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RECEIVED 11 June 2025

ACCEPTED 03 September 2025

PUBLISHED 17 September 2025

CITATION

Ji X, Ding X, Hu W and Qiu Y (2025)
The effect of shipping efficiency on marine
petroleum pollution: an empirical analysis
of China's 11 coastal regions.
Front. Mar. Sci. 12:1645175.
doi: 10.3389/fmars.2025.1645175

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The effect of shipping efficiency on marine petroleum pollution: an empirical analysis of China's 11 coastal regions

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Introduction: Marine petroleum pollution has adversely affected marine ecosystems and human living environments, while improvements in shipping efficiency offer a new avenue for mitigating such pollution.

Methods: Based on panel data from 11 coastal regions in China spanning 2010 to 2022, this study examines the impact mechanisms of shipping efficiency on marine petroleum pollution and further analyzes the moderating effects of port specialization and environmental regulation.

Results: The results indicate that, overall, shipping efficiency in coastal regions has shown a steady upward trend, with an average efficiency index of 1.046 and an annual growth rate of 4.6%. However, some regions, such as Liaoning, Shandong, and Tianjin, have experienced declines in efficiency, highlighting regional disparities in development. Regression analysis reveals a significant negative relationship between shipping efficiency and marine petroleum pollution. The two-way fixed effects model shows that a 0.01 increase in shipping efficiency corresponds to an approximate 0.01% reduction in marine petroleum pollution, suggesting that enhanced shipping efficiency effectively contributes to improving marine environmental quality. Furthermore, the moderating effect analysis demonstrates that both port specialization and environmental regulation exert significant negative moderating effects on the relationship between shipping efficiency and marine petroleum pollution.

Discussion: Overall, this study enriches the theoretical understanding of the relationship between the operational efficiency of transport infrastructure and environmental pollution and provides robust empirical support for formulating green and efficient shipping policies and advancing sustainable marine environmental governance in coastal regions.

KEYWORDS

shipping efficiency, marine petroleum pollution, fixed effect, moderating effect, coastal regions

1 Introduction

Marine pollution has become one of the most significant challenges to global environmental security. By disrupting and even degrading marine ecosystems, it poses a severe threat to marine biodiversity and has profound impacts on human living environments (Bani Hani et al., 2019). According to a report by the Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP), more than 80% of marine pollution originates from land-based sources, with petroleum pollution being one of the most significant forms (United Nations Environment Programme (UNEP), 2021). It is estimated that approximately 1.5 to 10 million tons of petroleum hydrocarbons enter the marine environment each year, primarily resulting from anthropogenic activities, including untreated wastewater discharges, municipal and industrial runoff, and offshore and onshore petrochemical operations (Varjani and Upasani, 2017; Hazaimah and Ahmed, 2021). These pollutants, often consisting of persistent and recalcitrant compounds, alter the physical and chemical properties, including viscosity, of seawater, thereby posing a high risk to marine ecosystems (Yan et al., 2019).

The ecological impacts of petroleum pollution are highly complex, characterized by the multidimensional nature of its pollution mechanisms, the staged responses of ecosystems, and the long-term nature of ecosystem recovery processes. This implies that once ecological damage occurs, restoration often requires considerable time and incurs high ecological costs (Da Silva et al., 1997; Dey et al., 2023). Although the hazards of petroleum pollution have attracted widespread attention, existing research has predominantly focused on the following aspects: first, the sources of petroleum pollution (Latimer et al., 1990; Zhang et al., 2007; Guo et al., 2022); second, the removal and remediation of petroleum pollution (Das and Chandran, 2011; Mohammadi et al., 2020); third, the toxic effects and structural damage of petroleum pollution on ecosystems (Gao et al., 2022; Koduvayur Habeebullah et al., 2025; Mohanta et al., 2024); and fourth, the potential threats of petroleum pollution to human health (Freije, 2015; Adipah, 2019). In summary, although current research has provided substantial evidence regarding the micro-level mechanisms of petroleum pollution, the relationship between pollution sources and macro-level structural variables remains underexplored, highlighting the urgent need for further in-depth analysis of the driving factors behind marine petroleum pollution.

At present, research specifically addressing the drivers of marine petroleum pollution remains limited, with most existing studies focusing on the broader determinants of marine pollution and examining them from multiple perspectives. The literature indicates that the level of economic development and regional characteristics are important variables influencing marine pollution (Wang et al., 2020). While the growth of the marine economy has contributed positively to industrial upgrading, its impact on the discharge of marine pollutants (such as industrial wastewater) exhibits certain nonlinear characteristics (Hou and Zhan, 2023). In addition, typical marine industries such as coastal tourism, mariculture, and shipbuilding exert direct pressure on the aquatic environment and are widely recognized as key contributors to water quality degradation (Ji and

Ding, 2024a; Yu et al., 2024). Trade liberalization is also viewed as an external shock variable that exacerbates pollution (Ullah et al., 2023), while seafood trade has been found to exert a dual effect—intensifying pollution pressures in the short term but promoting sustainable governance in the long term (Liu F. et al., 2022). At a deeper level, the extensive use of fossil fuels and the lag in environmental governance capacity constitute fundamental causes of the persistent nature of marine pollution (Alsaleh and Abdul-Rahim, 2024). It is worth noting that shipping, as an integral part of coastal and marine development, exerts significant direct and indirect impacts on the marine environment (McConnell, 2002; Venkatesh et al., 2017). However, current research still lacks a systematic perspective on how shipping influences marine petroleum pollution, with its theoretical mechanisms and empirical pathways remaining insufficiently explored.

Building on this foundation, this study aims to achieve the following three specific research objectives: (1) to construct an integrated analytical framework from the perspective of shipping operational efficiency, systematically examining the mechanisms through which shipping efficiency affects marine petroleum pollution, thereby addressing the lack of holistic framework-based analysis in existing research; (2) to empirically test the actual impact of shipping efficiency on land-based marine petroleum pollutant emissions using panel data from 11 coastal regions in China covering the period 2010–2022, providing quantitative evidence for pollution control; and (3) to focus on analyzing the moderating roles of port specialization and environmental regulation in the relationship between shipping efficiency and marine petroleum pollution, identifying key external conditions that influence emission reduction effectiveness and enriching the theoretical understanding of pollution mitigation mechanisms.

2 Literature review

2.1 Related research on the impact of transportation infrastructure on environmental pollution

The relationship between transportation infrastructure and environmental pollution has been the subject of extensive academic inquiry. Makarova et al. (2020) highlight the negative environmental impacts of urban motorization, particularly noise pollution and vehicle emissions, and emphasize the critical role of transportation infrastructure and management systems in regulating traffic flow and mitigating environmental effects. Research indicates that optimizing infrastructure in key corridors can effectively enhance traffic efficiency and alleviate environmental pressure. Xie et al. (2016) demonstrate that transportation infrastructure exerts significant direct negative effects on the urban environment and generates adverse spatial spillover effects on surrounding areas. Similarly, Y. Guo et al. (2020) point out a nonlinear relationship between transportation investment and air quality, identifying vehicle density as a key moderating variable: in areas with low vehicle density, transportation investment improves air quality, whereas in high-density areas, it may lead to

environmental degradation. The differentiated environmental impacts of various transportation modes have also received considerable scholarly attention. Erdogan (2020), using data from OECD countries, finds that rail investment helps mitigate environmental pollution, while investment in road and air transport significantly exacerbates carbon emissions. Liu Y. et al. (2022), in testing the Environmental Kuznets Curve (EKC) hypothesis, also concludes that rail investment suppresses environmental degradation. Likewise, Wang et al. (2023) further confirm that investments in different types of transportation infrastructure have markedly divergent environmental impacts: rail investment contributes to emissions reduction, whereas road and air investments tend to worsen pollution. Focusing on developing countries, Dzator et al. (2021) report that both air and rail infrastructure contribute to increased carbon emissions, particularly in nations where the energy structure has not yet transitioned toward greener sources; in such contexts, rail infrastructure may even intensify the relationship between per capita GDP and carbon emissions. Meanwhile, Acheampong et al. (2022), employing a system GMM approach, reveal an inverted U-shaped relationship between rail and freight infrastructure investment and carbon emissions, suggesting that moderate investment can achieve emissions reduction, whereas excessive investment may have counterproductive effects. Wang and Wang (2023) constructed a maritime supply chain model comprising ports, shipping companies, and freight forwarders under the background of green maritime transportation, focusing on the impact of green investment in transportation infrastructure and vertical alliances on the mitigation of shipping pollution. The study finds that the construction of green transportation infrastructure, when combined with coordinated governance across upstream and downstream enterprises, can significantly reduce shipping emissions. Furthermore, some studies have explored the indirect pathways through which transportation infrastructure affects the environment. For instance, Sun C. et al. (2019) show that road infrastructure can lower pollution intensity and enhance urban green development by fostering green technological innovation and promoting regional integration. Sun D. et al. (2019) find that rail transit offers a significantly greater marginal benefit for improving air quality compared to road improvements, although its construction phase may introduce short-term negative environmental impacts.

It is worth noting that Lo Storto and Evangelista (2023) is among the few studies that examine the relationship between transport infrastructure efficiency and environmental outcomes. This study employs Data Envelopment Analysis (DEA) to assess the efficiency of road and rail infrastructure and constructs an environmental impact index based on greenhouse gas emissions and major air pollutants. The findings reveal that few countries can simultaneously enhance the operational efficiency of transport infrastructure while reducing its environmental impacts. Moreover, the study highlights that in most countries, policymakers often struggle to clearly distinguish between the objectives of improving efficiency and reducing pollution when formulating policies.

2.2 Related research on petroleum pollution

As one of the core variables in this study, petroleum pollution has long attracted widespread academic attention due to its significant negative environmental impacts. Current research on petroleum pollution mainly focuses on its sources, environmental impact mechanisms, and governance strategies. From the perspective of pollution sources, petroleum pollution primarily stems from human activities, with substantial leakage and discharge risks occurring during oil exploration, extraction, transportation, and refining processes (Sharma et al., 2024; Zhang et al., 2019). In addition, municipal and industrial wastewater discharges, surface runoff, and petrochemical operations in coastal and inland areas are also recognized as major land-based contributors to marine petroleum pollution (Hazaimeh and Ahmed, 2021). According to the GESAMP report, over 80% of marine pollution originates from land-based sources, with petroleum pollution identified as one of the main pollutants. The Global Program of Action for the Protection of the Marine Environment from Land-based Activities (GPA) also lists petroleum hydrocarbons among the nine major categories of land-based pollutants. In terms of pollutant characteristics, petroleum pollutants are chemically complex and include substances such as crude oil, heavy fuel oils, and highly toxic light fuel oils. Their main components are hydrocarbons, which exhibit notable persistence and resistance to degradation, allowing them to remain in sediments and ecosystems for extended periods (Blumer and Sass, 1972). Furthermore, the petroleum refining and petrochemical industries are significant sources of hazardous air pollutants, including polycyclic aromatic hydrocarbons (PAHs), heavy metals, and other volatile organic compounds (VOCs), posing dual threats to atmospheric quality and public health (Tavella et al., 2025). Numerous studies have further elucidated the environmental impacts of petroleum pollution from both regional and specific pollution perspectives. For example, Ejiba et al. (2016), using the Niger Delta as a case study, highlighted that oil spills and gas flaring are key drivers of local environmental degradation. Although companies often attribute spills to sabotage, aging infrastructure and management negligence are also critical contributing factors. Ekpenyong and Udofia (2015), in their assessment of water quality in oil-producing regions, found significantly elevated concentrations of heavy metals such as lead (Pb), cadmium (Cd), chromium (Cr), and nickel (Ni), with overall water quality parameters falling well below acceptable standards—indicating severe impacts on the aquatic environment. Habeebullah et al. (2025) take the northwestern Arabian Gulf as a case study and find that total petroleum hydrocarbon contamination in marine sediments is severe, with concentrations in some samples exceeding moderate pollution thresholds by several orders of magnitude, thereby significantly heightening ecological risks. The study indicates that even in designated marine protected areas, petroleum-based pollutants may continue to pose a persistent threat to ecosystem health. Petroleum pollution causes not only physical ecological damage but also profound human health effects.

Nriagu et al. (2016) found that exposure to petroleum pollution induces physical health symptoms, functional impairments, and significantly increases psychological burdens, including fear, irritability, and emotional disorders. Buonocore et al. (2023), in their assessment of emissions from the U.S. oil and gas industry, emphasized that reducing such emissions can yield substantial public health benefits in addition to mitigating climate change. At the ecosystem level, petroleum pollution exerts destructive effects on both terrestrial and marine life. Ozigis et al. (2020) reported that oil spills alter the spectral reflectance of forest and grassland vegetation, leading to marked declines in vegetation health. Walker et al. (2006) found that in areas near oil and gas facilities, lichen community diversity significantly decreased, and soil concentrations of lead and nitrogen increased—early indicators of soil ecosystem disturbance due to petroleum-related activities. During transportation, petroleum spills likewise pose major environmental risks. Jha and Dahiya (2022) underscored the high toxicity and broad ecological destructiveness of petroleum spills, which can impact a wide range of species, including fish, seabirds, invertebrates, and phytoplankton. While land-based spills tend to be localized events, they can still alter microbial community structures. Marine oil spills, however, are subject to greater uncertainties due to factors such as weather and currents, making their prediction and management more challenging. Samsuria et al. (2025) comprehensively reviewed the threats posed by petroleum pollution in aquatic environments to human health, aquatic ecosystems, and economic activities, noting that under the combined effects of meteorological and hydrological factors, petroleum pollutants are more prone to dispersion, persistent retention, and enhanced toxicity—potentially resulting in long-term environmental burdens in the absence of effective monitoring and governance. Adeola et al. (2022), from the perspective of developing countries, emphasized that although petroleum development generates fiscal revenues, it also degrades land, pollutes water resources, and undermines livelihoods. In contexts of weak regulation and corporate malpractice, issues of resource misallocation and environmental degradation are particularly severe.

2.3 Research gap

The research gap in this study is mainly reflected in the following three aspects, which form the basis for the corresponding research objectives. First, although existing studies have explored the relationship between shipping activities and environmental pollution, they lack a unified analytical framework from the perspective of shipping efficiency to systematically reveal the mechanisms through which it affects marine petroleum pollution. To fill this gap, this study proposes a comprehensive theoretical framework that clarifies the pathways through which shipping efficiency influences marine pollution, providing new theoretical insights to the field. Second, the current literature primarily focuses on the impact of shipping on air pollution, while insufficient attention has been given to land-based marine

petroleum pollution, a type of pollution that is more ecologically sensitive and more challenging to manage, thus limiting the applicability of related findings. To address this shortcoming, this study uses empirical data to systematically evaluate the effect of shipping efficiency on land-based marine petroleum pollutant emissions, thereby broadening the scope and depth of environmental pollution research. Finally, existing studies offer limited exploration of the transmission channels through which shipping efficiency contributes to marine petroleum emission reduction and how external conditions moderate this process. Therefore, this study identifies the key mechanisms at play and places particular emphasis on empirically examining the moderating effects of port specialization and environmental regulation, aiming to deepen the theoretical understanding of pathways for achieving pollution reduction.

3 Methodology and data

3.1 Econometric model

3.1.1 Benchmark regression model

To assess the impact of shipping efficiency on marine petroleum pollution, this study employs models with individual fixed effects (Equation 1), time fixed effects (Equation 2), and two-way fixed effects (Equation 3). The model is specified as follows:

$$PET_{it} = \alpha + \beta SE_{it} + \delta X_{it} + \mu_i + \varepsilon_{it} \quad (1)$$

$$PET_{it} = \alpha + \beta SE_{it} + \delta X_{it} + v_t + \varepsilon_{it} \quad (2)$$

$$PET_{it} = \alpha + \beta SE_{it} + \delta X_{it} + \mu_i + v_t + \varepsilon_{it} \quad (3)$$

In this model, for coastal province or city i and year t , PET_{it} represents the level of marine petroleum pollution in the respective province or city, while SE_{it} denotes shipping efficiency. X_{it} is a vector of control variables, including marine economic development, technological innovation, population size, and industrial structure. μ_i represents province/city fixed effects, which account for all time-invariant regional heterogeneity factors, such as natural conditions and cultural background. v_t captures year fixed effects, controlling for the influence of unobserved time-varying factors, such as economic growth and policy adjustments. ε_{it} is the random error term.

3.1.2 Moderating effect model

To further examine the moderating effects of port specialization (Equation 4) and government environmental regulation (Equation 5), this study constructs the following moderating effect models:

$$PET_{it} = \alpha + \beta SE_{it} + \lambda PSI_{it} + \theta SE_{it} \times PSI_{it} + \delta X_{it} + \mu_i + v_t + \varepsilon_{it} \quad (4)$$

$$PET_{it} = \alpha + \beta SE_{it} + \lambda ER_{it} + \theta SE_{it} \times ER_{it} + \delta X_{it} + \mu_i + v_t + \varepsilon_{it} \quad (5)$$

Where, PSI_{it} denotes the port specialization index, and $SE_{it} \times PSI_{it}$ is the interaction effect between shipping efficiency and the

port specialization index. ER_{it} represents the intensity of environmental regulation, and $SE_{it} \times ER_{it}$ captures the interaction effect between shipping efficiency and environmental regulation intensity. The remaining variables are consistent with those in (Equation 3).

3.2 Variable selection and data sources

3.2.1 Dependent variable

The dependent variable in this study is marine petroleum pollution. With continuous population growth, accelerating urbanization, and increasingly intensive industrial activities, estuarine regions are facing escalating challenges of water pollution (Niu et al., 2021). As critical transitional zones between land and sea, estuaries have become primary pathways through which land-based pollutants enter marine ecosystems, posing significant threats to coastal and marine environments (Li et al., 2023). In particular, the discharge of large volumes of organic pollutants into water leads to rapid depletion of dissolved oxygen during aerobic decomposition, thereby severely disrupting the habitats of aquatic organisms (Lim et al., 2006). Notably, the petrochemical industry, as a key pillar of China's coastal economy, entails considerable risks of organic pollutant emissions throughout its production, processing, and transportation processes, with petroleum-based pollutants being the most prominent (Crain et al., 2009; Zhao et al., 2020). Considering this, following Ji and Ding (2024); Liu et al. (2011) and Peng (2015), this study adopts the volume of land-based marine petroleum pollutant emissions in China's coastal regions as the indicator for marine petroleum pollution. The data are sourced from The Bulletin of Marine Ecology and Environment Status of China.

3.2.2 Independent variable

The independent variable is shipping efficiency. Shipping efficiency refers to the ratio of inputs to outputs in waterway transportation within port cities (including ports and shipping companies), reflecting the overall level of resource allocation and utilization (Wu and Wang, 2022). In recent years, driven by national economic growth and supportive policies, China's shipping industry has experienced rapid development. Leveraging advantages such as low cost, large transport capacity, and broad coverage, the industry now handles approximately 90% of the country's import and export freight, playing a crucial role in supporting foreign trade and contributing to national economic and social development (Chen et al., 2024; Wang et al., 2025). However, challenges related to resource waste and insufficient output in resource allocation persist within the shipping sector (Jian et al., 2022). Analyzing and enhancing shipping efficiency is therefore essential not only for optimizing transportation resource allocation and reducing operational costs but also for strengthening China's competitiveness and standing in global markets with respect to resource utilization. To construct a sound indicator system for measuring shipping efficiency, this study reviews

relevant literature on efficiency evaluation in the port and shipping sector. Table 1 summarizes commonly used input and output variables in existing studies, providing a theoretical foundation for the analysis.

At present, there is limited research on the measurement of shipping efficiency. This study adopts the shipping efficiency indicators proposed by Wu and Wang (2022). According to the Solow growth model, the input factors driving economic growth include capital and labor. In addition, a review of relevant literature indicates that berth length and the number of berths is also important input variables. Therefore, this study considers input variables from three dimensions: infrastructure, capital investment, and labor. Specifically, the number of berths, berth length, fixed asset investment in waterway transportation, and the number of employees in the water transport industry are selected as input variables. For output variables, the study uses waterway cargo throughput and waterway cargo turnover. Waterway cargo throughput serves as an indicator of shipping operational capacity, production scale, and efficiency, directly reflecting the capabilities and competitiveness of the shipping industry (Ding et al., 2025). Waterway cargo turnover captures both the volume of transport and the transport distance, providing a comprehensive measure of the production outcomes of waterway transportation (Ma, 2021). All data used to calculate shipping efficiency are sourced from the China Port Yearbook.

This study employs the DEA-Malmquist index method to measure shipping efficiency across 11 coastal regions in China, including Zhejiang, Tianjin, Shanghai, Shandong, Liaoning, Jiangsu, Hebei, Hainan, Guangxi, Guangdong, and Fujian, from 2010 to 2022. The Malmquist index was originally proposed by Swedish economist and statistician Malmquist, and Caves et al. (1982) subsequently applied it to assess changes in productivity. Later (Charnes et al., 1997), integrated the index with the DEA model, leading to the development of the DEA-based Malmquist index method (Lu and Wang, 2023).

Unlike the traditional DEA model, which can only conduct static efficiency analysis, the DEA-Malmquist index method can handle datasets with multiple inputs and outputs and enables dynamic evaluation of productivity changes across different time periods, thereby offering a more comprehensive perspective for analyzing the sources of efficiency variation (Färe et al., 1997; Thrall, 2000; Nguyen et al., 2021; Zhang, 2021). The Malmquist Productivity Index (MPI) consists of two core components: "Catch-up" and "Frontier-shift". The "Catch-up" component reflects changes in the efficiency of decision-making units (DMUs), indicating the extent to which a DMU has improved its efficiency. In contrast, the "Frontier-shift" component captures changes in the production frontier between two time periods, representing technological progress or regression in the environment (Eraqi et al., 2009; Manh, 2023; Nong and Ha, 2023).

The analytical procedure of this method is like that of the basic DEA model. However, its distinct feature lies in the need to separate data from period t and period $t + 1$. Specifically, for each DMU_k ($k = 1, \dots, n$), it is necessary to consider its input-output combinations in both periods, $(x_k, y_k)^t$ and $(x_k, y_k)^{t+1}$, where $x_k \geq 0$, $y_k \geq 0$.

TABLE 1 Input and output variables used in prior research.

Papers	Year	Inputs	Outputs	Methods
Monteiro (2018)	2018	Land, labor, number of cranes, number of other equipment, number of berths	Volume of cargo traffic in million tons, number of vessels handled	DEA Malmquist
Nguyen et al. (2019)	2019	Berth length, number of quay cranes, container yard area, the number of industrial parks at port's hinterland area, the population of port's hinterland area	Container throughput, the number of vessel call	DEA Malmquist, DEA-BBC, DEA-CCR
Nguyen et al. (2021)	2021	Gross crane productivity, crane intensity, berth length, berth depth	Calls, moves, elapsed time	DEA Malmquist
Nikolaou and Dimitriou (2021)	2021	Infrastructure and equipment context of port terminals	TEUs	DEA-CCR
C.-N. Wang et al. (2021)	2021	Total assets, Owner's equity, Liabilities, Operation expenses	Revenue, net profit	DEA Malmquist
Ben Mabrouk et al. (2022)	2022	Number of berths, the total number of gears, and the total number of workers	Cargo throughput	DEA Malmquist, DEA-BBC, DEA-CCR
C.-N. Wang et al. (2022)	2022	Terminal length, equipment, ship calls	Cargo throughput, container throughput	DEA Malmquist
Yu et al. (2022)	2022	Number of berths, length of the wharf	Cargo throughput, container throughput	DEA Malmquist, DEA-BBC
Nong (2023)	2023	Capital, operational expenses, labor, area, quay length, and depth	Sales revenue and cargo throughputs	DEA-BBC, DEA-CCR
Yen et al. (2023)	2023	Port cost	Cargo throughput	DEA-BBC, DEA-CCR

According to the DEA model equations, the distance function of the MPI is expressed as $E^t(x_k^{t+1}, y_k^{t+1})$. Accordingly, following (Nguyen et al., 2021; Ben Mabrouk et al., 2022; Wang et al., 2022), the formula for calculating the MPI of the k -th decision-making unit from t to $t + 1$ is presented in Equation 6 and its equivalent form in Equation 7:

$$MPI(x_k^t, y_k^t, x_k^{t+1}, y_k^{t+1}) = \left[\frac{E^t(x_k^{t+1}, y_k^{t+1})}{E^t(x_k^t, y_k^t)} \times \frac{E^{t+1}(x_k^{t+1}, y_k^{t+1})}{E^{t+1}(x_k^t, y_k^t)} \right]^{\frac{1}{2}} \quad (6)$$

$$MPI(x_k^t, y_k^t, x_k^{t+1}, y_k^{t+1}) = \frac{E^{t+1}(x_k^{t+1}, y_k^{t+1})}{E^t(x_k^t, y_k^t)} \times \left[\frac{E^t(x_k^{t+1}, y_k^{t+1})}{E^{t+1}(x_k^{t+1}, y_k^{t+1})} \times \frac{E^t(x_k^t, y_k^t)}{E^{t+1}(x_k^t, y_k^t)} \right]^{\frac{1}{2}} \quad (7)$$

When the MPI value equals 1, it indicates that the productivity of the DMU remains stable between the two periods. If the MPI value is greater than 1, it suggests that the DMU's productivity has improved during this period; conversely, if it is less than 1, it indicates a decline in productivity.

3.2.3 Moderating variable

Considering the mechanisms that influence the relationship between shipping efficiency and marine petroleum pollution, this study selects two moderating variables, port specialization and environmental regulation.

Port specialization is regarded as an effective approach to mitigating intense competition among ports, and the quantification of port specialization has become a key focus of interest and in-depth research among port geography scholars

(Zhang et al., 2021). Following the approach of (Zhang et al., 2021) and (Zhou et al., 2023), this study employs the Port Specialization Index (PSI) to measure the level of specialization of ports across various provinces and municipalities in China. Given that PSI demonstrates strong applicability and explanatory power for cross-provincial comparisons of port specialization in coastal China, it is adopted in this study as a moderating variable. The calculation formulas for PSI are shown in Equations 8 and 9:

$$PSI_i = \frac{n_i}{n_i - 1} \times \sum_{j=1}^{n_i} (t_{ij} - \bar{t})^2 \quad (8)$$

$$\bar{t} = \frac{\sum_{j=1}^{n_i} t_{ij}}{n_i} \quad (9)$$

PSI_i represents the port specialization index for province i . t_{ij} denotes the share of cargo type j in the total port cargo throughput of province i , and n_i refers to the total number of cargo types in province i . The PSI ranges from 0 to 1, with higher values indicating a greater degree of port specialization in the province. Data on port throughput by cargo type are sourced from the China Port Statistical Yearbook.

This study also incorporates environmental regulation as a moderating variable in the model. Drawing on the approaches of Yang et al. (2021) and Zeng et al. (2019), the study uses the total investment in industrial pollution control as a proxy variable for the intensity of environmental regulation. This indicator captures capital expenditures directed toward the treatment of industrial pollutants, including wastewater, waste gas, and solid waste. Generally, larger investment amounts are associated with more

advanced pollution control equipment and technologies, thereby enhancing the overall efficiency of industrial pollution mitigation (Yang et al., 2021). Building on this, strengthening the intensity of environmental regulation can improve the capacity to control pollutant emissions, more effectively curtail the discharge of land-based pollutants into the marine environment, and ultimately improve environmental quality in coastal regions (Sun et al., 2023). The relevant data are sourced from the China Statistical Yearbook.

3.2.4 Control variables

This study incorporates four control variables. First, Gross Ocean Product (GOP) refers to the total final output generated by various marine economic activities in coastal regions during a given period. It is calculated as the sum of the value added by the three major categories of marine industries and provides a comprehensive reflection of regional marine economic development (Ji and Ding, 2024; Shao et al., 2021a). Following (Shao et al., 2021b), this study employs per capita GOP as an indicator of marine economic development, with data sourced from the China Marine Statistical Yearbook. Second, technological innovation is widely recognized as contributing to the mitigation of ecological pressures on the marine environment (Ren and Ji, 2021), and patents serve as an important indicator of technological innovation (Li et al., 2022). Accordingly, following (Liu et al., 2021), this study adopts the number of marine research and development institutions as the proxy variable for technological innovation, with data also obtained from the China Marine Statistical Yearbook. In addition, population size is measured by total year-end population, with data drawn from the China Statistical Yearbook. Finally, consistent with the approach of (Jiang and Li, 2021), this study uses the proportion of the secondary industry's value added to GDP as a proxy variable for industrial structure. The sources and

definitions of all variables are presented in Table 2, and Table 3 are the descriptive statistics of the variables.

4 Empirical results and discussion

4.1 Shipping efficiency calculation results

Shipping efficiency in China's coastal regions shows an overall upward trend, while some provinces have experienced a decline in efficiency, indicating notable regional disparities. As shown in Table 4, the average shipping efficiency index in China's coastal regions from 2010 to 2021 was 1.046, indicating an average improvement of 4.6% in shipping efficiency during this period and demonstrating a steady upward trend. However, it is noteworthy that some provinces, such as Liaoning, Shandong, and Tianjin, experienced a decline in shipping efficiency. This phenomenon may reflect certain shortcomings in these regions regarding resource allocation, technological upgrading, or management capabilities, which have hindered their ability to adapt promptly to structural adjustments in shipping and evolving market demands. Furthermore, the industrial structure in these provinces remains heavily reliant on traditional heavy industries, with a high proportion of high-pollution enterprises, which may also constrain further improvements in shipping efficiency. Overall, although most regions have seen steady gains in shipping efficiency, regional disparities still warrant attention.

4.2 Baseline regression results

Improvements in shipping efficiency significantly reduce marine petroleum pollution, with the results from the two-way

TABLE 2 Variables and data sources.

Variable	Symbol	Specification	References	Data source
Marine petroleum pollution	<i>PET</i>	The logarithm of land-based marine petroleum pollution	(Ji and Ding, 2024)	China Marine Statistical Yearbook
Shipping Efficiency	<i>SE</i>	DEA-Malmquist index method estimation	(Wu and Wang, 2022)	China Port Statistical Yearbook
Port Specialization Index	<i>PSI</i>	Estimation of the port specialization index	(Zhang et al., 2021; Zhou et al., 2023)	China Port Statistical Yearbook
Environmental Regulation	<i>ER</i>	The logarithm of completed investment in industrial pollution control	(Zeng et al., 2019; Yang et al., 2021)	China Statistical Yearbook
Marine Economic Development	<i>PGOP</i>	The ratio of gross ocean product to total population	(Shao et al., 2021b)	China Marine Statistical Yearbook
Technological Innovation	<i>TECH</i>	The logarithm of the number of marine research and development institutions	(Liu et al., 2021)	China Marine Statistical Yearbook
Population Size	<i>POP</i>	The logarithm of the total population	(Li et al., 2019)	China Statistical Yearbook
Industrial Structure	<i>IND</i>	The ratio value added of the secondary industry to GDP	(Jiang and Li, 2021)	China Statistical Yearbook

TABLE 3 Descriptive statistics of variables.

Variable	Obs.	Mean	Std. dev.	Min	Max
PET	143	3.008	2.499	-4.605	6.543
SE	143	1.083	0.262	0.310	2.200
PSI	143	0.218	0.185	0.003	0.769
ER	143	12.030	1.247	6.165	14.164
PGOP	143	1.390	1.031	0.126	4.194
TECH	143	2.536	0.585	1.099	3.689
POP	143	8.387	0.768	6.767	9.448
IND	143	0.407	0.084	0.190	0.528

fixed effects model proving to be the most robust. Specifically, Table 5 presents the regression results on the impact of shipping efficiency on marine petroleum pollution in coastal provinces. Column (1) reports the results controlling only for provincial fixed effects, Column (2) reports the results controlling only for time fixed effects, and Column (3) reports the results of the two-way fixed effects model controlling for both provincial and time fixed effects. The findings indicate that improvements in shipping efficiency significantly reduce marine petroleum pollution across all models. We adopt the two-way fixed effects model as the baseline model, as it effectively controls unobserved regional heterogeneity and time trends, thereby reducing omitted variable bias. The baseline regression results show that for every 0.01 increase in shipping efficiency, marine petroleum pollution decreases by approximately 0.01% on average, suggesting that improvements in shipping efficiency play a significant role in enhancing the marine environment.

We argue that the improvement of shipping efficiency, as a key manifestation of the operational efficiency of transportation infrastructure, can effectively mitigate land-based marine petroleum pollution through two main channels: (1) enhancing pollution prevention and control capacity via the optimization of shipping facilities, and (2) promoting green industrial transformation by reducing transportation costs.

First, the improvement of shipping facilities significantly strengthens the system's ability to control pollution sources, thereby reducing the risk of petroleum pollutants entering the ocean. With the continuous upgrading of waterway

transportation infrastructure, the environmental performance of port operations has steadily improved (Hua et al., 2020). For instance, intelligent centralized pollutant treatment systems help reduce emissions during loading, unloading, and transportation processes; meanwhile, automated monitoring and emergency response systems enable the real-time detection of, and rapid response to, unexpected pollution incidents, thereby effectively curbing the spread of pollutants into the marine environment (Yang et al., 2018; Durán et al., 2025).

Second, the improvement of shipping efficiency helps to lower overall logistics costs and enhance the reliability of the transportation system, which is particularly important for high-end manufacturing and modern service industries that are highly sensitive to cost control. As port and shipping systems operate more efficiently, these low-pollution, high value-added industries are increasingly drawn to port cities, gradually replacing traditionally dominant, high-pollution sectors such as petroleum refining, heavy chemical industries, and coal handling (Fan et al., 2021). This industrial shift elevates the level of industrial development in port areas and promotes the green transformation of regional economies, thereby alleviating environmental pressures on coastal ecosystems (Su et al., 2024).

In summary, improvements in shipping efficiency are reflected not only in enhanced shipping facilities but also in reduced transportation costs and industrial restructuring (Psaraftis and Kontovas, 2013). The former strengthens pollution control capacity and operational cleanliness, effectively reducing pollutant emissions; the latter diminishes the dominance of high-pollution industries, thereby constraining petroleum-related pollutant emissions at the source. These two mechanisms complement each other, making the enhancement of shipping efficiency an important pathway for addressing land-based marine petroleum pollution.

4.3 Moderating effects results

Port specialization and environmental regulation both exert negative moderating effects on the role of shipping efficiency in reducing marine petroleum pollution. In other words, in regions with lower levels of port specialization or relatively lenient environmental regulation, improvements in shipping efficiency have a more pronounced effect on pollution reduction, indicating a certain degree of substitutability between the two. Specifically, as

TABLE 4 Shipping efficiency calculation results of coastal provinces and cities.

Region	Shipping efficiency	Ranking	Region	Shipping efficiency	Ranking
Fujian	1.129	2	Liaoning	0.856	11
Guangdong	1.122	3	Shandong	0.997	9
Guangxi	1.148	1	Tianjin	0.915	10
Hainan	1.077	6	Zhejiang	1.049	7
Hebei	1.045	8	Shanghai	1.081	5
Jiangsu	1.091	4			

TABLE 5 Baseline regression results.

Variable	(1)	(2)	(3)
<i>SE</i>	-0.854** (0.399)	-1.081** (0.453)	-1.023** (0.425)
<i>PGOP</i>	-0.706* (0.409)	-0.098 (0.361)	-0.300 (0.449)
<i>TECH</i>	0.777** (0.345)	1.246*** (0.368)	0.959** (0.380)
<i>POP</i>	-4.592 (4.044)	-0.002 (0.735)	-1.572 (4.912)
<i>IND</i>	-0.995 (3.707)	-7.369 (5.789)	-15.260* (8.080)
Constant	41.860 (34.067)	5.146 (4.849)	22.720 (39.589)
Year Fixed Effect	NO	YES	YES
Province Fixed Effect	YES	NO	YES
Observations	143	143	143

The values enclosed in parentheses represent standard errors. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

TABLE 6 Moderating effects results.

Variable	(1)	(2)	(3)	(4)
<i>SE</i>	-0.876** (0.435)	-2.468*** (0.525)	-1.000** (0.426)	-15.520*** (3.437)
<i>PSI</i>	1.005 (2.960)	-6.757** (3.295)		
<i>SE</i> × <i>PSI</i>		6.323*** (1.503)		
<i>ER</i>			0.152 (0.181)	-1.269*** (0.374)
<i>SE</i> × <i>ER</i>				1.258*** (0.296)
<i>PGOP</i>	-0.248 (0.502)	-0.413 (0.455)	-0.321 (0.451)	-0.298 (0.420)
<i>TECH</i>	0.010 (0.398)	1.466*** (0.376)	0.987** (0.382)	1.612*** (0.385)
<i>POP</i>	3.588 (5.107)	-6.504 (4.750)	-2.061 (4.953)	-2.610 (4.621)
<i>IND</i>	-13.590 (8.476)	-10.540 (7.766)	-13.99* (8.230)	-15.540** (7.684)
Constant	-19.170 (40.124)	61.610 (38.220)	24.350 (39.687)	44.540 (37.314)
Year Fixed Effect	Yes	Yes	Yes	Yes
Province Fixed Effect	Yes	Yes	Yes	Yes
Observations	143	143	143	143

The values enclosed in parentheses represent standard errors. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

shown in Table 6, the regression results in column (2) indicate that the interaction term $SE \times PSI$ has a regression coefficient of 6.323, which is significantly positive at the 1% level. This suggests that port specialization exerts a significant negative moderating effect on the relationship between shipping efficiency and marine petroleum pollution. Specifically, in coastal provinces with lower levels of port specialization, improvements in shipping efficiency have a more pronounced suppressive effect on marine petroleum pollution. This finding indicates a certain degree of “substitutability” between port specialization and shipping efficiency in the context of pollution control.

Figure 1 further validates the above findings by illustrating the moderating effect of port specialization on the relationship between shipping efficiency and marine petroleum pollution. The results show that when *PSI* is below approximately 0.3, the marginal effect of *EFFI* on *PET* is significantly negative, indicating that in regions with lower levels of port specialization, improvements in shipping efficiency exert a stronger suppressive effect on pollution. This suggests that in contexts where port functions are blurred and operational processes are less standardized, enhancing efficiency becomes a key means of improving environmental performance. In contrast, when *PSI* exceeds 0.3, the marginal effect gradually increases and becomes insignificant, implying that as port specialization intensifies, the pollution reduction effect of shipping efficiency is either substituted or diminished, thereby weakening the moderating effect.

When the degree of port specialization is low, the division of functions within the port is unclear, operational processes are not well standardized, and there is a lack of effective collaboration and pollution control mechanisms. Under such circumstances, improving shipping efficiency becomes an important means of mitigating environmental pollution, with a more pronounced emission reduction effect. In contrast, when the degree of port specialization is high, pollution sources are generally brought under initial control through rational functional division and spatial zoning, and the port itself tends to possess strong pollution treatment capabilities. In this context, the additional emission reduction benefits resulting from enhanced shipping efficiency diminish, exhibiting a trend where greater efficiency improvements yield increasingly limited pollution reduction effects. Overall, although port specialization and shipping efficiency follow different pathways in pollution control, both contribute positively to reducing marine petroleum pollution and can, to some extent, serve as substitutes for each other.

Moreover, the results in column (4) show that the regression coefficient of the interaction term $SE \times ER$ is 1.258, which is also significant at the 1% level, further confirming that environmental regulation exerts a negative moderating effect on the relationship between shipping efficiency and marine petroleum pollution. Specifically, in regions where environmental regulation is relatively weak, with insufficient emission standards, regulatory frameworks, and pollution control requirements, ports and shipping enterprises generally face limited external policy constraints. Under such conditions, their environmental

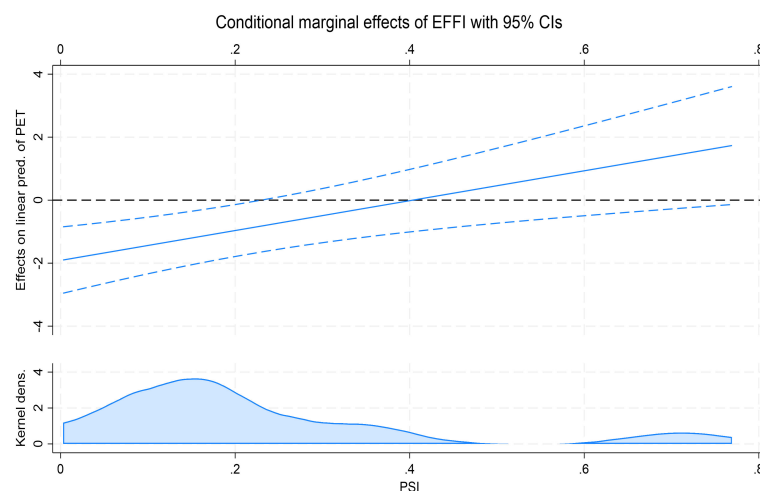


FIGURE 1

Marginal effect of shipping efficiency on marine petroleum pollution at varying levels of port specialization.

performance relies more heavily on improvements in internal operational efficiency, making shipping efficiency a key mechanism for driving pollution reduction.

Figure 2 provides a visual illustration of the moderating effect. The results show that when the intensity of environmental regulation is below 12, the marginal effect of EFFI on PET is significantly negative, indicating that improvements in shipping efficiency have a stronger pollution-reducing effect in regions with weaker regulatory enforcement. In this phase, EFFI functions as a “substitute mechanism” for policy regulation, indirectly achieving pollution control objectives through enhanced operational efficiency. However, as environmental regulation strengthens ($ER > 12$), the marginal effect gradually becomes insignificant, suggesting that in regions with stricter regulation, the

independent emission-reduction effect of EFFI is weakened by policy constraints, and the moderating effect tends to diminish.

Improvements in shipping efficiency are typically accompanied by cost reductions, technological upgrades, and streamlined processes. Although these changes are not primarily aimed at environmental protection, they can effectively reduce pollution in practice. In regions where external environmental policies are relatively weak, enhanced shipping efficiency can partially compensate for regulatory shortcomings and serve as an alternative means of pollution control. Therefore, in areas with less stringent environmental requirements, the pollution-reducing impact of improved shipping efficiency becomes more pronounced, demonstrating its greater environmental potential.

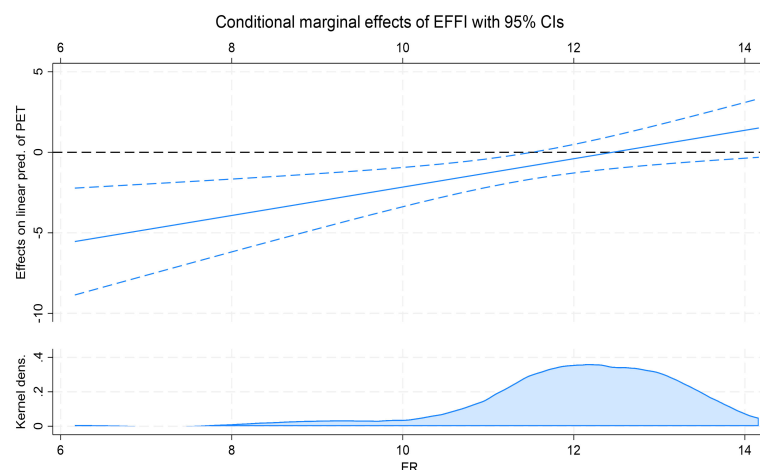


FIGURE 2

Marginal effect of shipping efficiency on marine petroleum pollution at varying levels of environmental regulation.

5 Conclusion

Based on panel data from 11 coastal regions in China spanning the period from 2010 to 2022, this study investigates the impact of shipping efficiency on marine petroleum pollution. The main findings are as follows. First, overall, shipping efficiency in China's coastal regions has shown a steady upward trend, although some provinces, such as Liaoning, Shandong, and Tianjin, still exhibit declines in efficiency, indicating regional disparities in development. Second, the baseline regression results reveal that shipping efficiency has a significant negative impact on marine petroleum pollution, suggesting that improvements in shipping efficiency contribute substantially to mitigating marine petroleum pollution. Third, port specialization and environmental regulation exhibit significant negative moderating effects on the relationship between shipping efficiency and marine petroleum pollution.

Based on the above findings, the following policy recommendations are proposed. First, shipping efficiency in provinces such as Liaoning, Shandong, and Tianjin remains relatively low, primarily due to a narrow industrial structure, outdated port facilities, and poor transport connectivity. It is essential to accelerate the intelligent upgrading of shipping infrastructure, promote the adoption of automated loading and unloading systems and intelligent scheduling, and enhance operational efficiency. In addition, coastal industries should be guided toward higher value-added and lower-pollution sectors to reduce dependence on traditional energy-intensive industries. Efforts should also be made to improve the intermodal transport network by promoting rail-waterway integration and developing a coordinated and efficient port logistics system. Second, given that improvements in shipping efficiency help reduce marine petroleum pollution, coastal regions should expedite the development of green shipping systems. This includes strengthening technological upgrades in port operations, introducing energy-saving equipment and intelligent management systems to reduce fuel consumption and leakage risks during operations. Furthermore, standardized environmental protection facilities, such as waste oil-water recovery systems, shore power systems, and emergency response equipment, should be installed to control pollution at its source. Third, management strategies should be tailored to different levels of port specialization. For ports with a lower degree of specialization, priority should be given to pollution control through efficiency improvements, emphasizing operational enhancements as the primary emission reduction pathway. For highly specialized ports, greater emphasis can be placed on functional division, pollutant-specific management, and supporting facilities to improve the overall level of environmental management and enhance the systematization and precision of pollution control. Fourth, the intensity of environmental regulation should be carefully calibrated to avoid unintended negative consequences. In regions with relatively weak regulatory foundations, local governments should first be encouraged to reduce emissions through efficiency improvements, and more stringent standards should be introduced gradually as their capacity increases, following an efficiency-first,

policy-following approach. In regions with stronger regulatory frameworks, greater emphasis should be placed on the synergy between policy instruments and market mechanisms to prevent cost pressures from discouraging local governments from investing in environmental protection, thereby ensuring the sustainability and effectiveness of regulatory policies.

This study has certain limitations, which provide opportunities for further research. On the one hand, due to data availability constraints, the study period is limited to 2022. Future research could extend the time span as updated data become available, allowing for a more comprehensive examination of the dynamic relationship between shipping efficiency and environmental impact. On the other hand, the current analysis is based primarily on regional-level panel data and does not capture micro-level differences at the port or firm level. Future studies may incorporate more granular data (such as port-level or firm-level data) to explore the heterogeneous effects of shipping efficiency on environmental outcomes under different port types, transportation routes, and operational characteristics.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: China Marine Statistical Yearbook; China Port Statistical Yearbook; China Statistical Yearbook; The Bulletin of Marine Ecology and Environment Status of China.

Author contributions

XJ: Conceptualization, Methodology, Formal Analysis, Data curation, Writing – original draft. XD: Methodology, Validation, Conceptualization, Writing – review & editing, Supervision. WH: Formal Analysis, Data curation, Writing – original draft. YQ: Validation, Supervision, Writing – review & editing.

Funding

The author(s) declare financial support was received for the research and/or publication of this article. This work is supported by the Universities in Guangxi Young and Middle-Aged Teachers' Basic Ability Improvement Project "Measurement and Enhancement Path of Green Total Factor Productivity in Guangxi Beibu Gulf Ports" (2025KY0452), by the National Social Science Fund of China (21BGJ034), and by the BK21 FOUR Program through Jeonbuk National University Research Grant.

Acknowledgments

The authors would like to thank the Editors and the reviewers for the useful and constructive comments.

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