frontiers | Frontiers in Marine Science

TYPE Original Research
PUBLISHED 18 June 2025
DOI 10.3389/fmars.2025.1580304

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RECEIVED 20 February 2025
ACCEPTED 19 May 2025
PUBLISHED 18 June 2025

CITATION
Bai D, Chu H, Feng Y, Wang L and Yin M (2025) The distribution of nutrients and chlorophyll-a in the temperate coast of China: implications for marine ecological risks in the context of global warming. *Front. Mar. Sci.* 12:1580304. doi: 10.3389/fmars.2025.1580304

The distribution of nutrients and chlorophyll-a in the temperate coast of China: implications for marine ecological risks in the context of global warming

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Introduction: Nutrients directly regulate the level of primary productivity, which is crucial for the stability of marine ecosystems. However, under the context of human activities leading to global warming, factors influencing alterations in coastal nutrient dynamics remain a mystery.

Methods: A study was conducted to investigate the spatial distribution characteristics of nutrients and chlorophyll-a at 55 stations in the Bohai Bay region during the autumn of 2021.

Results: The dominant factor influencing coastal zone ecology in the surveyed area was identified as temperature. Multiple factors (e.g., riverine input, sediment release, atmospheric deposition, and hydrodynamics) collectively impacted nutrient dynamics. The temperature along the north-south transect was consistent, with a distinct demarcation at 118.68°E (19°C), where the temperature gradient exhibited a pronounced east-high, west-low pattern. The temperature difference between the surface and bottom waters was minimal. In the high-temperature eastern region, the redox potential was high (above 100 mV), and very few locations had low dissolved oxygen levels, indicating active aerobic microbial activity. This led to the decomposition of substantial organic matter, resulting in elevated ammonia-nitrogen concentrations, and low pH levels. The presence of ammonia-nitrogen promoted the growth and reproduction of planktonic organisms.

Discussion: Therefore, we are concerned that global climate warming may trigger changes, and even worsen, marine ecological environments in temperate coastal regions, necessitating heightened attention from researchers.

KEYWORDS

nutrients, temperate coastal ecosystems, global warming, distribution characteristics, seawater

1 Introduction

Eutrophication is an emerging global issue associated with essential nutrients such as nitrogen, phosphorus, and silicon, which are vital for the formation of the material foundation of marine ecosystems (Maúre et al., 2021). They played a pivotal role in the growth and reproduction of phytoplankton, thereby regulating primary marine productivity (Ma et al., 2019, 2021). Once assimilated by phytoplankton, these nutrients were returned to the marine environment through microbial decomposition, establishing a regenerative nutrient cycle within seawater (Zhou et al., 2017a; Jiang et al., 2023a; Wang et al., 2023). Over recent decades, human activities had significantly increased the global flux of nitrogen and phosphorus from rivers (Jiang et al., 2023b; Chu et al., 2024). Remote sensing technology and neural network models have provided us with effective ecological risk warnings in the field of aquatic ecology (Mozafari et al., 2023; Saravani et al., 2025). Alterations in nutrient concentrations and compositions not only affected water quality but also contribute to harmful algal blooms, hypoxia, and acidification. These phenomena posed serious threats to the survival of aquatic organisms and the overall health of marine ecosystems (Li H. M., et al, 2014; Cao et al., 2018; Wang et al., 2021). Estuaries and coastal marine ecosystems that had experienced high nutrient loading could exhibit limitations in the availability of one or multiple essential nutrients (Conley et al., 2009). However, the role of temperature in shaping the chemical environment might be overlooked. Nutrient concentrations were subject to seasonal and spatial variations (Liu X., et al, 2019), and the factors influencing these patterns warranted a more comprehensive discussion. Therefore, further research was needed to better understand the significance of temperature as a pivotal factor in governing nutrient dynamics.

Bohai Bay (BHB) is a semi-enclosed body of water situated on the western periphery of the Bohai Sea. Over recent decades, neighboring cities such as Beijing, Tianjin, and Tangshan had witnessed accelerated economic growth (Tong et al., 2014). This rapid expansion had led to an intensification and diversification of human activities, which in turn had significantly influenced nutrient conditions. While earlier studies predominantly focused on terrestrial factors like sewage treatment, fertilizer use, and water management (Jiang et al., 2005; Ning et al., 2010), it had been observed that nutrient concentrations in waters closer to the shore, especially near the estuary, were consistently higher than those in offshore areas (Wu et al., 2021).

Recent investigations had underscored the roles of atmospheric deposition and sediment release in this context (Wu et al., 2011, 2023). Atmospheric nitrogen contributed significantly more to the total nitrogen concentration (TN) in the Bohai Sea than riverine input nitrogen, accounting for an average of 84.79% (Shou et al., 2018). Anoxic zones within the mouth of BHB, where dissolved oxygen (DO) levels were approximately 3 mg L^{-1}, promoted the involvement of oxygen electron acceptors in mineralizing organic matter in sediment (Zhang H., et al, 2016). These anoxic conditions markedly increased the release of phosphorus and silicon from sediments into the overlying waters (Kang et al., 2018), thereby altering nutrient conditions.

Recent studies in BHB revealed that higher concentrations of Dissolved Inorganic Phosphate (DIP) and Dissolved Silicate (DSi) were more common in offshore waters than in nearshore waters (Wang et al., 2009; Li G. J., et al, 2012). This suggested that sediment release or exchange from other marine regions might have a significant impact, which merited further investigation through additional field observations. We hypothesize that the gradual increase in *in-situ* seawater temperature will lead to consistent alterations in the chemical composition of the marine environment. To investigate the current state of temperature-sensitive temperate coastal ecosystems, this study conducted a cruise survey in the autumn, measuring the physical and chemical parameters of seawater at 55 stations. The research objectives include: 1. Investigating the influence of temperature on the *in situ* marine chemical field, with a focus on parameters related to eutrophication such as oxidation-reduction potential (Eh), DO, pH, nitrate nitrogen (NO_3-N), DIP, and DSi. 2. Predicting the response of coastal marine environmental indicators, including Chemical Oxygen Demand (COD), and sulfide.

2 Study site

The Bohai Sea was the deepest submerged gulf of the East Asian marginal seas, with an average water depth of about 18 m (Shi et al., 2016). It was connected to the Yellow Sea by a narrow Bohai Strait (Li et al., 2020). In winter, the relatively high-salinity and warm Yellow Sea Warm Current (YSWC) entered the Bohai Sea from the Yellow Sea (Xu et al., 2009). The North Shandong Coastal Current (NSCC), which existed in both winter and summer, originated from the west coast of Bohai Bay (Figure 1) and flowed along the northern shoreline of Shandong Peninsula (Yuan et al., 2020). The dominant tidal constituent observed in the Bohai Sea was the semidiurnal (M_2) tide with an average amplitude of 2 m (Li et al., 2019). The Yellow River, Haihe River, and Luan River were the main rivers flowing into the Bohai Sea, delivering large amounts of terrigenous sediments to the Bohai Bay located in the western part of the Bohai Sea (Wang et al., 2014; Tian et al., 2017). The Loess Plateau was a buffer barrier for the Yellow River to transport sediments from the Qinghai-Tibet Plateau to the ocean and was also a major source of nearshore sediments (Nie et al., 2015; Liu S., et al, 2022). The Haihe River originated from the Taihang Mountains and transported alluvial-proluvial sediments to the ocean (Yao et al., 2012; Liu et al., 2021). The Yanshan Mountains were widely exposed with ancient metamorphic rocks and various types of volcanic rocks, which were the main sources of Luan River sediments (Li et al., 2020; Dong et al., 2018).

3 Methods

During October, 2021 (autumn), water samples were collected from both the surface and bottom layers at 55 distinct stations in BHB. The surface samples were obtained at a depth of about 0.5 m below the water surface, while the bottom samples were collected

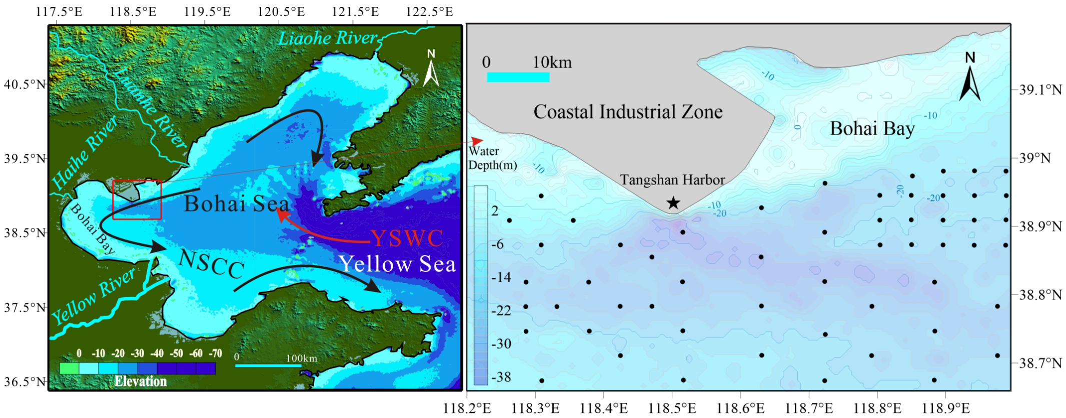

FIGURE 1
Locations of sampling stations (Solid black dots) of seawater in the northern Bohai Bay. NSCC is an abbreviation for the Northern Shandong Coastal Current, while YSWC stands for the Yellow Sea Warm Current.

about 1.0 m above the seabed. Underwater samplers were fixed with cables, and the sampling position was determined based on the length of the cable lowered from the water surface or raised from the seabed. This survey collected and measured various parameters including temperature, Eh, DO, pH, NO_3-N, Nitrite nitrogen (NO_2-N), Ammonia nitrogen (NH_4-N), DIP, DSi, COD, Sulfide, Suspended Particulate Matter (SPM), Total Nitrogen (TN), Total Phosphorus (TP), Total Carbon (TC), and Chlorophyll a (Chl a). The nutrients were determined using the water samples filtered through a 0.45 μm filter membrane. The detection limits of the measured nutrients are as follows: 0.1 μmol/L (DSi), 0.02 μmol/L (DIP), 0.03 μmol/L (NH_4-N), 0.05 μmol/L (NO_3-N), and 0.02 μmol/L (NO_2-N). Sample collection and analysis were conducted in accordance with relevant references (Li et al., 2024; Wen et al., 2024), specifically adhering to the Marine Monitoring standard (GB 17378-2007) and Marine Survey standard (GB 12763-2007).

In an acidic solution, accurately add an excess of potassium dichromate standard solution, heat reflux to oxidize reducible substances (mainly organic matter) in the water sample. The excess potassium dichromate is indicated by ferroin, and titrate with ammonium iron (II) sulfate standard solution. Calculate the COD based on the amount of potassium dichromate standard solution consumed.

TP was measured as follows: The seawater samples were oxidized with potassium persulfate under acidic conditions at a temperature of 110-120°C. Organic phosphorus compounds were converted into inorganic phosphate, while inorganic polymeric phosphorus hydrolyzed into orthophosphate. The generated free chlorine during digestion was reduced using ascorbic acid. The orthophosphate in the digested water sample reacted with ammonium molybdate to form phosphomolybdenum yellow. In the presence of potassium antimony tartrate, the phosphomolybdenum yellow was reduced to phosphomolybdenum blue by ascorbic acid and measured by spectrophotometry at a wavelength of 882 nm.

TN was measured as follows: The seawater samples were oxidized with potassium persulfate under alkaline conditions at a temperature of 110-120°C. Organic nitrogen compounds were converted into nitrate nitrogen. At the same time, nitrite nitrogen and ammonium nitrogen in the water were quantitatively oxidized to nitrate nitrogen. The nitrate nitrogen was reduced to nitrite salt and underwent diazotization reaction with sulfanilamide. The resulting product then reacted with 1-naphthyl ethylenediamine dihydrochloride to form a deep red azo dye, which was measured by spectrophotometry at a wavelength of 543 nm.

The spectrophotometric method for testing chlorophyll-a was as follows: Algal cells were filtered and ground, and chlorophyll-a was extracted using an acetone solution. After centrifugation, the absorbance of the extracted solution was measured at specific wavelengths, such as 630 nm, 647 nm, 664 nm, and 750 nm. The chlorophyll-a concentration was then calculated based on the absorbance readings.

4 Results and discussions

4.1 Spatial distribution of physical and chemical parameters

Temperature of the surface and bottom water exhibited a gradual increase from west to east, ranging from 15.2 to 21.2 degrees Celsius (Figure 2). In autumn, the average sea water temperature in the Bohai Sea is higher than that on land (Deng and Zhao, 2020). Coastal currents flow from east to west, suggesting that the temperature difference may be attributed to water mass movement (Yuan et al., 2020). There were no significant differences between surface and bottom temperatures. The monsoon wind and tidal action might be the primary factors influencing vertical mixing (Luo et al., 2021). The mass concentration range of total nitrogen in the surface seawater was 0.181-0.277 mg/L, with an average value of 0.218 mg/L. The survey area showed a distribution pattern where the total nitrogen content in surface seawater was lower in the central region and higher in the eastern and western peripheries.

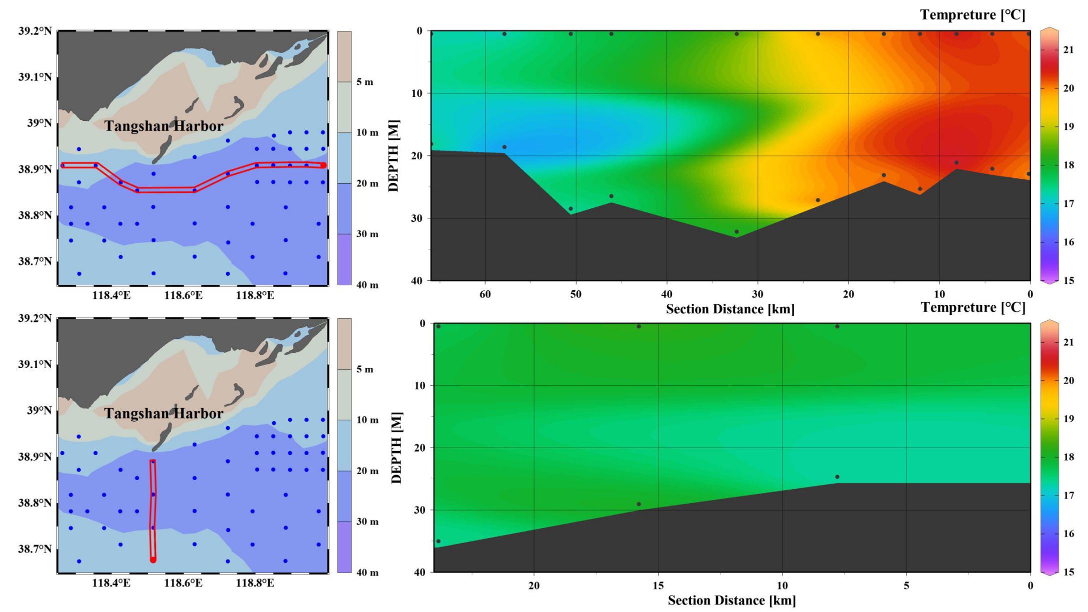

FIGURE 2
The distribution of water chemical sampling stations in the survey area, as well as the east-west and north-south temperature sections. On the left side, the sampling stations and the locations of the seawater sections are shown, while on the right side, the corresponding temperature field distributions for these sections are displayed. ODV software was used (https://odv.awi.de/).

The mass concentration range of total nitrogen in the bottom seawater was 0.205-0.265 mg/L, with an average value of 0.232 mg/L. The distribution of total nitrogen in the bottom seawater was similar to that in the surface seawater, which might be related to potential groundwater discharge or sediment release (Liu J., et al, 2017; Noori et al., 2021; Zhang et al., 2024). The mass concentration range of total phosphorus in the surface seawater was 0.10-0.14 mg/L, with an average value of 0.12 mg/L. Individual high-value stations were sporadically distributed in the northwestern and northeastern regions of the survey area, similar to the distribution in the bottom water. it be linked to localized sediment resuspension (Figure 3). The N/P ratios were significantly higher than the Redfield ratio (16), averaging around 58, indicating a clear phosphorus limitation in the coastal area. The mass concentration range of sulfide in the surface seawater was 0-9.4 μg/L, with an average value of 3.2 μg/L. In the surveyed area, the surface sulfide content was higher in the eastern region compared to the western region, which differed from the bottom seawater. The sulfide content in the bottom seawater showed little variation, indicating that the redox conditions were not significantly different. This suggested that river transport might be responsible for the low sulfide concentration in the western region. The concentration range of nitrate in the surface seawater was 0.068-0.171 mg/L, with an average content of 0.107 mg/L. In the surveyed area, there were slightly more high-content stations in the eastern region compared to the western region, mirroring the pattern observed in the bottom seawater. Nitrate content displays a significant vertical gradient, with surface nitrate concentrations generally exceeding those at the bottom, indicating varying nitrogen sources' contributions. The western marine area receives a higher proportion of river inputs (Yu et al., 2024). There is evidence of nitrification processes occurring in bottom waters, with a higher proportion of sediment input in the eastern region (Li et al., 2022). The concentration range of nitrite is 0.013-0.025 mg/L, with an average content of 0.018 mg/L. In both surface and bottom seawater, nitrite levels in the western region of the surveyed area are higher than in the eastern region. Generally, nitrite concentrations in surface seawater are higher than those in bottom seawater. Since nitrite is an intermediate in nitrification and denitrification processes, differences in microbial activity in nitrite oxidation may arise due to temperature variations (Taylor et al., 2019). The concentration range of ammonia nitrogen is 0.006-0.093 mg/L, with an average content of 0.055 mg/L. In the eastern region of the surveyed area, surface seawater ammonia nitrogen content is significantly higher than in the western region, with a relatively dense high-content area. In contrast, bottom ammonia nitrogen content is more evenly distributed. Overall, surface seawater ammonia nitrogen content is consistently higher than that in the bottom layer. The spatial distribution characteristics of ammonia nitrogen may be attributed to biological uptake, as a warming ocean could potentially suppress offshore ammonia oxidation (Zheng et al., 2020). The concentration range of reactive silicate is 0.018-0.033 mg/L, with an average content of 0.024 mg/L. In the eastern region of the surveyed area, surface seawater silicate content is significantly higher than in the western region. High-content silicate stations in bottom seawater are distributed in a point-like manner, and the average silicate content in the bottom layer is slightly higher than that in the surface layer, with a relatively stable distribution. This suggests that sediment release dominates the

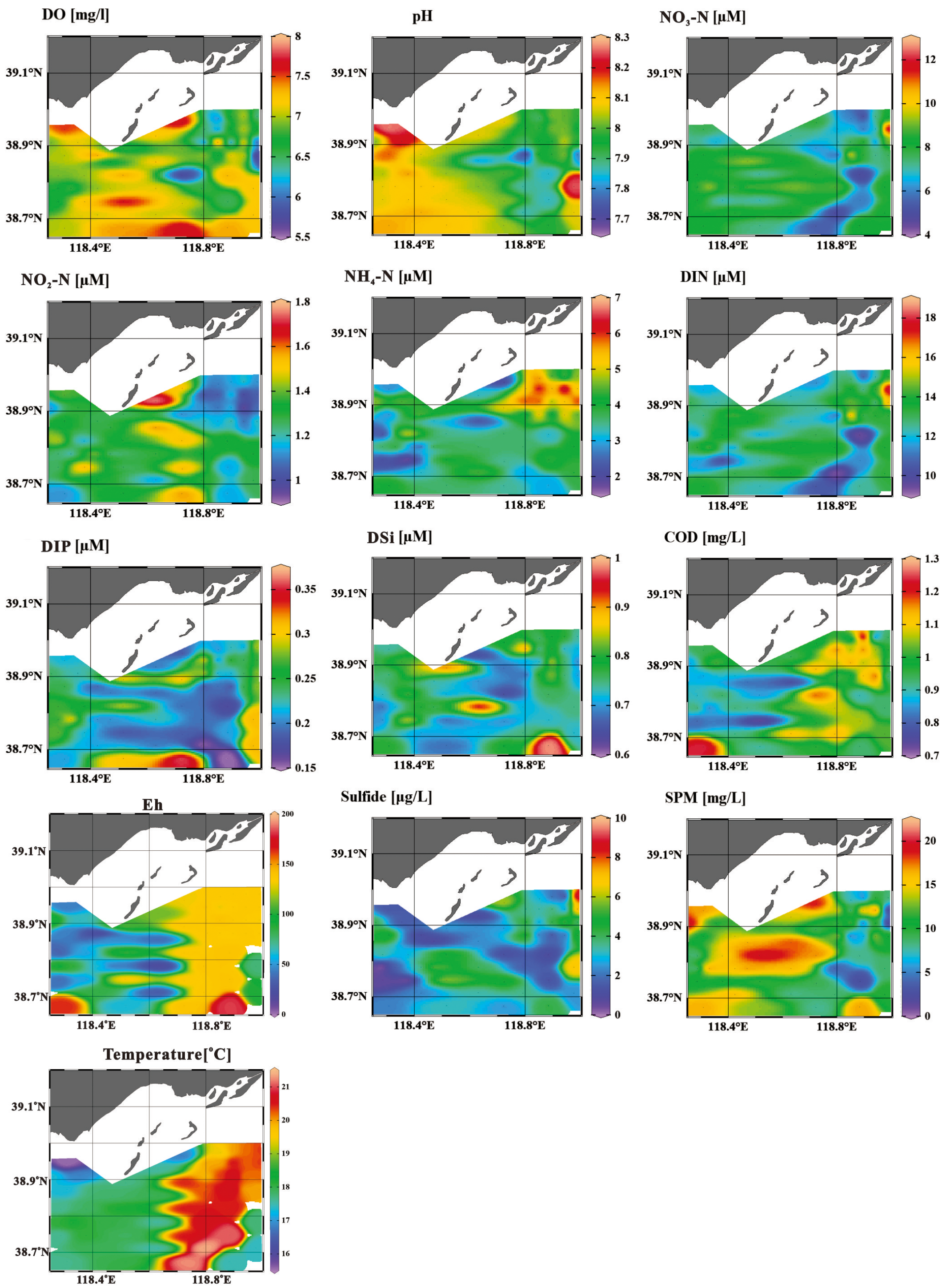

FIGURE 3
Distribution map of physical and chemical parameters in the surface seawater of the survey area. ODV software was used (https://odv.awi.de/).

supply of DSi, which is consistent with the distribution of TN (Figure 4). The upwelling caused by the west-high and east-low seabed topography in the Bohai Bay plays a decisive role in the spatial distribution of DSi. Phosphate in seawater does not exhibit significant vertical or planar differentiation characteristics. The concentration range is 0.004-0.013 mg/L, with an average content of 0.007 mg/L (Figure 3). Phosphate is positively correlated with the distributions of TN and TP. In the previously mentioned study area, phosphorus limitation may primarily be attributed to phosphate as a limiting factor in primary production.

4.2 Sources and impact factors related to the spatial distributions of nutrients

The autumnal spatial distribution of nutrients suggests that the sources and influencing factors for Dissolved Inorganic Nitrogen (DIN), Dissolved Inorganic Phosphorus (DIP), and Dissolved Silica (DSi) vary. The three primary sources of nutrients in the Bohai Sea are typically recognized as land inputs, atmospheric deposition, and sediment release, with the flux through these sources fluctuating based on the type of nutrient and physical-chemical conditions (Liu et al., 2003; Song, 2010). Furthermore, hydrodynamic conditions significantly influence nutrient transport (Millero, 2013). The estuaries of rivers are concentrated along the western coast, such as the Hai River, Chaobai River, and Majia River, which significantly impacts the western coastal waters due to river inputs (Liu et al., 2019). Our research indicates that high values of DIN (Dissolved Inorganic Nitrogen) are consistently observed in the western coastal waters. Atmospheric nitrogen deposition influences the spatiotemporal distribution of DIN in the Bohai Sea, with the Bohai Bay (BHB) being the most polluted region. This is particularly evident in the western coastal waters near Tianjin and Huanghua (Shou et al., 2018). Bohai Sea sediments typically serve as a source of ammonium and a sink for nitrate and nitrite, with ammonium nitrogen accounting for 88% of the benthic flux of DIN, primarily migrating from sediments to seawater (Liu et al., 2011).

The Bohai Bay region is densely populated and highly industrialized, serving as a crucial coastal economic zone connecting the Beijing-Tianjin-Hebei region. However, with rapid economic development, the associated marine environmental pressures have increased, leading to frequent occurrences of marine disasters such as red tides in recent years. Principal Component Analysis (PCA) revealed that temperature is the dominant factor influencing the ecology of coastal waters in the study area during autumn (Figure 4). The temperature along the north-south transect is consistent, with a clear demarcation at 118.68°E (19°C), where the temperature gradient is distinctly higher in the east and lower in the west. We speculate that it is influenced by the convergence of water masses and coastal upwelling because the study area is located near the boundary between coastal riverine freshwater input and nearshore tidal currents, while the topography is higher in the west and lower in the east (Naderian et al., 2025). The temperature variance between the surface and bottom waters is negligible. In the high-temperature eastern region, the redox potential was high (above 100 mV), and very few locations had low dissolved oxygen levels were low, while the redox potential was high (above 100 mV), indicating active aerobic microbial activity (Noori et al., 2018). This leads to the decomposition of large amounts of organic matter, resulting in high ammonia nitrogen content, high CO_2 partial pressure, and low pH. The elevated ammonia nitrogen promotes the growth and reproduction of phytoplankton, leading to a higher diversity and abundance of phytoplankton species in the eastern region compared to the west. The eutrophic layer in the eastern region exhibits weaker nitrification, resulting in lower concentrations of nitrate and nitrite, while the western region, with higher SPM concentrations, promotes nitrification. The growth of phytoplankton increases the COD content in the water. The planar distribution of silicate, SPM, and sulfide is similar. So, we link these parameters due to the combined effects of riverine input, sediment resuspension, and biogeochemical cycling.

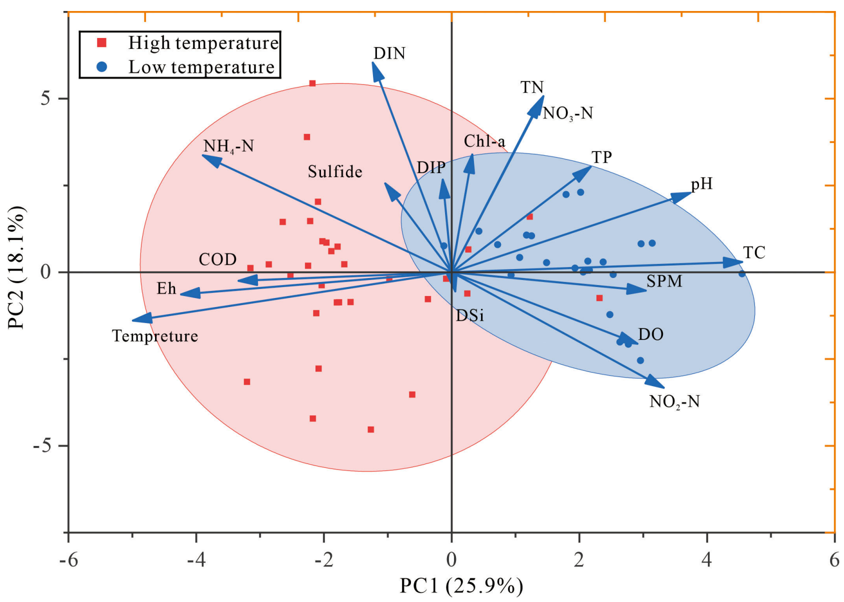

FIGURE 4
Correlation analysis between nutrients and environmental parameters. Blue dots represent high-temperature samples, while red dots represent low-temperature samples. Circles indicate the 95% confidence intervals for the two sample groups.

5 Conclusions

The dominant factor influencing the coastal ecosystem of the Bohai Bay during autumn is temperature. The north-south temperature profile remains consistent, with a demarcation at 118.68°E (19°C), where the east-west temperature gradient exhibits a distinct pattern of higher temperatures in the east and lower temperatures in the west. The temperature difference between the surface and bottom waters is minimal. In the high-temperature eastern region, the redox potential was high (above 100 mV), and very few locations had low dissolved oxygen levels were low, while the redox potential was high (above 100 mV), fostering aerobic microbial activity and the decomposition of abundant organic matter, resulting in elevated ammonia nitrogen concentrations and low pH levels. The proliferation of phytoplankton is stimulated by the high ammonia nitrogen content. The surface seawater in this region exhibits weak nitrification, leading to lower concentrations of nitrate and nitrite. Conversely, the western region, characterized by higher suspended particulate matter concentrations, facilitates nitrification. The global warming trend may alter the nutrient structure of seawater, potentially precipitating a certain degree of ecological crisis.

Data availability statement

The raw data supporting the conclusions of this article will be made available on request.

Author contributions

DB: Conceptualization, Resources, Writing – original draft. HC: Conceptualization, Formal analysis, Funding acquisition, Investigation, Supervision, Writing – original draft, Writing – review & editing. YF: Investigation, Writing – review & editing. LW: Formal analysis, Visualization, Writing – review & editing. MY: Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. This study was jointly funded by the Science and Technology Innovation Foundation of Comprehensive Survey & Command Center for Natural Resources (KC20240016), and the projects from China Geological Survey (grant nos. DD20230073, DD20211553, DD20243124, and DD20220990).

Acknowledgments

The authors would like to express their gratitude to the team members for their assistance in the field work.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Publisher's note

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