Frontiers in Marine Science

TYPE Original Research
PUBLISHED 22 March 2023
DOI 10.3389/fmars.2023.1020373

Analyzing efficiency measurement and influencing factors of China's marine green economy: Based on a two-stage network DEA model

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SPECIALTY SECTION
This article was submitted to Marine Affairs and Policy, a section of the journal Frontiers in Marine Science

RECEIVED 18 August 2022
ACCEPTED 03 January 2023
PUBLISHED 22 March 2023

CITATION
Zou W, Yang Y, Yang M, Zhang X, Lai S and Chen H (2023) Analyzing efficiency measurement and influencing factors of China's marine green economy: Based on a two-stage network DEA model. *Front. Mar. Sci.* 10:1020373. doi: 10.3389/fmars.2023.1020373

This research adopts a two-stage network DEA model to measure marine green economy efficiency from 2006 to 2018 and employs the panel Tobit model to analyze the influencing factors. The results indicate that total efficiency and production efficiency of China's marine green economy generally show a fluctuating downward trend. Further investigation of influencing factors shows that foreign direct investment and opening up have a significantly positive effect on total efficiency of the marine green economy, while industrial development level and marine economy development level have a negative effect on it. Additionally, these variables have varying impacts on different stages of the marine green economy. Our findings help identify the operational characteristics of the marine green economy at different stages and can assist policymakers in optimizing the development pattern of the marine economy.

KEYWORDS
two-stage network DEA model, marine green economy, production efficiency, governance efficiency, blue economic

1 Introduction

The marine economy as a new economic form has gradually become a driving force for the sustainable development of China's economy since the start of the 21st century. In 2018 its total marine output value was 8.34 trillion yuan, 1.8 times greater compared to 2008. However, the extensive development pattern of the marine economy has also led to serious ecological and environmental problems. Overexploitation of marine resources, increased discharge of marine pollutants, and extensive damage to the marine environment continue to emerge (Ren et al., 2018). According to the Bulletin on the State of China's Marine Ecological Environment, the average area percentage of the four inferior types of water quality in China's coastal waters from 2018 to 2021 is more than 9.5%. In 2021, among 44 bays with a monitored area of over 100 square kilometers, 11 bays (25%) have inferior water quality. Some studies have pointed out that about 10% of China's bays are seriously polluted, more

 10.3389/fmars.2023.1020373

than 17% of shorelines suffer from erosion, and about 42% of the coastal zones are overloaded with resource and environmental carrying capacity (Yao et al., 2020). Compared to the 1950s, the coastal wetland area in China has shrunken by over 60%, and the loss rate is higher than the global average (Yao et al., 2020). It can be seen that China's marine environmental pollution is increasing, and the construction of ecological civilization is facing great challenges. Therefore, how to effectively coordinate the relationship between marine economy development and environmental protection and to promote this economy's sustainable development have become major practical issues that need to be solved.

The China government in recent years has attached great importance to the sustainable development of the marine economy. In 2016, the government issued the National Plan for Prosperity by Science and Technology (2016-2020), which is committed to forming a long-term mechanism for innovation-driven marine development. Subsequently, the 13th Five-Year Plan for National Marine Economic Development released in 2017 took green development and ecological priority as important principles for marine economy development. Since then, the report of the 19th National Congress of the Communist Party of China stressed the importance of protecting the marine ecological environment, indicating that the development of marine resources and the protection of the marine environment are equally important.

To improve the quality of marine economy development, China has issued and implemented a series of policies and regulations. Despite this, problems such as marine pollution and ecosystem degradation are still relatively prominent, threatening the sustainable development of the marine economy (Ye et al., 2021). Moreover, with the proposal of the concept of green development, the marine green economy has also become the focus of policy makers and academia (Chen et al., 2020a; Chen et al., 2022a; Chen et al., 2022b). The development of this conomy targets the organic combination of economic development and environmental protection and is committed to the maximum utilization of marine resources under the premise of protecting the marine environment, so as to achieve its sustainable development.

The efficiency of the marine green economy is an important indicator to measure its sustainable development (Wei et al., 2021; Ye et al., 2021). At present, scholars mainly have used stochastic frontier method (SFA) and data envelopment analysis (DEA) to evaluate marine green economy efficiency and technical efficiency (Wu, 2018; Zheng et al., 2019; Wang et al., 2021a; Chen et al., 2020b; Chi et al., 2022). By incorporating undesired output indicators such as marine pollutants into the evaluation system, the overall efficiency of the marine economy in the context of environmental constraints is examined (Ding et al., 2020; Zhao et al., 2021).

Most existing studies, however, have regarded the development of the marine green economy as an independent process and failed to consider the stage characteristics of the operation of the marine green economy, thus making it difficult for a comprehensive estimation of the marine green economy efficiency (Ding et al., 2018). In the development process of the marine economy, there is a sequence of pollutant generation and treatment, and the marine pollution treatment stage must occur after the production process. Therefore, it is necessary to conduct in-depth discussions on the different stages of marine green economy development. Based on the two-stage network DEA model, this study evaluates the marine green economy efficiency of 11 coastal provinces and cities in China from 2006 to 2018 and further examines the efficiency changes and influencing factors in different stages.

The rest of the paper runs as follows. Sn2 ectio presents the literature review. Sn3 ectio describes the research model, variable measurement, and data. Sn4 ectio reports and explores the research results. Sn5 ectio summarizes the empirical results and puts forward suggestions.

2 Literature review

The strategic position of the ocean in the world has become increasingly prominent in recent years and has helped to gradually enrich research on the marine economy. By combing the relevant literature, we find that existing research on the marine green economy mainly focuses on efficiency evaluation and analysis of the influencing factors.

First, most studies have focused on evaluating marine industry efficiency from the perspective of input and output. At present, the assessment of marine industry efficiency involves marine fishery and marine transportation. On the one hand, from the perspective of efficiency evaluation of marine fisheries, Jamnia et al. (2015) took 300 fishing boats in their study area as samples and analyzed the technical efficiency of fisheries in the Chabahar region of southern Iran by using the stochastic production frontier method. Li et al. (2020) investigated fishery production efficiency in China's coastal areas based on the DEA-Malmquist index, showing results that fishery output efficiency has improved to a certain extent. Similarly, the Malmquist index method has also been used to calculate the total factor productivity and its decomposition index of marine fisheries (Song, 2020). In addition, some scholars have applied more complex DEA models to explore the efficiency of marine fisheries (Ton Nu Hai et al., 2018; Liu et al., 2021a). For example, Ton Nu Hai et al. (2018) employed two-stage bootstrap DEA to study the cost efficiency of marine cage lobster farms in Vietnam and its influencing factors. There is also a large amount of literature on marine port transportation efficiency. Bray et al. (2015) constructed a DEA model based on the fuzzy theory to evaluate the efficiency of international container ports and compared the results with the traditional DEA model. Pham et al. (2020) combined a two-stage uncertainty DEA and fuzzy C-means clustering method to comprehensively measure the operational efficiency of the world's top 40 container ports for five consecutive years. A large strand of studies has analyzed efficiency of the port industry from an environmental perspective (Sun et al., 2017; Wang et al., 2019; Chi et al., 2022). For example, Qi et al. (2020) used the RAM-DEA model to assess the unified efficiency of a port from the two aspects of operational performance and environmental balance and combined the types of scale gains and scale losses to select the direction suitable for a port's sustainable development.

Second, research on marine green economy efficiency has received extensive attention. As the extensive growth pattern of the marine economy leads to the continuous deterioration of the ecosystem, scholars have incorporated undesired outputs into the measurement model to explore the development level of the marine green economy under environmental constraints. Wu (2018) applied the methods of the stochastic frontier model, coefficient of variation, Gini coefficient, and entropy to explore the spatiotemporal evolution trend of green production efficiency of the marine economy in China's coastal areas. Ren et al. (2018) introduced undesirable output into the evaluation system of total factor productivity and utilized the global Malmquist-Luenberger index model to estimate and decompose green efficiency of the marine economy. Ding et al. (2020) considered the connection between economic production and environmental treatment in the marine circular economy and proposed a new cooperative game network DEA model for evaluating marine environmental performance. Wei et al. (2021) combined the super-efficiency slack-based measure model and the global Malmquist index model to calculate the green total factor productivity of the marine economy. Zhu et al. (2021) respectively estimated the elasticity and efficiency of China's marine economy based on the core variable method and the slacks-based measure of super-efficiency method. In addition, there are numerous studies examining marine green economy efficiency from the perspective of policy measures, including Maritime Silk Road and Belt and Road Initiative (Zhao et al., 2021; Wang et al., 2021a).

Finally, scholars have also focused their research on the influencing factors of marine green economy efficiency. The research content mainly involves industrial structure, environmental regulation, technological innovation, and foreign direct investment. Wu (2018) pointed out that the level of marine economy development, marine industrial structure, marine human capital, marine material capital, opening up, and marine environmental governance all affect the green total factor productivity of the marine economy in coastal areas. Sun (2020) confirmed the positive effect of digital finance on marine ecological efficiency. Wei et al. (2021) discussed the impact of the evolution of marine industrial structure on the green total factor productivity of the marine economy and found that the relationship between the two exhibits an inverted U-shape trend of promotion first and then inhibition. Ye et al. (2021) used the differential Gaussian Mixture model to empirically test the impact of government preference and environmental regulation on green development of the marine economy and noted that both government environmental preference and environmental regulation promote such green development, while industrial preference has a negative effect on this green development. In addition, some scholars have discussed the influencing factors of marine green economy efficiency from the perspective of spatial correlation. For example, Guo et al. (2022) constructed a spatial Durbin model to investigate the influence mechanism of marine economy efficiency from the aspects of economic development level, openness, marine industrial structure, and marine R&D investment.

Based on the literature review, we find that the existing literature provides a relatively in-depth analysis of the marine green economy and offers many useful insights, but there are still some deficiencies in existing studies. Most of them applied single-stage input-output indicators to assess marine green economy efficiency and treated the development of this type of economy as an independent operational process, while ignoring the operational laws and differential characteristics within its system. Moreover, the existing literature has failed to examine the influencing factors of marine green economy efficiency at different stages, thus not revealing the differential effects of external factors on marine green economy development. Therefore, our study focuses on the phased characteristics of marine green economy efficiency, which helps to analyze the operation law of this type of economy and its mechanism of action more comprehensively.

The main contributions of this study include the following. First, we divide the operation process of the marine green economy into the marine production stage and the pollution control stage and employ the two-stage network DEA model to calculate the total efficiency, production efficiency, and governance efficiency of this economy, which is conducive to more comprehensively revealing its operation in different stages. Second, this study explores the convergence characteristics of marine green economy efficiency in China's coastal areas and investigates the regional gaps in total efficiency, production efficiency, and governance efficiency of the marine green economy, thereby providing useful supplements to the existing literature. Finally, based on the efficiency measurement results, we apply the Tobit model suitable for the data characteristics to examine the influencing factors of marine green economy efficiency at different stages. Our findings should assist policy makers in optimizing the marine economy development pattern and building a high-quality marine economy development system.

3 Methods

3.1 Two-stage network DEA model

Since the traditional DEA model fails to consider the internal operation process of the system, the efficiency measurement may be biased (Kao and Hwang, 2008; Wang et al., 2020a). The two-stage network DEA model can analyze the specific structure within the system and help obtain more abundant information (Kao and Hwang, 2008; Kao, 2014). The two-stage network DEA model assumes that the whole production system is composed of two sub-stages, and there is a certain correlation between the two stages, that is - the input of the second stage involves all or part of the output of the first stage.

Because the traditional two-stage network DEA model cannot link the whole process with different stages, the measurement results do not have integrity. Therefore, referring to the results of Kao and Hwang (2008), we integrate the traditional two-stage DEA model and then obtain a research model that more comprehensively measures the efficiency value of different stages and the overall process.

Suppose there are n decision-making units (DMUs) in the study, where X represents the input of DMU, Y represents the output of DMU, and Z represents the intermediate output of DMU, denoted by $X_j=(x_{1j}, x_{2j},\ldots, x_{mj})^T$, $Y_j=(y_{1j}, y_{2j},\ldots, y_{sj})^T$, and $Z_j=(z_{1j}, z_{2j},\ldots, z_{qj})^T$, respectively. Details are as follows:

$$
\begin{aligned}
&E_k = \max \ \sum_{r=1}^{s} u_r Y_{rk} / \sum_{i=1}^{m} v_i X_{ik} \\
&s.t. \quad \sum_{r=1}^{s} u_r Y_{rj} / \sum_{i=1}^{m} v_i X_{ij} \le 1, j = 1, 2, \ldots, n \\
&\sum_{p=1}^{q} w_p Z_{pj} / \sum_{i=1}^{m} v_i X_{ij} \le 1, j = 1, 2, \ldots, n \\
&\sum_{r=1}^{s} u_r Y_{rj} / \sum_{p=1}^{q} w_p Z_{pj} \le 1, j = 1, 2, \ldots, n \\
&u_r, \ v_i, \ w_p \ge \epsilon, \ r = 1, 2, \ldots, s; \ i = 1, 2, \ldots, m; \ p = 1, 2, \ldots, q
\end{aligned} \tag{1}
$$

On this basis, formula (1) is converted into a linear equivalent model as follows:

$$
\begin{aligned}
&E_k = \max \ \sum_{r=1}^{s} u_r Y_{rk} \\
&s.t. \quad \sum_{i=1}^{m} v_i X_{ik} = 1, \\
&\sum_{r=1}^{s} u_r Y_{rj} - \sum_{i=1}^{m} v_i X_{ij} \le 0, \ j = 1, 2, \ldots, n \\
&\sum_{p=1}^{q} w_p Z_{pj} - \sum_{i=1}^{m} v_i X_{ij} \le 0, \ j = 1, 2, \ldots, n \\
&\sum_{r=1}^{s} u_r Y_{rj} - \sum_{p=1}^{q} w_p Z_{pj} \le 0, \ j = 1, 2, \ldots, n \\
&u_r, \ v_i, \ w_p \ge \epsilon, \ r = 1, 2, \ldots, s; \ i = 1, 2, \ldots, m; \ p = 1, 2, \ldots, q,
\end{aligned} \tag{2}
$$

where v is the coefficient vector of the initial input X; u is the coefficient vector of the final output Y; and w is the coefficient vector of the intermediate output Z; ϵ is a small non-Archimedean number; $E_k = 1$ means that DEA is valid; and $E_k < 1$ means that DEA is invalid. At this time, $E_k = E_k^1 \times E_k^2$. However, Kao and Hwang (2008) believed that the optimal solution of the DMU obtained by Equation (2) may not be unique, which also makes the decomposition of the total efficiency value not unique. Therefore, they proposed to find a set of subsets that produce the maximum efficiency value and found the total efficiency of the DMU according to Equation (2). The research model is organized as follows.

$$
\begin{aligned}
&E_k^1 = \max \ \sum_{p=1}^{q} w_p Z_{pk} \\
&s.t. \quad \sum_{i=1}^{m} v_i X_{ik} = 1 \\
&\sum_{r=1}^{s} u_r Y_{rk} - E_k \sum_{i=1}^{m} v_i X_{ik} = 0 \\
&\sum_{r=1}^{s} u_r Y_{rj} - \sum_{i=1}^{m} v_i X_{ij} \le 0, \ j = 1, 2, \ldots, n \\
&\sum_{p=1}^{q} w_p Z_{pj} - \sum_{i=1}^{m} v_i X_{ij} \le 0, \ j = 1, 2, \ldots, n \\
&\sum_{r=1}^{s} u_r Y_{rj} - \sum_{p=1}^{q} w_p Z_{pj} \le 0, \ j = 1, 2, \ldots, n \\
&u_r, \ v_i, \ w_p \ge \epsilon, \ r = 1, 2, \ldots, s; \ i = 1, 2, \ldots, m; \ p = 1, 2, \ldots, q
\end{aligned} \tag{3}
$$

We can solve the efficiency value E_k^1 of the first stage through Equation (3) and solve the efficiency value of the second stage according to $E_k^2 = E_k / E_k^1$. Similarly, using the same method, we can obtain the efficiency value of the second stage and then solve the efficiency value of the first stage.

3.2 Convergence model

Common convergence models present σ convergence and β convergence. In order to further investigate the evolution trend of regional differences in China's marine green economy efficiency, we mainly test it from the two levels of σ convergence and absolute β convergence.

We interpret σ convergence as the discrete degree of marine green economy efficiency in different regions that shows a continuous downward trend over time. Based on the research of Lin et al. (2006), the present study adopts the standard deviation method to analyze the σ convergence of marine green economy efficiency. The specific model is as follows:

$$
\sigma_t = \sqrt{\frac{1}{N-1} \sum_{n=1}^{N} (y_{it} - \bar{y}_t)^2} \tag{4}
$$

where N represents the number of provinces; $\bar{y}_t$ represents the mean value, that is - the mean value of marine green economy efficiency; and σ_t is the standard deviation. If the standard deviation shows a downward trend over time, then there is σ convergence in marine green economy efficiency. Conversely, there is no σ convergence.

The proposition of β convergence stems from the idea of economic convergence in the neoclassical economic theory and was initially used to explore whether inter-regional economic growth tends to be stable over time. We can divide β convergence into absolute β convergence and conditional β convergence. Absolute β convergence means that the growth rate of marine green economy efficiency in all regions will eventually reach the same steady-state level. Referring to the study of Miller and Upadhyay (2002), we use the following model to calculate the absolute β convergence index.

$$
\begin{aligned}
&\frac{\ln(efficiency_{i,t+T} / efficiency_{it})}{T} \\
&= \alpha + \beta \ln(efficiency_{it}) + \mu_i + \eta_t + \epsilon_{it,}
\end{aligned} \tag{5}
$$

where i represents each province; t represents the year; α is the constant term; *efficiency* is the efficiency value of the marine green economy; β is the estimated coefficient value; μ_i represents the regional effect; η_t represents the time effect; and ϵ_{it} represents the stochastic error. If $\beta < 0$, then it indicates absolute β convergence, that is - regions with low marine green economy efficiency have higher growth rates and will eventually catch up with regions exhibiting high marine green economy efficiency, and the gap between regions will gradually narrow.

3.3 Tobit regression model

Marine green economy efficiency measured by the above research methods ranges from 0 to 1. It can be seen that the measurement results have the characteristics of being cut. If the OLS method is used for estimation, then a consistent estimator may not be obtained. In contrast, the Tobit model is able to effectively handle data with such characteristics (Chen, 2014). Therefore, this study constructs a panel Tobit model to explore the influencing factors of marine green economy efficiency. The specific model is set as follows:

$$efficiency_{it} = \begin{cases} efficiency_{it}, \ if \ efficiency_{it} > 0 \\ 0, \ \ if \ efficiency_{it} \leq 0 \end{cases} \tag{6}$$

On this basis, the regression model is:

$$efficiency_{it} = \lambda + \omega X_{it} + \rho_{it,} \tag{7}$$

where λ is the constant term; ω is the estimated coefficient; X_{it} is each influencing factor; and ρ_{it} is the stochastic error.

4 Empirical Analysis

4.1 Variable selection and data source

4.1.1 Input-output indicators

Due to the multi-stage characteristics of marine economy development, the research that regards such development as a "black box" is flawed. Ding et al. (2018) analyzed the operation process of the marine economy and pointed out that its development includes the two stages of production and environmental governance.

At the stage of marine production, most scholars point out that the input factors of the marine economy development system mainly include capital, labor, energy, and land (Song et al., 2019; Xu and Yan, 2022). Therefore, we draw on the study of Song et al. (2019) to select initial input indicators from four aspects, labor, capital, energy, and land, and measure them using the amount of marine employment, marine economy capital stock, total energy consumption of the marine economy, and the mariculture area, respectively. Considering data availability, capital stock and total energy consumption of the marine economy are revised by the ratio of the gross marine product to the gross regional product.

In terms of intermediate output indicators, marine factor inputs aim to improve the level of marine economy development (Ding et al., 2015; Liu et al., 2021b). On the one hand, gross marine product, as an aggregate indicator to measure the development status of a country's or region's marine economy, often reflects the level of regional marine economy development (Wang, 2021). Therefore, actual gross marine product is selected to represent the desired intermediate output indicator. On the other hand, in the context of considering environmental factors, the output of the production stage also involves undesired output indicators - namely, the generation of marine environmental pollutants (Ding et al., 2015). Hu (2018) and Wang (2021) pointed out that continuous exploitation of marine resources, while improving regional marine economy benefits, also brings about undesired outputs that affect the marine environment such as wastewater and industrial solid waste. Therefore, based on the content of their study, we select the amount of wastewater directly discharged into the sea and the amount of solid waste produced by the marine industry to measure the undesired intermediate output indicators. Similarly, in the absence of direct indicators of marine industrial solid waste production, we apply the above method to adjust the amount of industrial solid waste production.

In the stage of environmental governance, as the level of marine pollution increases, the government will inevitably invest in the management of marine environmental pollution. Ding et al. (2017) noted during marine economy development that the China government attaches importance to the marine environmental pollution problem and is continuously increasing investment in marine environmental governance. Therefore, this study regards the amount of wastewater directly discharged into the sea and the amount of marine industrial solid waste in the previous stage as the input indicators of this stage. Drawing on the study of Ding (2017), we select total investment in marine industrial pollution treatment as the additional input of the second stage.

With regard to the final output indicators, the purpose of environmental pollution treatment is to reduce marine pollutants such as wastewater and industrial solid waste and improve the quality of marine environment. Considering the unique characteristics of the marine economy, offshore water quality and the amount of marine industrial solid waste utilization in coastal areas are important indicators to reflect the effectiveness of environmental treatment. Therefore, we choose the proportion of excellent water quality in offshore waters and the comprehensive utilization of marine industrial solid waste as the final output indicators. Table 1 lists the specific input-output indicators involved in marine green economy efficiency.

4.1.2 Influencing factors

Existing studies have pointed out that the marine green economy, as an environmentally dependent regional economy, not only has locational advantages of the marine economy, but also is influenced by many factors such as the coastal areas' economy (Ding et al., 2018). Combined with the related literature, we examine the factors influencing marine green economy efficincy from the level of marine technology, the state of the marine economy, and the development of coastal areas, respectively.

From the perspective of marine technology, scientific and technological progress and innovation are powerful driving forces for marine economy development. Technological innovation is conducive to reducing the production cost of enterprises, enhancing the competitiveness of the marine industry, and promoting the upgrading of marine industrial structure (Wang et al., 2021b; Yang and Wen, 2021; Liu et al., 2022; Zhang et al., 2022; Zou et al., 2022). Many studies have confirmed a close relationship between marine technological innovation and the level of marine green economy development (Wang et al., 2020b; Liu et al., 2021b), meaning that marine technological innovation needs to be factored into regression models. We measure marine technology innovation (*innovation*) using the number of scientific and technological projects of marine scientific research institutions in each region.

From the perspective of marine economy status, some scholars argue that regions with higher levels of marine economy development can provide substantial financial and infrastructural support for the development of marine industries, which in turn improve the efficiency of marine resource utilization (Ji and Wang, 2018; Chen, 2022c; Wang et al., 2023). However, some scholars also stated that a

TABLE 1 Input-output indicators of marine green economy efficiency.

	Category	Specific indicator
Marine production stage	Initial input	Number of sea-related employees
		Marine economy capital stock
		Total energy consumption of marine economy
		Mariculture area
	Intermediate output	Actual gross marine product
		Amount of wastewater directly discharged into the sea
		Amount of marine industrial solid waste
Environmental governance stage	Intermediate input	Amount of wastewater directly discharged into the sea
		Amount of marine industrial solid waste
		Total investment in marine industrial pollution control
	Final output	Proportion of Class I and Class II offshore water quality
		Comprehensive utilization of marine industrial solid waste

higher level of marine economy development can bring about a significant increase in resource consumption and pollutant emissions, which may seriously destroy the balance of marine resources and ecological environment and is not conducive to the improvement of marine green economy efficiency (Shi et al., 2022; Zhao et al., 2022a; Zhao et al., 2022b; Nogué-Algueró, 2020; Peng et al., 2020; Wang, 2021). It can be seen that the level of marine economy development is an important factor affecting the efficiency of marine green development and must be added to the model. We use the ratio of the gross marine product of each region to the gross regional product to assess the level of marine economy development (*egop*).

From the perspective of coastal areas' development, it has been well documented that foreign direct investment (FDI), the level of terrestrial industry, and opening up play important roles in marine total factor productivity (Zheng et al., 2022; Wang et al., 2021a; Zhao et al., 2021). In recent years, the impact of FDI on the green economy has shown a more complex manifestation (Qiu et al., 2021; Gao et al., 2022). The view of existing studies can be summarized in that FDI may improve marine green economy efficiency through technology spillover effects or may have negative effects on the marine environment through pollution transfer (Zheng et al., 2022). It can be seen that it is important to focus on the role of FDI on marine green economy efficiency. We use the proportion of actually utilized foreign direct investment in regional GDP to characterize foreign direct investment (*fdi*).

Industry is an important source of environmental pollution in coastal areas, and most pollution sources of nearshore water quality come from industrial pollution discharges in coastal inland areas (Ding et al., 2018). Therefore, we include the development level of terrestrial industry (*industry*) in our analytical model and measure it using the proportion of the actual industrial added value to the region's actual GDP. In addition, opening up is a key factor affecting the allocation of marine resources and the level of marine industry development (Ji and Wang, 2018; Lu et al., 2019). With the deepening of China's opening up to the outside world, international cooperation in the field of the marine economy is becoming more frequent, which will undoubtedly have a certain degree of effect on marine green economy development. In this study we use the proportion of total imports and exports to GDP to assess opening up (*open*).

4.1.3 Data sources

Considering data availability, this study selects panel data of 11 coastal areas in China from 2006 to 2018. The data of each index come from China Statistics Yearbook, China Marine Economic Statistics Yearbook, China Offshore Water Environmental Quality Bulletin, China Ecological Environment Bulletin, China Environmental Statistics Yearbook, China Energy Statistics Yearbook, China Urban Statistics Yearbook, and statistical yearbooks of each province. Table 2 presents the descriptive statistics of the regression variables involved in this paper.

4.2 Change trend of marine green economy efficiency in coastal areas of China

4.2.1 Measurement results of marine green economy efficiency

Based on the above research methods, we obtain marine green economy efficiency of different stages in China's coastal regions from 2006 to 2018. In order to compare marine green economy efficiency in different regions, we calculate the mean value of marine green economy efficiency in coastal regions of China. The results appear in Table 3. In terms of total efficiency, Liaoning's marine green economy level is the lowest, with an average efficiency value of less than 0.6. This is because most of Liaoning's marine economy development relies on traditional marine industries, and emerging marine industries account for a relatively small share, which limits the ability of high-quality development of the marine economy (Du et al., 2020; Liu and Xie, 2021). Moreover, Liaoning is a heavy industrial base in China, and most raw materials are for high energy-consuming and high-polluting products, resulting in a large discharge of industrial pollutants. Most industrial pollutants in coastal areas are

TABLE 2 Descriptive statistics of the regression variables.

Variable	Obs	Mean	Std. Dev.	Min	Max
efficiency	143	0.8740	0.1525	0.4769	1.0000
efficiency1	143	0.8771	0.1514	0.5640	1.0000
efficiency2	143	0.8849	0.2038	0.2187	1.0000
innovation	143	805.77	834.08	10.00	4889.00
fdi	143	0.0325	0.0208	0.0016	0.0819
egop	143	0.1800	0.0883	0.0524	0.3772
industry	143	0.3998	0.0910	0.1967	0.5262
open	143	0.5328	0.3961	0.0967	1.7215

TABLE 3 Mean values of marine green economy efficiency at different stages in each province.

Province	Total efficiency	Production efficiency	Governance efficiency
Tianjin	1.0000	1.0000	1.0000
Hebei	1.0000	1.0000	1.0000
Liaoning	0.5530	0.8335	0.3562
Shanghai	0.9986	1.0000	0.9972
Jiangsu	0.9822	0.9661	1.0000
Zhejiang	0.7947	0.6921	0.9174
Fujian	0.7522	0.8216	0.6971
Shandong	0.8166	0.7123	0.9394
Guangdong	0.7975	0.7758	0.8269
Guangxi	0.9527	0.9102	1.0000
Hainan	0.9665	0.9367	1.0000
Mean	0.8740	0.8771	0.8849

directly discharged into the adjacent sea area, which makes the deterioration of Liaoning's marine environment increasingly prominent and reduces marine green economy efficiency. We further analyze the efficiency of different stages and find that the low level of governance is the main reason to explain the low total efficiency of marine green economy in Liaoning.

Although the marine economy output values of Fujian, Zhejiang and Guangdong rank at the front in China, their marine green economy efficiency values are not high. The reason may be that, on the one hand, these regions overly pursue the rapid transformation of the marine economy, which makes the regional marine industry layout unreasonable (Du et al., 2020). Moreover, the higher level of marine economy development in these regions will also attract a large influx of foreign capital and labor, whereas some of the low levels of foreign capital inflow and industrial transfer will also reduce the marine green production efficiency (Zhao et al., 2018; Ding et al., 2018). On the other hand, rapid development of the marine economy is also accompanied by a large consumption of resources and energy, which may inhibit improvement of marine green economy efficiency. Moreover, a higher level of marine economy implies rapid development of the port economy, and the process of cargo transportation is bound to produce a large amount of pollutants, which pose a threat to marine ecology environment. By further analyzing the efficiency of different stages, we find that the lower total efficiency of the marine green economy in Fujian mainly stems from the lack of marine governance capacity, while those for Zhejiang and Guangdong are mainly caused by low production efficiency.

Tianjin, Shanghai, Jiangsu, and Hebei rank high in terms of marine green economy efficiency, which is due to their better geographical location and higher level of economic development. Among them, Shanghai and Tianjin have a strong economic foundation and superior geographical location and have invested heavily in marine education and marine science and technology with high utilization rates. Coupled with the rapid development of marine emerging industries, marine green economy development in Shanghai and Tianjin has achieved remarkable results.

The phenomenon of high efficiency of the marine green economy in Hebei is different from the results of some studies. This may be due to the fact that Hebei is close to Beijing and Tianjin, and so it is susceptible to the spillover effects of advanced regional technologies. The Beijing-Tianjin-Hebei Integration policy has greatly contributed to the improvement of the level of marine technological progress in Hebei (Wang et al., 2020c). Most scholars have shown that Hebei's marine technology efficiency is high (Kang et al., 2020;

Ning et al., 2020; Wang et al., 2020d). Moreover, according to the China Offshore Water Environment Quality Bulletin, the percentage of excellent water quality in Hebei's offshore waters exceeded 75% from 2006 to 2018, and the percentage of excellent water quality reached 100% in 2018. It can be seen that the water quality situation of Hebei's near-shore sea is relatively good and stable, which is one of the reasons to explain the high efficiency of its marine green economy.

The relatively high efficiency of the marine green economy in Hainan and Guangxi is mainly a result of the high efficiency of environmental governance. The industrial scale of the land area of Hainan and Guangxi is small as is industrial pollution emission, making indicators of the marine ecology environment at the forefront of the country. Among them, Hainan has abundant marine resources, and the marine tertiary industry accounts for a high proportion, which in turn effectively promotes improvement of marine production efficiency (Wang et al., 2021c). In recent years, Guangxi has also been actively promoting the level of marine industry structure, carrying out a blue bay improvement action (Ding et al., 2015), which can be taken as a reason to explain the high efficiency of marine governance in Guangxi. In addition, coastal tourism is the advantageous industry of Hainan and Guangxi, which determines their emphasis on environmental governance and environmental protection.

To sum up, the provinces that rank high in overall efficiency of the marine green economy are more efficient at different stages, implying that the marine production process is as important as the governance process. The common feature of these provinces is that they are not only committed to improving the efficiency of marine production process, but they also pay attention to the management of marine pollutants. On the one hand, these provinces combine their development advantages to continuously optimize the marine industry structure. Among them, Tianjin, Shanghai, Jiangsu, and Hebei have a high level of marine technology and are committed to actively developing new marine industries. Hainan and Guangxi vigorously promote the development of marine tertiary industries mainly in coastal tourism. On the other hand, these provinces may pay more attention to marine environmental protection and continue to step up efforts to regulate offshore waters. This has led to efficient management of marine pollutants, thus promoting marine green economy efficiency.

4.2.2 Trends in the evolution of marine green economy efficiency

In order to analyze marine green economy efficiency in different periods, we plot the changing trend of this efficiency in different stages from 2006 to 2018. The results appear in Figure 1. The figure illustrates that total efficiency and production efficiency of the marine green economy have a fluctuating downward trend in general. The total efficiency of China's marine green economy decreased from 0.9249 in 2006 to 0.8763 in 2018, which indicates that the level of its marine green development still has much room for improvement. Among them, the change trends of total efficiency and production efficiency are roughly the same, but differ from that of governance efficiency. Specifically, production efficiency showed a relatively large decline in 2008, which is mainly due to the impact of the global financial crisis in 2008. The import and export trade in China's coastal areas and investment in the marine industry decreased significantly, and the production process of the marine economy was restricted, which in turn hindered improvement of marine green production capacity. However, governance efficiency did not show a downward trend in 2008, and only began to decline in 2009. This is because there is a lag effect in pollution governance efficiency, and pollution governance behavior and effect are generally based on previous policy measures. Moreover, the impact of a financial crisis first acts directly on the marine production process, making the marine economy output drop significantly. On this basis, it may lead to a reduction of pollution control investment, which in turn affects marine environmental governance efficiency.

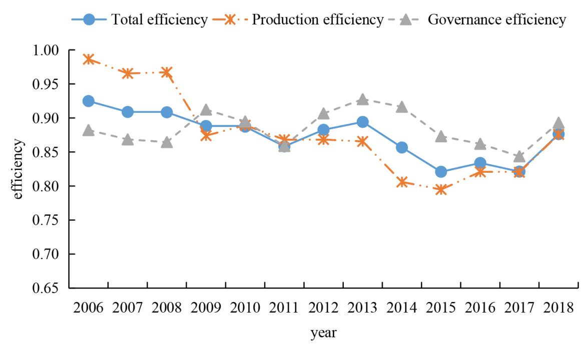

FIGURE 1
Trends of marine green economy efficiency in different stages from 2006 to 2018.

In 2012, marine governance efficiency changed from a downward trend to an upward trend. This may be due to the introduction of the 12th Five-Year Plan, making local governments pay more attention to marine economy development and comprehensive marine management, increasing the protection and restoration of marine ecosystems, and ultimately improving the efficiency of marine environmental governance. Subsequently, during 2013-2015, marine production efficiency declined, largely due to frequent marine disasters, especially the severe marine disaster in 2013. Its subsequent effects caused huge losses to China's marine green economy. Since 2016, the marine production efficiency has been rising, because 2016 is the first year of the 13th Five-Year plan. The China government attaches great importance to the marine economy and has formulated a series of measures to accelerate the development of both marine science and technology and the marine industry. For example, the National Science and Technology Plan for Marine Development (2016-2020) was introduced in 2016, which is conducive to the formation of a long-term mechanism for innovation-driven development to improve marine green economy efficiency.

4.3 Convergence analysis of marine green economy efficiency

Figure 2 portrays the σ convergence results of marine green economy efficiency at different stages. From the overall stage, the σ coefficient of China's marine green economy efficiency shows a fluctuating trend. It shows a gradual increasing trend during 2008-2011 and 2013-2016, indicating that there is no σ convergence in marine green economy efficiency at this stage, that is - regional

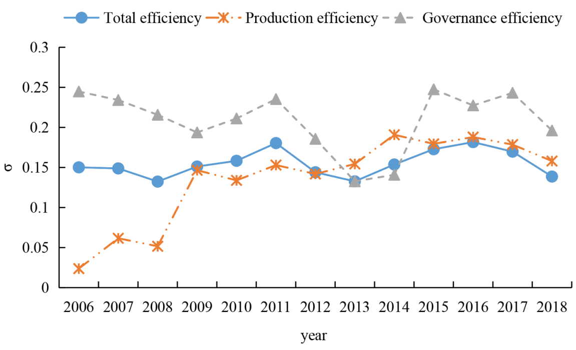

FIGURE 2
Trends of σ convergence coefficients of marine green economy efficiency at different stages.

differences in marine green economy efficiency keep expanding. In other time periods, σ coefficients show a decreasing trend, indicating that marine green economy efficiency has σ convergence characteristics, that is - regional differences of marine green economy efficiency are gradually narrowing. From the perspective of the production stage, the σ coefficient of China's marine production efficiency shows a process of rising first and then falling. The rising stage mainly occurred in 2006-2014, and the σ coefficient increased by 0.1671 in 2014 compared with 2006. This is an increase of about 7 times, indicating dispersion characteristics of marine production efficiency, that is - regional differences in production efficiency are expanding. The downward trend of the σ coefficient from 2014 to 2018 is obvious. Compared with 2014, the coefficient value in 2018 decreased by 0.0328 or 17.17%, which means that marine production efficiency tended to converge in 2014-2018. The σ coefficients of ocean governance efficiency show an increasing trend during 2009-2011 and 2013-2015, which suggests no σ convergence characteristic of governance efficiency, that is - the regional disparity of marine governance efficiency increases. Other than that, the σ coefficients of other time periods show a decreasing trend, which implies σ convergence in governance efficiency, that is - the regional disparity in governance efficiency is significantly reduced.

Table 4 reports the results of absolute β convergence for the marine green economy efficiency at different stages. In terms of total efficiency, the estimation results of both fixed-effect and random-effect models indicate that the absolute β convergence coefficient is negative, and both pass the significance level test. The results mean absolute β convergence in the total efficiency of the marine green economy, and changes in marine green economy efficiency in each coastal region converge to the same steady-state level over time. In other words, provinces with low levels of marine green economy have faster growth rates compared to those with high levels, and the regional gap will gradually narrow. The estimated coefficients of absolute β convergence for both marine production efficiency and governance efficiency are significantly negative at least at the 10% statistical level, which indicates that both efficiencies have absolute β convergence characteristics, and that regional disparity will keep narrowing and eventually reach the steady-state level. The results also reflect the catch-up effect of the lagging regions to the advanced regions, that is - provinces and cities with low levels of marine green production and governance have a high convergence rate.

4.4 Analysis of the influencing factors of marine green economy efficiency

Based on the above analysis, this study uses the Tobit model to conduct regression tests on the influencing factors of marine green economy efficiency. The Tobit model with fixed effects cannot find sufficient statistics of individual heterogeneity for conditional maximum likelihood estimation, and the estimates obtained are inconsistent if dummy variables of panel units are added directly to the mixed Tobit regression (Chen, 2014). We find that the LR test results strongly reject the original hypothesis by using the panel Tobit model of random effects, which shows that there an individual effect and a random effects panel Tobit model should be used for regression analysis. The estimation results are in Tables 5 and 6.

4.4.1 Total efficiency

Table 5 reports the regression results of the influencing factors of marine green economy efficiency. As seen from the table, the coefficient of marine technology innovation on marine green economy efficiency is positive, but the result is not significant. This is consistent with the findings of Guo et al. (2022). This may be due to the fact that China's marine technology innovation is still in the exploration stage, and the number of marine scientific research institutions is small, resulting in insufficient technological R&D capacity. Moreover, the transformation rate of China's marine

TABLE 4 Absolute β convergence results of marine green economy efficiency at different stages.

Variable	Total efficiency		Production efficiency		Governance efficiency	
	FE	RE	FE	RE	FE	RE
α	-0.0759*** (-5.41)	-0.0273** (-2.19)	-0.0288 (-1.59)	-0.0246* (-1.67)	-0.1695*** (-6.65)	-0.0350 (-1.55)
β	-0.6211*** (-5.21)	-0.1020* (-1.89)	-0.4079*** (-4.13)	-0.1068* (-1.95)	-0.8487*** (-29.71)	-0.1311** (-2.58)
Time effect	Yes	Yes	Yes	Yes	Yes	Yes
Individual effect	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.4113	0.2376	0.3513	0.2719	0.5063	0.2467

***, **, and * indicate that the variables are significant at 1%, 5%, and 10% levels, respectively. The values in parentheses are t-statistics.

TABLE 5 Tobit regression results of marine green economy efficiency.

Variable	Total efficiency			
	Coefficient	Standard error	z	p>|z|
ln*innovation*	0.0045	0.0165	0.27	0.784
ln*fdi*	0.0385**	0.0184	2.09	0.036
ln*egop*	-0.2004***	0.0546	-3.67	0.000
ln*industry*	-0.2579*	0.1469	-1.76	0.079
ln*open*	0.0950***	0.0331	2.87	0.004
Cons	-0.5695***	.01989	-2.86	0.004

***, **, and * indicate the variables are significant at the 1%, 5%, and 10% levels, respectively.

TABLE 6 Tobit regression results of marine green economy efficiency at different stages.

Variable	Production efficiency				Governance efficiency			
	Coefficient	Standard error	z	p>|z|	Coefficient	Standard error	z	p>|z|
ln*innovation*	-0.0327	0.0205	-1.59	0.111	0.0519**	0.0263	1.97	0.049
ln*fdi*	0.0488*	0.0258	1.89	0.058	0.0525*	0.0280	1.87	0.061
ln*egop*	-0.2252***	0.0611	-3.69	0.000	-0.1092	0.0877	-1.24	0.213
ln*industry*	-0.3940***	0.1446	-2.72	0.006	-0.0341	0.2215	-0.15	0.878
ln*open*	0.1682***	0.0415	4.06	0.000	0.0001	0.0520	0.00	0.998
Cons	-0.4138	0.2550	0.105	0.105	-0.5172*	0.3136	-1.65	0.099

***, **, and * indicate the variables are significant at the 1%, 5%, and 10% levels, respectively.

scientific research results is not high, and many marine patents are difficult to be put into practical application. Thus, the positive impact of technological innovation on marine green economy efficiency fails to be highlighted. China still needs to further strengthen R&D in marine technology and continuously improve its marine green innovation capability, which is a key factor to support sustainable development of the marine economy (Wei et al., 2021).

The regression coefficient of foreign direct investment (FDI) is significantly positive at the 5% statistical level, indicating that FDI improves the efficiency of regional marine green development. The reason for this is that, on the one hand, the inflow of foreign investment accompanied by the transfer of advanced technology can improve the production process of enterprises, which in turn continuously optimize the marine ecological environment in coastal areas (Zhao et al., 2018; Zheng et al., 2022). In particular, the introduction of FDI related to marine industries brings advanced marine technology and marine management concepts to coastal areas and helps improve the degree of development and utilization of marine resources. On the other hand, foreign capital inflow provides conditions for the development of emerging marine industries in coastal areas, transforming the industrial structure to be more rationalized and high-end (Zheng et al., 2022). The transformation and upgrading of marine industrial structure help reduce resource consumption and marine environmental pollution and promote continuous improvement of marine green development efficiency (Ye et al., 2021; Wei et al., 2021).

The regression coefficient of the level of marine economy development is significantly negative at the 1% statistical level. This result differs from the general findings, which is probably due to the fact that the port economy is an important component of the marine economy, and the process of marine cargo transportation inevitably generates a large amount of pollutants that pose a threat to the marine ecological environment (Ding et al., 2018; Nogué-Algueró, 2020). In addition, even with the rapid development of China's marine tertiary industry in recent years, the output value of the secondary industry, mainly marine equipment manufacturing and sea salt chemical industry, still accounts for a large proportion. This brings about a significant increase in resource consumption and pollutant emissions, and the balance between marine resources and ecological environment has been seriously damaged, thus inhibiting the improvement of marine green economy efficiency (Wang, 2021). The regression coefficient of terrestrial industrial development level is significantly negative at the 10% statistical level, which means that growth of the terrestrial industrial scale reduces marine green economy efficiency, because coastal industrial pollution is the major source of marine environmental pollution (Naser, 2013; Anbuselvan and Sridharan, 2018). Industrial production in coastal areas produces a large amount of industrial wastewater and solid waste, and the vast majority of these pollutants are discharged into the ocean (Sheppard et al., 2010; Fu and Wang, 2011), which seriously impact water quality of the near coast and harm the development of the marine green economy (Ding et al., 2018).

The regression coefficient of opening up is significantly positive at the 1% statistical level, indicating that improvement of external openness helps promote marine green economy development. The possible explanations for this result are as follows. First, since the east coast is the pioneer area of China's opening up, regional governments have promulgated a series of policies and measures to encourage economic development, pushing a large amount of capital and labor at home and abroad to gather in the marine industry, thus effectively enhancing marine economy development (Zhao et al., 2016). Second, as the marine economy is export-oriented, further expansion of opening up is also conducive to the rapid development of marine tourism in coastal areas, which is an important measure to achieve marine economy growth (Bob et al., 2018; Rogerson and Rogerson, 2019). Moreover, the development of the marine tertiary industry, mainly tourism and other service industries, helps promote the upgrading of marine industries and improvement of the marine green development efficiency.

4.4.2 Production efficiency

Table 6 reports the regression results of marine green economy efficiency at different stages. In the production stage the regression coefficients of FDI and opening up are significantly positive, the coefficients of marine economy development level and terrestrial industrial development level are significantly negative, while the coefficient of marine technological innovation is not significant. This suggests that the improvement of FDI and opening up has a positive effect on marine production efficiency, while marine economy development and terrestrial industrial development inhibit the improvement of marine production efficiency. The results are consistent with the estimation of total efficiency.

4.4.3 Governance efficiency

In the governance stage the regression results of governance efficiency differ significantly from total efficiency and production efficiency. Among them, the regression coefficient of marine technological innovation is significantly positive at the 5% statistical level, implying that marine technological innovation effectively promotes the improvement of marine governance efficiency. Although marine technological innovation has failed to improve marine production stage efficiency, it has an important role in the governance of marine pollutants (Mintenig et al., 2017; Alpizar et al., 2020). This may be due to the fact that China's currrent marine technology innovation is more biased towards the application of environmental management technologies. Compared with the application of technology of reducing pollution in the production process, the application of the technology of direct treatment of pollutant emissions produces a faster and more obvious effect. Moreover, in recent years the China government has attached great importance to marine ecological issues that has led to certain breakthroughs in technological research focusing on water quality improvement and marine function enhancement.

The regression coefficient of FDI is significantly positive at the 10% statistical level, indicating that an increase of it has a positive contribution to pollution control efficiency. The reason is that the inflow of high-quality FDI brings advanced marine management concepts and pollution management standards and enhances marine governance technology through technology spillover effects (Zheng et al., 2022). Moreover, the introduction of FDI is bound to enhance regional economic development and increase funds for marine environment management and technology R&D in coastal areas, which can continuously improve marine pollution management efficiency (Zhao et al., 2018). In addition, to attract more FDI in the marine industry, local governments may strengthen the efforts of marine pollution management to provide a high-quality marine development environment for foreign-capitalized industries.

The level of marine economy development fails to pass the significance test. One possible explanation is that although the rapid development of the marine economy promotes the increase of marine governance funds, the environmental problems brought about by the process of such development cannot be ignored and also makes the pollution governance effect not obvious. The impacts of industrial development level and opening up on governance efficiency are also not significant. This is due to the fact that the impacts of an increase of industrial development level and opening up on marine economy development reflect more in the production stage and little in the governance stage.

5 Conclusions and policy recommendations

Based on panel data of 11 coastal provinces and cities in China from 2006 to 2018, we use a two-stage network DEA model to measure marine green economy efficiency. On this basis, the panel Tobit model allows us to examine the influencing factors of such efficiency.

The conclusions of this paper can be summarized as follows. First, there are great differences in total efficiency, production efficiency and governance efficiency of the marine green economy in different provinces and cities, and total efficiency and production efficiency of the marine green economy generally show a fluctuating downward trend. Second, the σ coefficient of marine production efficiency has a rising trend in general, that is - marine production efficiency has the characteristics of σ convergence, while total efficiency and governance efficiency do not have σ convergence. There is also an absolute β convergence phenomenon in total efficiency, production efficiency, and governance efficiency. Third, from the perspective of the overall stage and production stage, FDI and opening up are conducive to promoting total efficiency and production efficiency, while improvement of the marine economy development level and terrestrial industry development level reduces total efficiency and production efficiency. Moreover, the effect of marine technological innovation on total efficiency and production efficiency is not significant. From the perspective of the governance stage, marine technological innovation and FDI have a significantly positive role in promoting environmental governance efficiency.

According to the above conclusions, we put forward the following policy recommendations.

First, the government should accurately identify the gap between regional production efficiency and governance efficiency and take measures according to local conditions to promote high-quality development of the marine economy. For example, Liaoning should reduce industries with high pollution and energy consumption, lower the discharge of marine pollutants, and adopt strict marine supervision measures. At the same time, it can increase investment in marine pollution control and improve marine environmental governance efficiency. Some areas with high gross marine product should constantly optimize the marine industry layout, promote the transformation and upgrading of the marine economy in a rational and orderly manner, and avoid neglecting the protection of the ecological environment due to excessive pursuit of marine economy growth.

Second, the local government needs to further raise investment in marine science and technology research and development to improve the ability of marine technology innovation. The government should vigorously support marine frontier technology research, especially technology research and development in the process of marine production. At the same time, more funds are encouraged to stay in areas such as marine green technology and clean technology.

Third, it is necessary to optimize the structure of land and sea industries. All regions should vigorously develop the marine tertiary industry and marine emerging industries to reduce pollutant emissions and excessive consumption of marine resources. At the same time, industrial pollution discharge standards for land areas should be formulated to help authorities strictly supervise and control the discharge of industrial pollutants from land areas into the sea. In addition, the central government should implement a target responsibility system for energy conservation and emission reduction, increase the proportion of marine ecological environment in the assessment of local governments, and promote local governments to continuously improve laws and regulations, so as to provide impetus for marine green economy development.

Fourth, local governments should further introduce high-quality marine foreign investment and expand the degree of opening up. Local governments should continue to relax the restrictions on foreign investment access, expand the opening of marine industries with high technology and added value, actively guide foreign investment to marine emerging industries, and promote the rapid development of the marine green economy. At the same time, tax incentives and financial subsidies are also important ways to introduce high-level marine foreign-invested industries, which can help promote the transformation and upgrading of the marine industrial structure.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

Conceptualization: YY and HC. Methodology: HC. Software: YY. Validation: WZ, YY and HC. Formal analysis: XZ. Investigation: MY. Resources: SL. Data curation: YY, HC and WZ. Writing—original draft preparation: YY and HC. Writing—review and editing: WZ and YY. Visualization: YY and HC. Supervision: WZ. Project administration: WZ. Funding acquisition: WZ. All authors contributed to the article and approved the submitted version.

Funding

This research was funded by the Innovation Strategy Research Project of Fujian Province (No. 2022R0030); GF Securities Social Welfare Foundation Teaching and Research Fund for National Finance and Mesoeconomics.

Acknowledgments

The authors are grateful to the editor and the reviewers of this paper.

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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