably, individual sites exhibited anomalously high DIP values (0.026 mg/L) in summer 2020 (Fig.2b), with the maximum occurring near the Weihe River estuary (Fig.4b).

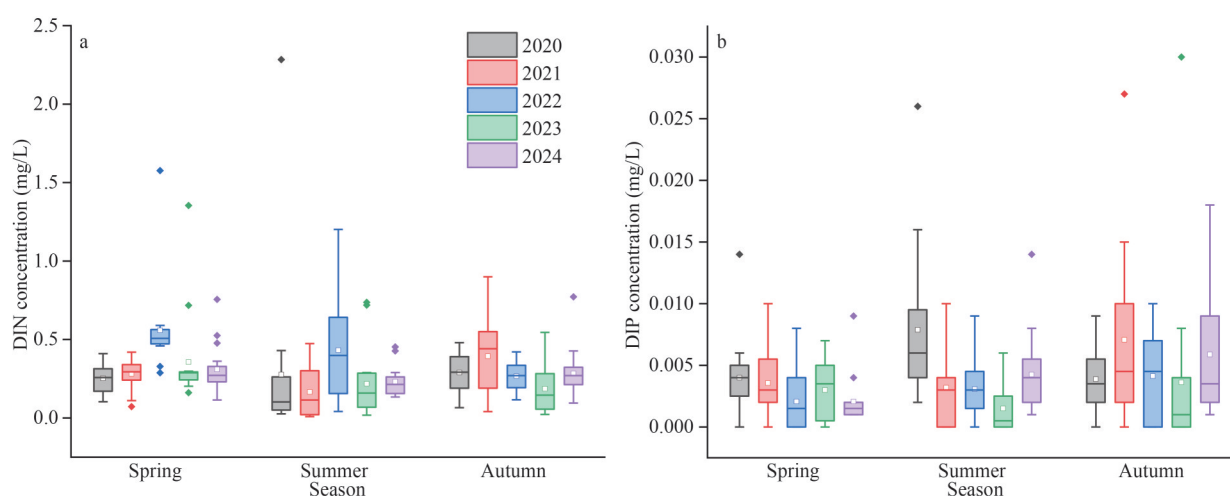


Fig.2 Box plots of DIN (a) and DIP (b) in Laizhou Bay from 2020 to 2024

DIN: dissolved inorganic nitrogen; DIP: dissolved inorganic phosphorus.

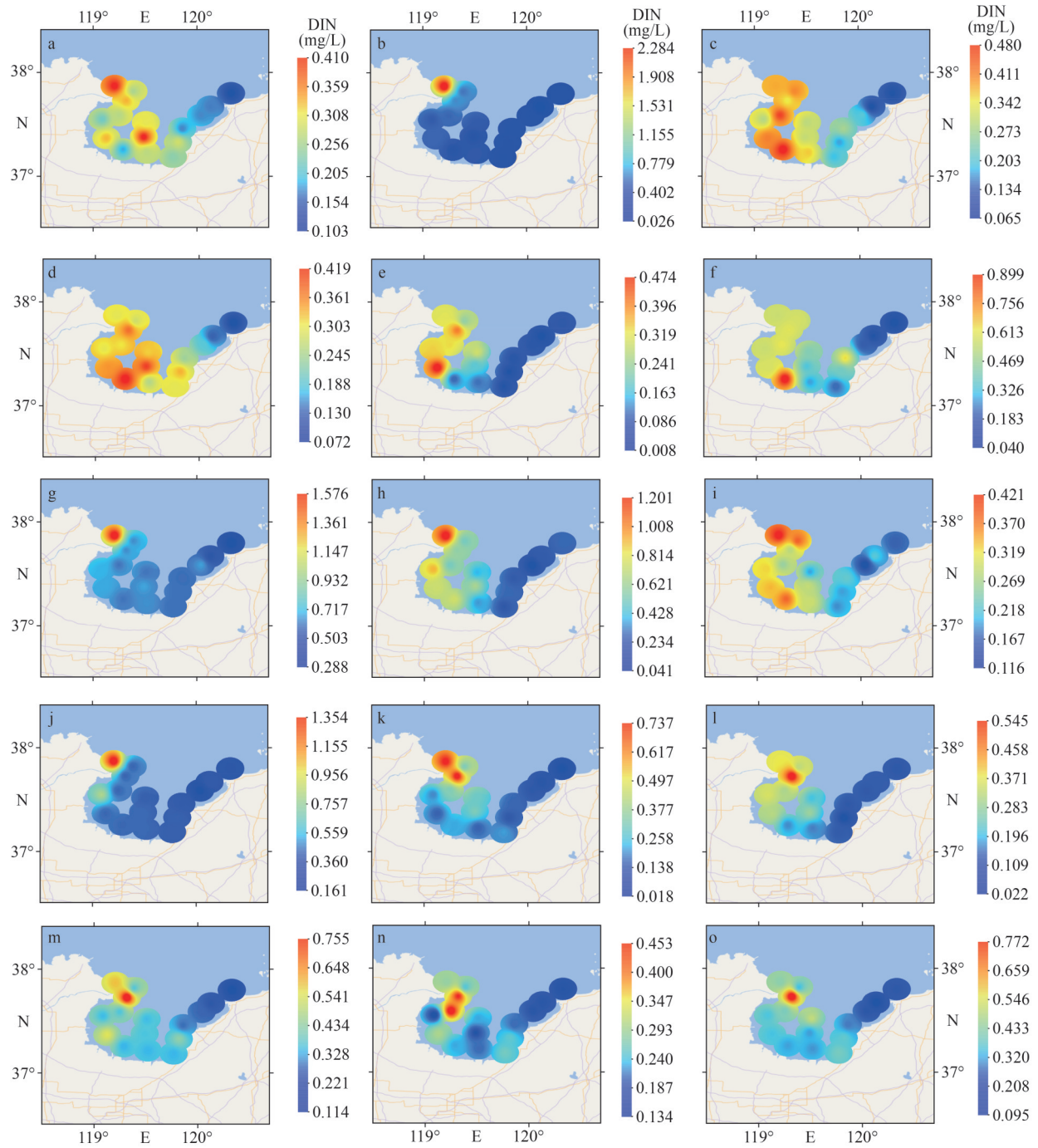


Fig.3 Spatial distribution of DIN concentration in Laizhou Bay from 2020 to 2024

a–c. spring, summer, and autumn in 2020, respectively; d–f. spring, summer, and autumn in 2021, respectively; g–i. spring, summer, and autumn in 2022, respectively; j–l. spring, summer, and autumn in 2023, respectively; m–o. spring, summer, and autumn in 2024, respectively. DIN: dissolved inorganic nitrogen.

3.2 Single factor evaluation result

For DIN, Laizhou Bay experienced a year of heavy pollution in 2022. In spring, the average P_i reached as high as 1.86, and the over-standard rate of DIN at monitoring sites was as high as 94%. In

summer, the average P_i stood at 1.44, with the over-standard rate of DIN at monitoring sites reaching 56%. Furthermore, the P_i values in all seasons throughout the year exceeded 1 (Supplementary Table S2).

In 2020, 2021, and 2024, the average SFPI

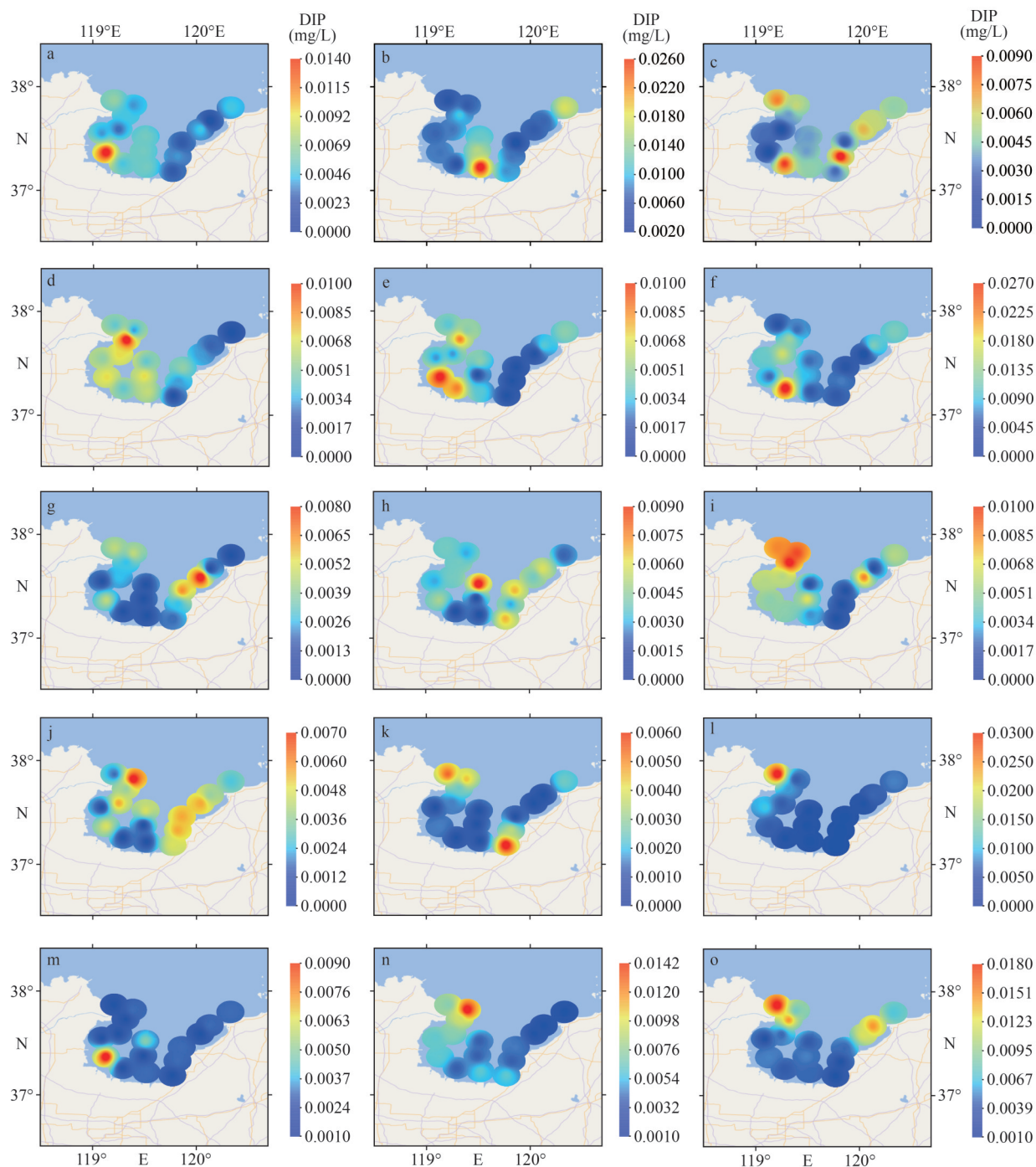


Fig.4 Spatial distribution of DIP concentration in Laizhou Bay from 2020 to 2024

a–c. spring, summer, and autumn in 2020, respectively; d–f. spring, summer, and autumn in 2021, respectively; g–i. spring, summer, and autumn in 2022, respectively; j–l. spring, summer, and autumn in 2023, respectively; m–o. spring, summer, and autumn in 2024, respectively. DIP: dissolved inorganic phosphorus.

values of DIN in spring and autumn ranged from 0.84 to 1.31, with mild pollution observed at some sites. However, the P_i values in summer were all below 1, indicating compliance with standards. The pollution in Laizhou Bay was the lightest in 2023.

Except for individual sites exceeding the standard in spring, both summer and autumn met the standard requirements.

From the perspective of seasonal distribution, DIN pollution was the most severe in spring, with

an average P_i value of 1.17 over the five years, among which the highest value (1.86) occurred in 2022. The maximum P_i values in summer 2020 and spring 2022 were 7.61 and 5.25 respectively, both showing local sudden increases. Nevertheless, the area of the high DIN concentration zone in 2022 was larger and the duration was longer. The P_i values based on DIP have consistently met the standard over the years (Supplementary Table S3).

3.3 N/P ratio

From 2020 to 2021, the average N/P ratio ranged from 135 to 196, indicating mild phosphorus limitation, although the N/P ratio at most stations remained far above the Redfield ratio (Supplementary Table S4). Notably, from autumn 2021 to summer 2022, the average N/P ratio in Laizhou Bay jumped to 288–499, with a maximum value of 1 318 recorded in autumn 2021. The average N/P ratio decreased in 2023 but remained significantly higher than the 2020–2021 levels. However, the N/P ratio increased again in spring 2024, reaching its highest average level in the past five years. Seasonally, the spring N/P ratio in Laizhou Bay exhibited substantial interannual fluctuations over the past five years, with particularly high levels in the springs of 2022 and 2024. The N/P ratio was relatively more stable in summer and autumn, except for extreme high values at individual stations. Overall, the nutrient structure in Laizhou Bay waters exhibited significant phosphorus-limited characteristics, with the N/P ratio consistently exceeding the Redfield ratio, indicating phosphorus as the primary limiting factor for primary productivity.

3.4 Eutrophication assessment result

The average EI from 2020 to 2024 ranged from 0.16 to 1.29, indicating a mild eutrophication level (Table 1). The seasonal average EI values in 2023 were the lowest recorded during the five-year period. From 2020 to 2024, the EI values in Laizhou Bay during spring and summer ranged from 0 to 2.65, all below 3.0 (Supplementary Table S5), indicating relative stability. The average autumn EI values were also below 3.0; however, in autumn 2021 and 2024, EI values at individual stations in Laizhou Bay exceeded 4, reaching a moderate eutrophication level. Overall, the EI level in autumn was significantly higher than that in spring and summer. The spatial distribution of EI values (Fig.5) shows a distinct pattern of “high at the bay top, low at the bay mouth; high on the western coast, low on

Table 1 Summary of eutrophication index (EI) values by season and year

Season	Year	Mean	Min.	Max.
Spring	2020	0.33	0	1.37
	2021	0.30	0	0.80
	2022	0.37	0	2.20
	2023	0.24	0	0.61
	2024	0.24	0.06	1.71
Summer	2020	0.51	0.03	2.65
	2021	0.26	0	1.87
	2022	0.33	0	1.25
	2023	0.16	0	1.15
	2024	0.35	0.02	1.07
Autumn	2020	0.36	0	1.72
	2021	1.29	0	4.09
	2022	0.38	0	1.03
	2023	0.32	0	2.52
	2024	0.60	0.08	4.78

the eastern coast.” The western coast of the bay top was identified as a high-risk area for eutrophication, while the open sea area remained oligotrophic throughout the year.

4 DISCUSSION

4.1 Spatiotemporal variation characteristics of nutrients

The DIN concentration in Laizhou Bay was high in 2022, dropped sharply in 2023, and then stabilized. This “rise-decline-stabilization” trajectory closely aligns with abrupt changes in the non-point source load from the watershed during that period. The precipitation in the Xiaoqing River basin in 2022 was 37.7% higher than the multi-year average (Jinan Urban and Rural Taxation Bureau, 2023), coinciding with the observation of DIN levels near the Xiaoqing River estuary reaching their peak in nearly five years (Fig.3). In contrast, the implementation of the “Nitrogen Reduction During Flood Season” special campaign in Shandong Province in 2023 led to a decrease in DIN flux into the sea. However, the 2023 Shandong Provincial Ecological and Environmental Status Bulletin indicated that the proportion of area with excellent water quality in Laizhou Bay was 45.8%, and substandard waters worse than Class IV were primarily distributed in the western part of Laizhou

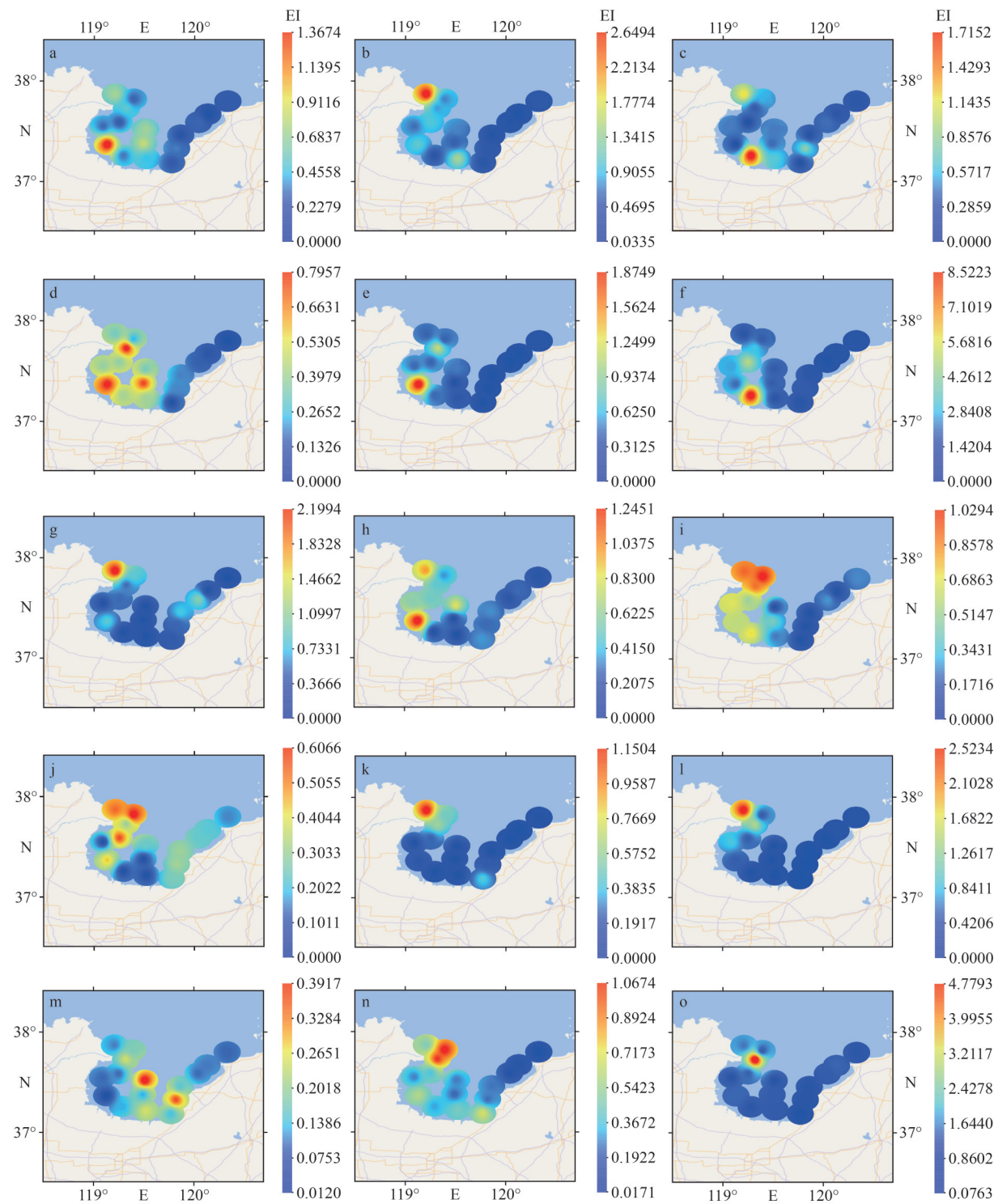


Fig.5 Spatial distribution of EI value in Laizhou Bay from 2020 to 2024

a–c. spring, summer, and autumn in 2020, respectively; d–f. spring, summer, and autumn in 2021, respectively; g–i. spring, summer, and autumn in 2022, respectively; j–l. spring, summer, and autumn in 2023, respectively; m–o. spring, summer, and autumn in 2024, respectively. EI: eutrophication index.

Bay, especially near the estuaries of the Xiaoqing River and Guangli River, with DIN remaining the main exceeded parameter (Department of Ecology and Environment of Shandong Province, 2023).

This is consistent with the observed high DIN concentrations in the western Laizhou Bay in May 2023 (Fig.3j). Compared with the historical data series, the DIN concentration from 2020 to 2024

was still significantly higher than the average value from 2004 to 2014, indicating that the total land-based nitrogen load has shown an overall upward trend in the past five years (Jiang et al., 2018). The average DIP concentration has remained at a relatively low level for a long time. It is worth noting that in different seasons during 2020–2024, the proportion of monitoring stations in Laizhou Bay where DIP concentration was lower than the absolute growth threshold of phytoplankton (approximately 0.009 mg/L) was as high as over 69%. This “lingering at a low level” is directly related to the comprehensive implementation of “phosphorus-free detergents+chemical phosphorus removal upgrading in sewage treatment plants” around the Bohai Sea. However, the interannual fluctuation of DIP is determined more by sediment resuspension-adsorption/desorption and rapid biological turnover, rather than by external input (Zheng et al., 2013; Liang et al., 2022).

The peak DIN concentration in Laizhou Bay occurred in spring 2022 (0.558 mg/L), correlating with high fertilizer nitrogen application in Shandong Province during that season, coupled with low precipitation and high evaporation, leading to a surge in non-point source nitrogen input (Kong et al., 2025). Summer DIN concentrations were the lowest, primarily controlled by the dual effects of “strong biological uptake and weak runoff.” When water temperatures are higher in summer, prolific phytoplankton growth consumes DIN, resulting in lower concentrations compared to spring (You et al., 2018). Furthermore, except for minor increases to 0.006–0.007 mg/L observed in summer 2020 and autumn 2021, DIP concentrations remained low in other seasons. Short-term increases are associated with typhoon-induced resuspension, but the relatively short residence time of DIP in the bay allows for a rapid return to low levels (Li et al., 2024).

Overall, the spatial distribution of DIN in Laizhou Bay was characterized by higher levels in the west and lower levels in the east (Fig.3). The annual average DIN concentration near the Xiaoqing River estuary-west of the Huanghe River estuary exceeded 0.30 mg/L (above China’s Class II seawater quality standard), with a single-point concentration reaching 1.576 mg/L in spring 2022, the highest in the entire bay. Among the nitrogen and phosphorus transported to Laizhou Bay by the surrounding estuaries, the Huanghe River makes the largest relative contribution, followed by the

Xiaoqing River, with their combined contributions exceeding 90% (Wang et al., 2023b). Furthermore, the Xiaoqing River estuary has become highly artificialized since 2010, resulting in poor self-regulation ability and resilience (Wang et al., 2024). Studies suggest that marine circulation significantly influences DIN distribution in Laizhou Bay. The prevailing clockwise circulation within the bay contributes to high DIN areas near the Xiaoqing River and Huanghe River estuaries (Lu et al., 2025). In contrast, east of the bay mouth, dilution by the Yellow Sea coastal current rapidly reduces DIN, creating a strong gradient from nearshore to offshore. For DIP, the distribution shows a weak “slightly higher at the bay top to very low in the open sea” gradient. Spatial differences in DIP are minor, with the relatively higher concentrations near the bay top coast primarily stemming from stable land-based inputs. Concurrently, adsorption onto suspended particles in the high-turbidity zone of the Huanghe River estuary prevents the formation of high-concentration DIP areas (Wang et al., 2022).

4.2 Long-term phosphorus limitation

The N/P ratio in Laizhou Bay over the past five years generally exceeded the Redfield ratio (Supplementary Table S4), indicating nitrogen surplus and primary phytoplankton growth limitation by phosphorus. Fluctuations in the N/P ratio may intensify competition among phytoplankton, potentially leading to shifts in community structure. Diazotrophic cyanobacteria, such as *Synechococcus*, might proliferate extensively, ultimately affecting the normal reproduction of diatoms and green algae (Ren et al., 2024). Diazotrophic cyanobacteria can gain an ecological advantage in waters with relative DIN surplus and phosphorus limitation by obtaining additional energy through nitrogen fixation (Igwaran et al., 2024). The proliferation of such functional groups can significantly impact ecosystem structure and function (Howarth and Marino, 2006). When cyanobacterial blooms form, water transparency decreases, bottom-layer DO is heavily consumed, and various toxic secondary metabolites are released, posing serious threats to aquatic ecosystem health and negatively affecting the survival and reproduction of aquatic organisms (Igwaran et al., 2024). The outbreak of a *Noctiluca scintillans* red tide in the northern Huanghe River estuary area in spring 2023 indicates substantial ecological risks associated with imbalanced nutrient structure.

As shown in Fig.6, the N/P ratio in Laizhou Bay

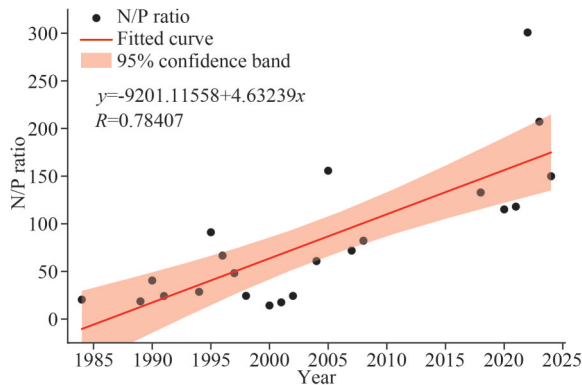


Fig.6 Temporal variation and linear fitting of annual mean N/P ratio in Laizhou Bay (1984–2024)

Data for 1984 to 2008 from Zhang et al. (2012), data for 2018 from You et al. (2021), and data for 2020–2024 were measured in this study.

exhibited a significant increasing trend from 1984 to 2024 ($R=0.78407$), with an annual increase of approximately 4.7 units. This change indicates that Laizhou Bay's ecosystem has been in a long-term state of phosphorus limitation, reflecting the intensifying anthropogenic disturbance of the nutrient structure in this sea area. Slow accumulation period (1984–2000): the N/P ratio remained at relatively low levels (approximately 50–120). Although this stage was already affected by terrestrial inputs, the marine self-purification capacity had not yet been exceeded. Agricultural non-point source pollution was the primary driving factor during this period (Liu et al., 2003), and nitrogen loss caused a continuous rise in the N/P ratio. However, the relatively inefficient application of phosphorus fertilizer constrained the rapid increase in the N/P ratio (Duan et al., 2000). Rapid rise period (2001–2015): the N/P ratio surged to the 120–200 range, coinciding with accelerated industrialization and urbanization in the Bohai Sea region. Discharge of industrial wastewater and domestic sewage significantly altered the nutrient load structure, with nitrogen inputs increasing far more rapidly than phosphorus (Liu et al., 2019; Zhai et al., 2020). High-level fluctuation period (2016–2024): the N/P ratio stabilized between 200 and 250, reaching 12–15 times the Redfield ratio (16:1), indicating a state of severe nitrogen excess in the ecosystem. Despite interventions by environmental policies such as the Action Plan for Water Pollution Prevention and Control (Water Ten Plan), the N/P ratio remained elevated due to the historical accumulation of nutrients in sediments (Zhang et al., 2018; Zhang and Jun, 2023).

4.3 Eutrophication assessment

From 2020 to 2024, the annual average EI in Laizhou Bay ranged from 0.07 to 0.98, indicating an overall mild eutrophication level. This level is consistent with findings from recent studies in areas like Bohai Bay and Dapeng Bay (Wu et al., 2024; Qu et al., 2025), suggesting that the overall water quality in Laizhou Bay has not reached a moderate or severe eutrophication state but shows a eutrophication trend. Notably, in autumn 2021, the EI value near the Mihe River estuary reached 8.52, the highest level recorded in the past five years. It is worth noting that the average EI values in Laizhou Bay were relatively low from autumn 2022 to summer 2023, potentially related to meteorological conditions, reduced riverine input fluxes, or strengthened pollution control measures during that period. Specifically, lower precipitation in the Huanghe River basin led to continuously lower salinity in Laizhou Bay, indicating reduced Huanghe River discharge and consequently decreased land-based nutrient inputs (Liu et al., 2024). Furthermore, Wang et al. (2023a) found that the Forel-Ule index in the Bohai Sea area, including Laizhou Bay, was lower in 2022, suggesting that measures such as controlling land-based pollution, reducing aquaculture pollution, and remediating sewage outfalls have a significant lagged positive effect on EI reduction. Although the Xiaoqing River water body remains in a moderate to severe eutrophication state, its contribution to the overall eutrophication in Laizhou Bay has weakened, especially during the wet season when the EI is significantly lower than in the dry season (Zhang et al., 2023). Despite EI values generally remaining below 3.0 in spring and summer, indicating relatively stable water nutrient status, EI values at individual stations exceeded 4.0 in autumn 2021 and 2024, reaching a moderate eutrophication level. This seasonal disparity is also observed in Jiaozhou Bay and Liaodong Bay. In autumn, phytoplankton uptake and utilization of nutrients decrease, while organic matter mineralization, decomposition, and sediment resuspension can lead to nutrient release, ultimately causing a significant increase in surface water nutrient concentrations (Zhang et al., 2022b; Wu et al., 2024).

The spatial distribution of EI values showed a clear pattern of “high at the bay top, low at the bay mouth; high on the western coast, low on the eastern coast,” consistent with the spatial distribution characteristics of DIN (Fig.3). The western coast of

the bay top was a high-risk area for eutrophication, while the open sea area maintained low levels year-round. This spatial heterogeneity is primarily controlled by concentrated land-based nutrient input, reduced water exchange capacity, and intense anthropogenic activities along the artificial shoreline (Li et al., 2015; Yang et al., 2021; Zhang et al., 2022b; Sun et al., 2024a). Similar spatial heterogeneity has been confirmed in Bohai Bay, where eutrophication levels in coastal areas are significantly higher than in the central bay, and N/P ratio imbalance is one of the main driving factors (Qu et al., 2025).

4.4 Correlation analysis among pH, DO, COD_{Mn}, and nutrients

Similar to findings in Bohai Bay (Qiao et al., 2025), the evolution of eutrophication in Laizhou Bay is reflected not only in changes in DIN and DIP concentrations but also in the dynamic variations of key water quality parameters like pH, DO, and COD_{Mn}, and their complex interactions with nutrients. Weak correlations were observed between pH and most nutrients (DIN, DIP, etc.) (Fig.7), with strong correlations appearing only in specific years and seasons. Specifically, significant negative correlations ($P < 0.05$) between pH and DIN were observed in the summers of 2020 and 2022 (Fig.7b & h). This suggests that under high nutrient load conditions, phytoplankton respiration and organic matter decomposition release CO₂, thereby lowering water pH (Cai et al., 2011). In the summer of 2024, a significant positive correlation ($P < 0.05$) was found between pH and COD_{Mn} in Laizhou Bay waters (Fig.7). In eutrophic bay waters, the seemingly paradoxical positive correlation between pH and COD_{Mn} actually represents a biomass-synchronized driving mechanism, which is fundamentally different from the traditional “organic matter degradation acid production” pattern typical in river systems. In most aquatic environments, elevated organic matter releases CO₂ through microbial respiration and lowers pH (Laurent et al., 2017). However, in eutrophic bays such as Laizhou Bay, COD_{Mn} is not merely an indicator of oxygen-consuming pollutants but primarily serves as a proxy for phytoplankton-derived particulate organic carbon (Li et al., 2019). In summer, higher Chl-*a* concentrations in seawater can directly elevate COD_{Mn} values through live biomass (Li et al., 2019); meanwhile, intense photosynthesis consumes dissolved CO₂, alters the carbonate balance, and

raises pH (Cai et al., 2011). This biogenic coupling results in a statistically synergistic variation—both parameters rise synchronously driven by phytoplankton acting as a biological pump (Wang et al., 2018).

DO showed some correlation with DIN and DIP (Fig.7b & n), which might be related to biological oxygen consumption processes. Relevant studies indicate a positive correlation between DO and Chl *a*, while Chl *a* is associated with variations in DIN and DIP (Baek et al., 2024). This study observed a significant positive correlation between DO and DIP in the surface water of Laizhou Bay during the summer of 2024 (Fig.7n), which differs from the common negative correlation patterns dominated by photosynthesis or sediment release in eutrophic systems. We propose that this phenomenon may be driven by the synergistic degradation of organic particles following algal blooms: during the microbial decomposition of fresh organic matter, oxygen is simultaneously consumed, and organically bound phosphorus is mineralized and released (Gobler and Baumann, 2016). In contrast, in strongly stratified bays such as Jinhae Bay in South Korea, hypoxia in the bottom water significantly promotes the release of phosphorus from sediments, often resulting in a negative correlation between DO and DIP, which is a typical manifestation of sediment-water interface interactions (Lee et al., 2018). In systems dominated by in situ productivity, such as tropical estuaries like the Sanya River, vigorous phytoplankton photosynthesis generates oxygen while rapidly absorbing DIP in the water to support growth, driving a seesaw-like negative correlation between DO and DIP in surface water. This reflects the core influence of the “biological production” process (Han et al., 2024). Therefore, when analyzing the relationship between DO and DIP, it is essential to comprehensively consider factors such as the environmental characteristics of the study area, seasonal variations, and biogeochemical processes.

COD_{Mn} typically showed significant positive correlations with nutrients (Fig.7a, e, f, & l), which might be related to their common sources and interconversions within the water body (Liang et al., 2022). Dong et al. (2023) found that DIN was significantly negatively correlated with salinity, indicating that terrestrial runoff input is an important source of nutrients in the coastal waters of Laizhou Bay. Meanwhile, Laizhou Bay is a semi-enclosed bay with weak hydrodynamics, where pollutants input by rivers accumulate in estuarine and

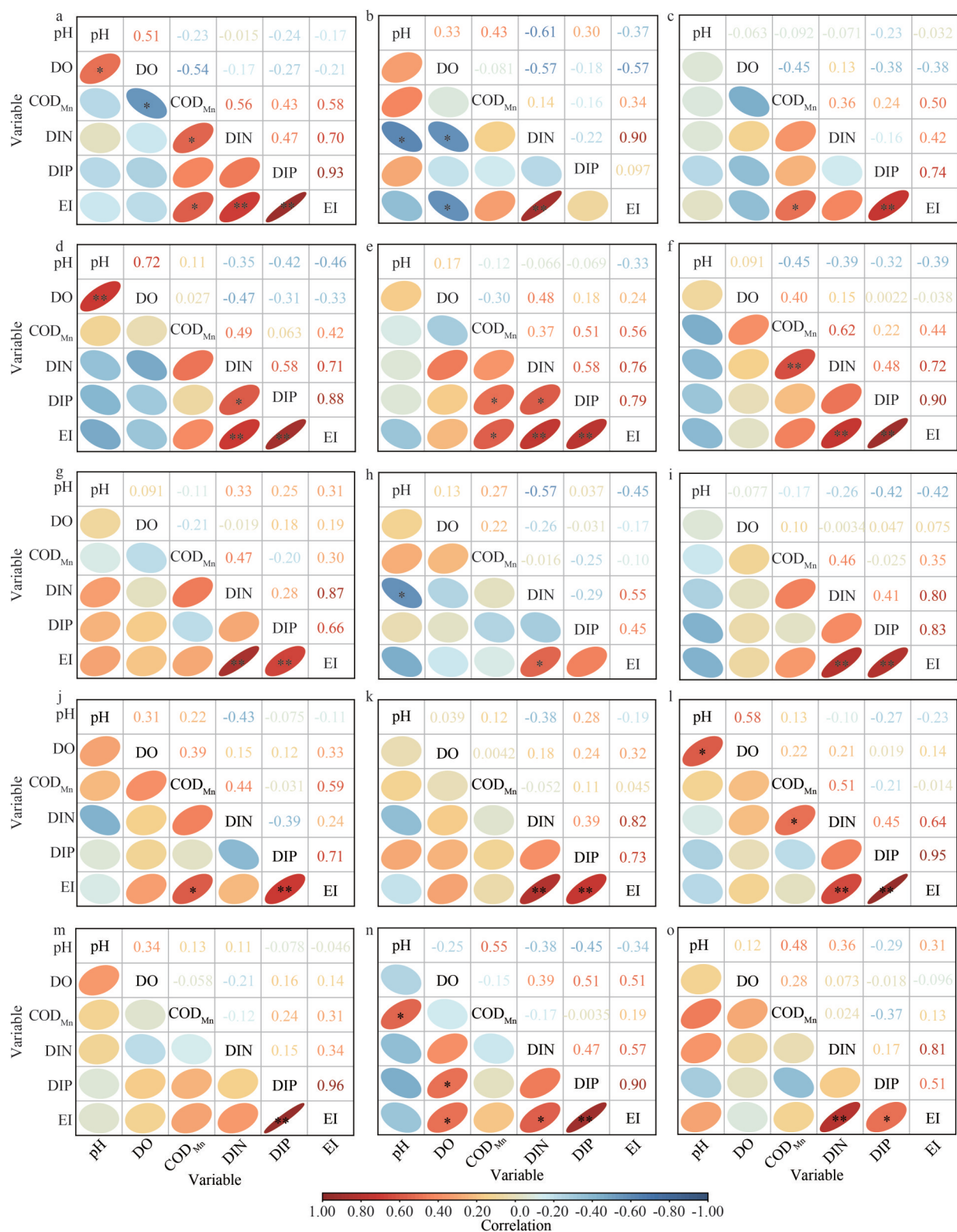


Fig.7 Correlation analysis of EI, DIN, DIP, pH, and DO in Laizhou Bay from 2020 to 2024

a–c. spring, summer, and autumn in 2020, respectively; d–f. spring, summer, and autumn in 2021, respectively; g–i. spring, summer, and autumn in 2022, respectively; j–l. spring, summer, and autumn in 2023, respectively; m–o. spring, summer, and autumn in 2024, respectively. *: $P < 0.05$, **: $P < 0.01$. EI: eutrophication index; DIN: dissolved inorganic nitrogen; DIP: dissolved inorganic phosphorus; DO: dissolved oxygen.

nearshore areas, leading to highly overlapping spatial distributions of COD_{Mn} and nutrients and thus exhibiting a statistically positive correlation (Guo et al., 2016). Additionally, the correlation between COD_{Mn} and nutrients may also be closely related to the decomposition process of organic matter (Wetzel, 2001). During organic matter decomposition, nutrients like nitrogen and phosphorus are released, further promoting the growth of algae and other aquatic organisms, consequently leading to increased COD_{Mn} and nutrient levels in the water body. Previous research results also indicated significant positive correlations between COD_{Mn} and both DIN and DIP in the western waters of Laizhou Bay (Zhang et al., 2017). The typically strong positive correlations among DIN, DIP, and COD_{Mn} might also be related to their common sources and interconversions within the water body (Liang et al., 2022).

5 CONCLUSION

Based on the survey data of Laizhou Bay from 2020 to 2024, this study draws the following conclusions: Laizhou Bay has been in a state of significant phosphorus limitation for a long time, with the N/P ratio in the water body consistently exceeding the Redfield ratio. Eutrophication exhibits distinct spatiotemporal differentiation characteristics: the concentration of DIN peaks in spring, driven by agricultural runoff, while autumn is the high-risk period for eutrophication; the high-risk areas are stably distributed along the western coast of the bay top, affected by the concentrated discharge of land-based pollutants and restricted water exchange. The biogeochemical coupling relationships are clear: COD_{Mn} shows a significant positive correlation with nutrients, whereas its correlations with pH and DO are highly variable and relatively weak. The intensification of eutrophication stems from the synergistic effect of excessive terrestrial nitrogen input and pollutant retention caused by the semi-enclosed topography. It is necessary to implement coordinated nitrogen and phosphorus control measures and strengthen monitoring and early warning in spring and autumn to support the construction of the “Beautiful Bays” initiative.

6 DATA AVAILABILITY STATEMENT

All data generated and/or analyzed during this

study are included in this published article and its supplementary information files.

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Electronic supplementary material

Supplementary material (Supplementary Tables S1–S5) is available in the online version of this article at <https://doi.org/10.1007/s00343-026-5440-x>.