Coastal Transformation and PAH Contamination in Bohai Bay (1995-2025): A Remote Sensing and Environmental Assessment

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Abstract. Understanding the relationship between coastline variation and polycyclic aromatic hydrocarbon (PAH) pollution is critical for assessing long-term ecological risks in rapidly industrializing coastal zones. While previous studies have assessed how the Bohai Bay coastline expansion influences the water dynamics and the land-use type, few studies have integrated the spatial-temporal shoreline evolution with pollutant dynamics in the Bohai Bay region. This study addresses that gap by extracting the coastlines from 1995 to 2025 based on Landsat imagery. An unsupervised classification approach named the ISODATA algorithm, guided by the Normalized Difference Water Index (NDWI) calculation results, was employed to differentiate land from water bodies. Then, the automated spatial tools were integrated with manual editing procedures to ensure accurate shoreline extraction. The historical length of shoreline was then combined with the PAH concentration data from existing literature to explore the relationship between coastal change and pollution accumulation. Primary results reveal significant seaward expansion of the coastline, particularly between 2005 and 2015, driven by land reclamation and industrial development. The study also showed an overall increase of traditional polycyclic aromatic hydrocarbons (t-PAHs) concentrations in the marine environment from 1995 to 2020, with high-molecular-weight (HMW) compounds dominating intertidal zones due to their low solubility and sediment affinity. However, a reduction in PAH levels in recent years is expected due to regulatory reforms, improved fuel standards, and reduced coal dependency. The study concludes that coastal geomorphological change is one of the major factors that influences the pollutant distribution and ecological exposure. Its contribution lies in linking geospatial analysis with environmental contamination analysis; it offers a reproducible workflow and highlights the need for continuous in situ monitoring for environmental assessment. These observations support sustainable coastal management and inform policy decisions in marine pollution control.

Keywords: Environmental science, Remote sensing, Marine pollution, Unsupervised classification, PAH, Bohai Bay coastline.

1. Introduction

Coastal zones and bays are among the most economically vital regions on Earth. Their dynamic interfaces between land and sea support dense populations, the formation of industrial hubs, and marine-dependent activities such as aquaculture, shipping, and tourism. However, bay areas are usually vulnerable to environmental changes. Chen et al. indicate that the bay area is relatively shallow and semi-enclosed by land, which restricts its hydrodynamic exchange with the open ocean [1]. Unlike deeper, more dynamic marine systems, the Bay Area lacks strong currents and deep-water circulation. The water in Bohai Bay, for instance, has a transport timescale exceeding one year; this means once the pollutants enter the sea, they tend to stay there for a long time before being diluted or removed.

Polycyclic aromatic hydrocarbons (PAHs) are a class of particle-reactive, hydrophobic organic compounds commonly detected in contaminated coastal waters [1]. Traditional polycyclic aromatic hydrocarbons (t-PAHs) include 16 priority PAHs identified by the U.S. Environmental Protection Agency, including naphthalene, anthracene, and fluoranthene. They are widely studied due to their toxicity, environmental persistence, and carcinogenic potential [2]. Chen et al. indicate that while their environmental bioavailability is generally lower due to poor solubility, they pose significant

bioaccumulation and toxicological risks to aquatic organisms that ingest contaminated materials [1]. Understanding the relationship between coastline evolution and PAH pollution is essential for assessing long-term ecological risks in these rapidly developing coastal zones. Because anthropogenic coastal modifications such as land reclamation, port construction, and urban expansion directly alter sediment dynamics, tidal flows, and pollutant pathways. These changes can intensify the deposition and remobilization of PAHs.

Previous research has explored coastline displacement in Bohai Bay and its consequences. For instance, Sun et al. analyzed changes from 1975 to 2015 using Landsat imagery and Envi software [3]. The study concluded a steady increase in artificial coastlines; it also observed that the coastal construction altered the water dynamics, including an increasing tidal wave amplitude and a decline in the propagation speed of tidal waves. Meanwhile, the sediment size is found to become finer over the study period. Similarly, Feng discussed the coastline change from 1986 to 2016 with emphasis on the spatial-temporal variation of the bay area and land-use type based on the GIS tools [4]. The study revealed a declining trend for the Bohai Bay Area, and a positive correlation between coastline expansion and the growth of aquaculture zones, construction sites, and agricultural land.

This study aims to investigate the impact of anthropogenic activities along the Bohai Bay coastline on PAH concentrations over the period 1995 to 2025. To extract and analyze shoreline changes, a combination of the Normalized Difference Water Index (NDWI) and unsupervised classification techniques will be employed. Coastlines from 1995 to 2025 were extracted using remote sensing images. Image preprocessing was conducted in ENVI, and coastline vectors were then obtained and analyzed. This workflow enabled the quantification of shoreline change and the identification of tiny coastal modifications. The Bohai Bay was selected as the case study because, as one of the three principal bays of the Bohai Sea, it has experienced significant coastal development and land reclamation over recent decades. Despite the PAH emission from these anthropogenic activities, Bohai Bay's shallow water and weak hydrodynamic exchange ability make it susceptible to chemical accumulation. Its semi-enclosed geography and weak circulation result in a prolonged pollutant retention and an amplification of ecological risks over time. Therefore, given its strategic importance, environmental vulnerability, and historical data availability, the Bohai Bay offers an ideal context for assessing how shoreline transformation influences PAH concentration. The primary objectives of this study are as follows: (1) To extract shorelines from 1995 to 2025 using remote sensing imagery; (2) To analyze the spatial-temporal evolution of the coastline; (3) To assess how anthropogenic coastal activities influence t-PAH concentrations in the marine environment; (4) To identify and evaluate the potential sources of PAHs affecting Bohai Bay.

2. Data and Methods

2.1. Study area

Bohai Bay, located in northeastern China and is bordered by Hebei, Shandong, and the municipality of Tianjin. It is a densely populated and economically vital zone. Since the Reform and Opening-Up Policy in 1978, the region has experienced rapid urbanization, with the urbanization rate rising from 17.9% to 63.89% by 2020 [5]. During this period, marine-dependent industries such as aquaculture, port development, and coastal tourism have expanded significantly, intensifying ecological pressures. Meanwhile, large-scale land reclamation has reshaped natural coastlines and reduced wetlands. Between 2000 and 2020, construction land increased by over 2,200 km^2, while farmland and natural habitats declined [7]. These dynamics make Bohai Bay a critical site for assessing the environmental impact of coastal development.

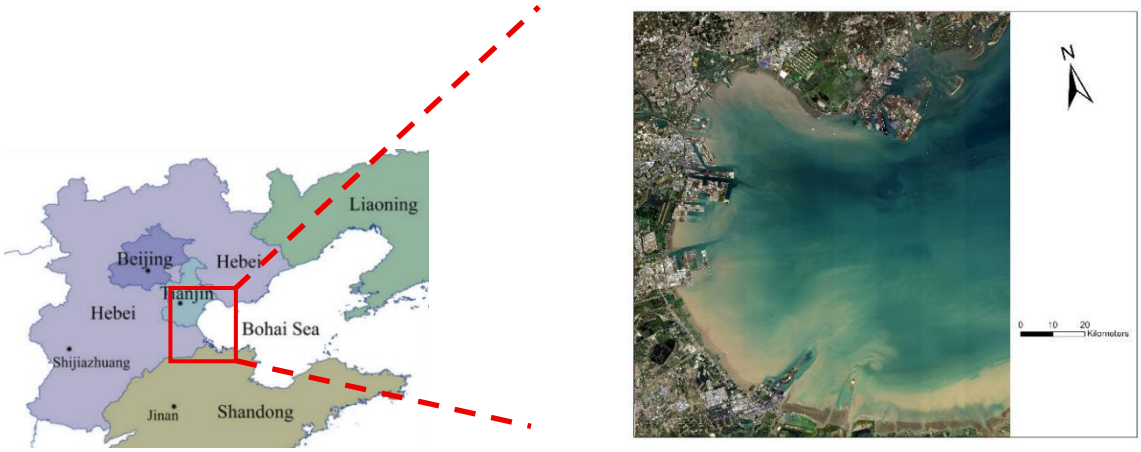


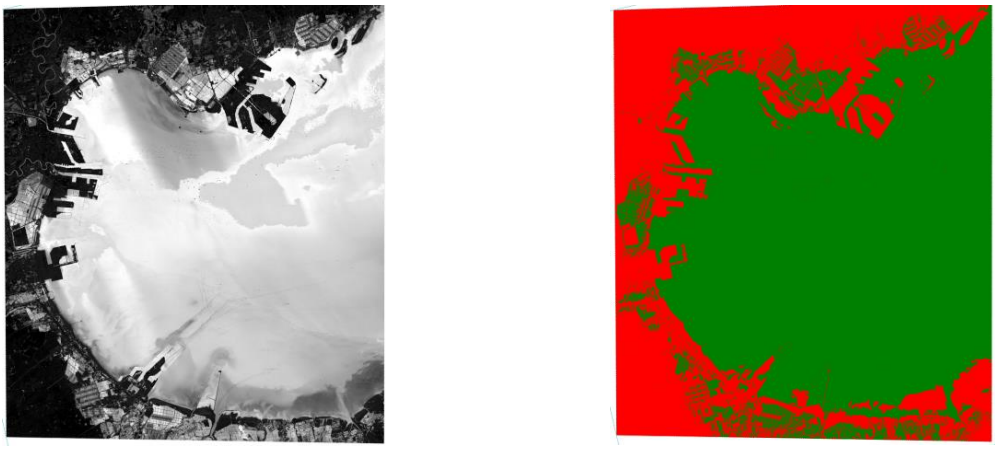
Figure 1. Study area (adapted from [6]) and remote sensing image of Bohai Bay in 2025

2.2. Extraction of the coastline

This study utilized Landsat series remote sensing imagery spanning from 1995 to 2025, from the USGS Earth Explorer platform. The downloaded images were first preprocessed on the Envi platform, key steps including Radiometric Correction, FLAASH Atmospheric Correction, and Image Registration Workflow. In terms of Image Registration, the remote sensing map from 2015 is selected as the base map due to its high spatial resolution and transitional landscape characteristics. At that time, coastal and urban development in Bohai Bay was still underway, resulting in a hybrid landscape where newly developed areas coexisted with the original landscape. This facilitated the identification of consistent features such as buildings and farmland across the entire temporal scale. Then, approximately 40 seed tie points were manually generated for each image based on these stable landscape features, to improve the geometric accuracy of Image Registration across the time series. To ensure the accuracy of the subsequent unsupervised classification, Band Math was used to calculate the NDWI.

$$\mathrm{NDWI} = \frac{(\mathrm{Green}-\mathrm{NIR})}{(\mathrm{Green}+\mathrm{NIR})} \tag{1}$$

The NDWI was calculated using Formula 1. It enhances the detection of open water bodies by exploiting the distinct reflectance properties of water relative to surrounding land and vegetation. Figure 2A shows the result of the NDWI calculation based on the 2015 remote sensing image.



(A) (B)

Figure 2 A. NDWI layer derived from 2015 remote sensing imagery.

Figure 2 B. Unsupervised classification result of 2015 remote sensing imagery.

Then, based on the NDWI layers, the study employed the ISODATA algorithm for unsupervised classification, with the number of iterations set to 80. It is an iterative clustering algorithm that

repeatedly refines classification results by grouping pixels with similar spectral characteristics. It is particularly effective for remote sensing applications where labeled training data are unavailable [8]. Therefore, it allows the identification of meaningful land cover categories such as water and urban areas. Since the study focuses on coastline extraction, the classification was simplified to two categories: Land and Waterbody. Figure 2B shows the result of classification for images of the year 2015. Then, the resulting raster layer was converted into vector format and imported into ArcGIS Pro for further spatial processing. Coastlines were extracted using the Polygon to Line tool, and manual editing, such as Split and Create features, was applied to ensure the coastline captured fine-scale features such as artificial aquaculture zones.

2.3. Pristane/Phytane (Pr/Ph) ratio

In marine contamination studies, the Pr/Ph ratio is useful for distinguishing between petrogenic and biogenic sources of hydrocarbons.

$$\text{Pr/Ph Ratio} = \frac{\text{Concentration of Pristane in Samples}}{\text{Concentration of Phytane in Samples}}$$

Specifically, it determines whether the hydrocarbons are derived from petroleum and fossil fuels or produced by natural biological processes, such as the degradation of plants. A PR/PH ratio between 3 and 5 indicates uncontaminated water and a predominance of terrestrial or biogenic input, while a ratio less than 1 suggests the appearance of petroleum-related contamination. This diagnostic tool complements PAH profiling by helping to trace the origin of organic pollutants in sediment samples.

3. Results and Discussion

3.1. Spatial-temporal change of the Bohai Bay's coastline

The study concluded that the length of the coastline in Bohai Bay increased during the period from 1995 to 2025. The temporal trend in coastline length is demonstrated in Figure 3D. From 1995 to 2000, no significant changes in coastline length were observed. However, beginning in 2000, a gradual expansion commenced, with a growth rate approaching 20%. A pronounced surge occurred between 2005 and 2010, during which the coastline length increased by 58.26%. Between 2010 and 2020, the rate of expansion slowed to 21.61%. From 2020 to 2025, the coastline length remained relatively stable, with measurements of 727.40 km in 2020 and 742.58 km in 2025. The increase in shoreline length reflects the influence of large-scale land reclamation and coastal infrastructure projects, particularly during the mid-2000s, followed by a phase of slowed shoreline modification in recent years.

Analysis of the spatial-temporal evolution of Bohai Bay's coastline further reveals a distinct pattern of seaward expansion, illustrated by Figure 3C. In 1995, large-scale land reclamation had not yet commenced in Bohai Bay. Figure 3B indicates the coastline remained natural or semi-natural, dominated by tidal flats, wetlands. Small-scale aquaculture ponds and salt fields are observed along the coastline. By 2000, large-scale land reclamation projects were initiated, with two major industrial zones Caofendian District and Tianjin Port, entering the early stages of development. By 2005, reclamation activities had intensified. The construction of dikes, embankments, and artificial platforms at Caofeidian and Tianjin Port visibly pushed the shoreline seaward. In 2010, the shoreline expansion became more pronounced, motivated by land reclamation for petrochemical industries, coastal infrastructure, and tourism. In addition to ongoing development at Caofeidian, Tianjin Port, and Huanghua Port, several recreational facilities, including coastal parks and the Tianjin National Maritime Museum, were under construction on reclaimed land. Yang et al. reported that between 1995 and 2010, over 450 km² of offshore area was reclaimed, including 218 km² of intertidal flats, which accounted for nearly one-

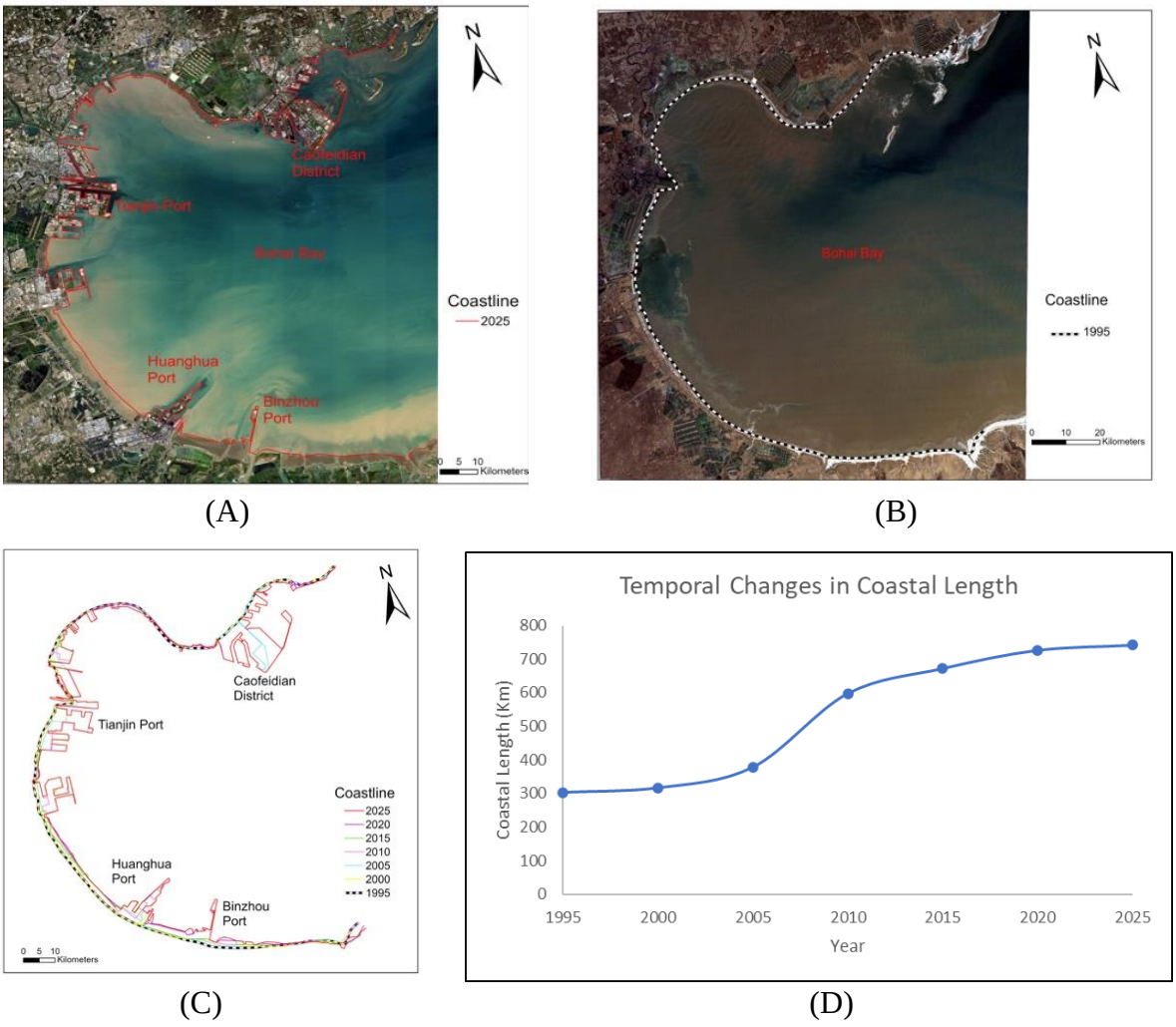


Figure 3. (A) The coastline position in 2025; **(B)** The coastline position in 1995; **(C)** The spatial variation of Bohai Bay coastline from 1995 to 2025; **(D)** The temporal trend in Bohai Bay coastal length from 1995 to 2025.

-third of the original tidal zone [9]. By 2015, major coastal construction projects were completed, and zones such as Caofeidian Industrial Area and Tianjin Port were in operation. Zhu et al. state that Tianjin Port is a massive port and coastal industrial zone; its total planned reclamation area is 2,270 km^2 [10]. Meanwhile, large-scale pond systems were established on reclaimed land. Wang and Liu indicate that there was a 538% increase in aquaculture area between 2005 and 2015 [11]. Huang et al. further observed that the land reclamation rate reached its peak, which is 150.9 km² per year, positioning Bohai Bay as one of China's most rapidly transformed coastal regions [12]. By 2015, artificial coastlines accounted for more than 95% of the total shoreline in Bohai Bay [3]. In 2020, construction of the new Binzhou Port was underway, and Tianjin Port's cumulative reclamation area had reached 201.03 km² by 2018. Compared to 2020, no significant changes in coastline configuration were observed in 2025. As illustrated in Figure 3A, the current status of the Bohai Bay area reflects the substantial transformation since 1995. In addition to a marked urban expansion, extensive infrastructure development has occurred along the coastline, including the construction of industrial zones and port facilities. Zhu et al. indicate that post-2020, the land reclamation entered a phase of deceleration and fine management, as government policies began emphasizing optimization of land use and ecological mitigation. Nevertheless, the Bohai Sea Port Development Plan outlines continued expansion. The port area will continue to expand and will reclaim an area of approximately 620.4 km^2 by 2030 [10]. The planned reclamation areas include 122.8 km² for Binzhou Port and 79.8 km² for Huanghua Port. The reclamation intensity in these zones exceeds 8 ha/km. Between 2000 and 2010, Cui et al. concluded that there was a rapid expansion of construction land across the Bohai Bay

region, accompanied by a marked decline in natural wetlands [7]. This trend reflects the intensification of land reclamation and urban development during the early stages of industrialization of Bohai Bay. From 2010 to 2020, the proliferation of artificial wetlands further contributed to the increase in built-up land area. Meanwhile, the forest areas experienced a reduction, partly due to conversion into agricultural land to support regional food production and urban demand.

3.2. Influence of coastline expansion on the t-PAHs concentration

Decades of intensive coastal construction and industrial development have shaped the Bohai Rim Region into a major economic hub. However, this transformation has also led to Bohai Bay exhibiting some of the highest concentrations of PAHs among China's coastal waters [6]. This is partially because of the contamination derived from the industrial activities along the shore. For example, Zeng et al. identified Caofeidian District as a dominant source of PAHs as of 2020, with industrial emissions and petroleum volatilization contributing 44% and 30% of total PAH loads, respectively [13]. Followed by shipping activities and coal combustion, which take 15% and 11%. Historical data and sediment sampling across the Bohai Bay region reveal an increasing trend in the concentrations of t-PAHs from 1995 to 2020, with peak levels observed around 2020 [2].

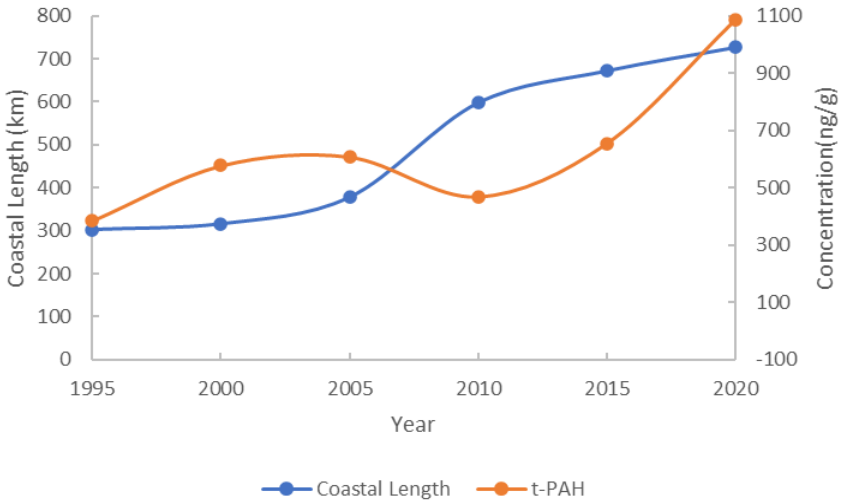


Figure 4. Temporal variation of Bohai Bay coastline length and t-PAH concentration from 1995 to 2020.

The historical concentration of t-PAHs, as shown in Figure 4, reveals an overall increasing trend from 1995 to 2020, with notable fluctuations around 2010. Between 1995 and 2005, during the initial phase of land reclamation along the Bohai Bay coastline, a modest increase in reclaimed shoreline corresponded with a moderate rise in t-PAH concentrations, from approximately 400 ng/g to 600 ng/g. From 2005 to 2010, there was a rapid coastal expansion occurred along the Bohai coastline. However, t-PAH levels unexpectedly declined. This inverse response is likely attributed to changes in hydrodynamic conditions caused by large-scale land reclamation and port development, which may have altered tidal flows and current patterns. Such modifications could have diluted PAH concentrations in surface waters or redistributed them away from sampling locations. Following this period, the continued anthropogenic activity evidenced by the sustained coastline growth contributed to renewed PAH accumulation, causing it to surge to approximately 1000 ng/g by 2020.

Among t-PAHs, approximately 50% of detected compounds were four-ring structures, specifically fluoranthene and pyrene, while 23% of them were three-ring compounds, such as phenanthrene and anthracene. Since the 1980s, the proportion of HMW t-PAHs has steadily increased, with HMW compounds accounting for roughly 81% of total t-PAHs detected in Bohai Bay [2]. The HMW t-PAHs are highly persistent and tend to accumulate in intertidal zones such as rocky shores and beaches due to their low solubility and mobility in water. In contrast, LMW t-PAHs are more soluble and volatile, allowing them to disperse farther offshore and accumulate in open water areas.

Before the mid-1970s, PAH concentrations in China increased moderately due to geopolitical disruptions such as World War II and the Civil War, which curtailed industrial activity and energy consumption. After the 1978 Reform and Opening-Up policy, rapid industrialization and urbanization caused intensified coal and petroleum combustion, especially in coastal cities like Tianjin and Tangshan. Bohai Bay emerged as a major logistics hub, and the expanded ports and land reclamation motivated the increased PAH levels in coastal waters. Since the 2000s, although the energy consumption has continued to grow, the rate of PAH accumulation has slowed due to government regulation.

3.3. Potential Source of PAH along the Bohai Bay coastline

Rapid industrialization around the Bohai Rim Region has led to the construction of more than 11 major ports along the Bohai Sea shoreline, including Tianjin Port, each with cargo handling capacities exceeding 100 million tons per year [6]. These ports, along with other coastal industries, have significantly degraded air and marine environments through emissions generated during vessel maintenance, engine operation, and dockside machinery use. Scrubbers are systems installed on ships to remove sulfur oxides and other pollutants from exhaust gases, and they are commonly used near port areas. However, Wu et al. indicate that the scrubbing process produces wash water enriched with PAHs, which is often discharged directly into the marine environment [6]. The maritime corridor connecting Caofeidian District, Tianjin Port, and Huanghua Port is particularly active, with vessels transporting coal, petroleum products, fertilizers, grain, ores, and containers. Ships typically burn fuel oil, and the incomplete combustion of fossil fuels releases PAH-enriched atmospheric particles. Dockside machinery, including cranes, loaders, and diesel trucks also powered by diesel or heavy fuel oil. These machines emit toxic gases rich in HMW PAHs such as benzo[a]pyrene and fluoranthene. These PAHs are released as fine particulate matter (e.g., PM2.5), which subsequently settles into nearby waters and sediments. Therefore, both atmospheric deposition and wastewater discharge contribute to PAH accumulation in coastal sediments. Zhu et al. estimate that approximately 5.94 tons of PAHs are released into Bohai Sea waters annually via particulate matter generated from port activities, atmospheric deposition, direct discharge, and coastal runoff [10].

Land reclamation activities further exacerbate PAH contamination. The industrial waste and construction debris generated from the land reclamation process may contain PAHs that then leach into the surrounding water. Huang et al. proposed that altering coastline geometry through tidal flow obstruction, artificial embankments, and seawall construction can disrupt nearshore hydrodynamics [12]. Since the redirected currents can lift sediments into the water column, legacy PAHs stored in sediments are remobilized and added to the current pollutant load. Moreover, the reclamation process can create semi-enclosed basins with reduced flushing and dilution capacity, which facilitate the accumulation of PAHs from coastal runoff and heavy industrial discharge in intertidal and nearshore zones.

Petroleum-related activities represent another significant source of PAH contamination in the Bohai Sea. Wu et al. confirmed that the unintentional or accidental oil spills, diesel leakage, and oil seepage from industrial activities have caused high PAH concentrations in coastal sediments, particularly in the seaport, fish landing harbors, and ship-breaking yards [6]. Recently, an investigation regarding the presence of exogenous petroleum pollution was conducted in the Bohai Sea. The study found the PR/PH ratios at most sampling sites were near 1 [14]; this confirms the presence of external petroleum inputs likely originating from shipping activities, oil spills, and industrial discharge. According to statistics, oil spill accidents occurred almost every year in the Bohai Sea from 2009 to 2018 [14]. These spills, combined with daily maritime operations, increase the risk of PAH enrichment in sediments and the broader marine environment.

To mitigate PAH concentration in the Bohai Sea, China has implemented several regulatory measures. Illegal PAH emissions are now prohibited, and the *2013 Air Pollution Prevention and Control Action Plan* aimed to reduce coal dependency and improve the fuel quality. By 2019, coal's share in energy consumption dropped from 67.4% to 57.7%, and 86% of coal-fired power plants were

upgraded to meet stricter emission standards. The rise of electric vehicles, reaching 3.81 million by 2019, also helped reduce PM2.5 emissions, which carry HMW PAHs [6]. A declining trend in PAH concentrations has been observed in recent years, which reflects the effectiveness of regulatory interventions.

4. Conclusion

This study analyzes the spatial-temporal evolution of the Bohai Bay coastline from 1995 to 2025 and its relationship with t-PAH contamination. Landsat imagery and geospatial tools reveal a seaward shoreline expansion driven by industrialization, land reclamation, and urban growth. These factors have contributed to the accumulation of HMW t-PAH, as they have been linked to coastal industrial emissions and reclamation-induced sediment resuspension. Although PAH concentrations in Bohai Bay remain elevated, recent regulatory interventions have contributed to a downward trend.

The study is based on data and findings from previous research, primarily spanning the years 2000 to 2022. To improve the temporal resolution and reliability of environmental assessments, future investigations should incorporate in situ sampling and laboratory-based chemical analyses. These approaches are essential for capturing real-time pollutant dynamics and validating remote sensing interpretations. Moreover, urban expansion and farmland conversion also warrant investigation for their impact on the marine environment. Emerging tools like Google Earth Engine (GEE), combined with machine learning models such as CNNs (convolutional neural networks) and XGBoost, could significantly improve the efficiency and precision of coastal pollution assessments.

Overall, this study highlights the complex interplay between coastal development and marine pollution, emphasizing the importance of integrated spatial-temporal analysis, long-term maritime environment monitoring, and sustainable management strategies to protect the Bohai Sea's ecological integrity.

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