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Research on the impact mechanism of scientific and technological innovation on the high-quality development of the marine economy

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Promoting the high-quality development of the marine economy is an inevitable choice for building a maritime power, and technological innovation can provide strong impetus for the high-quality development of the marine economy. Therefore, it is urgent to clarify the impact mechanism of technological innovation on the high-quality development of the marine economy, and promote the high-quality development of the marine economy. This study employs panel data from 11 coastal provinces and municipalities (autonomous regions) in China, spanning the years 2006 to 2020. The objective is to empirically evaluate the mechanism through which scientific and technical innovation impacts the high-quality development of the marine economy. This is achieved by utilizing the PVAR model and the mediation effect model. The research findings indicate that there is a noteworthy impact of enhancing scientific and technological innovation on the marine economy of China. Moreover, there exists a significant reciprocal relationship between scientific and technological innovation and the pursuit of high-quality development in the marine economy. It is observed that scientific and technological innovation not only has a positive influence on the high-quality development of the marine economy by enhancing green total factor productivity and optimizing the industrial structure, but it also facilitates the advancement of the marine economy through the chain mediation path of "improving green total factor productivity and optimizing industrial structure".

KEYWORDS

scientific and technological innovation, high-quality development of marine economy, influencing mechanism, PVAR model, mesomeric effect

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1 Introduction

The concept of "high-quality development" was initially proposed in the report of the 19th National Congress of the Communist Party of China. This signifies a new era in the Chinese economy, characterized by enhanced quality, efficiency, and the pursuit of high-quality development as a fundamental necessity and significant objective in China's economic progress. The marine economy has significant strategic importance for China's national economy, serving as a new focal point for high-quality development. Simultaneously, the advancement of scientific and technological innovations assumes a pivotal role in driving economic development. As General Secretary Xi Jinping made evident in the 19th Party Congress report, "innovation is the first driving force for development." In order to fully exert the influence of science and technology innovation on the high-quality development of the marine economy and to promote the high-quality development of the marine economy, it is imperative that the relationship between scientific and technological innovation and the high-quality development of the marine economy be explored, and the mechanism by which scientific and technological innovation contributes to the high-quality development of the marine economy be clarified.

The idea of "high-quality development of the marine economy" has drawn a lot of attention from the academic community since it was introduced. Numerous experts and scholars have studied the scientific meaning of "high-quality development of the marine economy" (Sun C. et al., 2023), as well as its development efficiency (Guo et al., 2022), development dynamics (Liu et al., 2021; Wu F. et al., 2023) and comprehensive level (Sun Z. et al., 2023; Wu C. et al., 2023). The achievement of high-quality development in the marine economy is attributed to several factors. These include the quantitative expansion of the marine economy to a specific threshold, the enhancement of the oceans' overall capacity, the optimization of the marine industry's structure, the improvement of the distribution of social welfare related to marine activities, and the preservation of a harmonious marine ecological environment. These factors collectively contribute to establishing a dynamic equilibrium within the "economic-social-resource-environmental" system of human-sea interactions. The primary drivers behind the pursuit of high-quality development in the marine economy encompass capital, technology, labor, and advancements in technology (Shan and Cao, 2022). In relation to the comprehensive assessment of the high-quality advancement of the marine economy, certain scholars posit that the total factor productivity (TFP) of marine green sectors can partially reflect the extent of such development. To quantify this, scholars employ methodologies such as the SBM model and the DEA Malmquist index for computation (Lingui et al., 2021; Wei et al., 2021). Scholars often assess the high-quality development level of marine economy by establishing an evaluation index system (Yu and Xing, 2021; Gao et al., 2022).

In relation to the study on the correlation between technological innovation and high-quality economic development, certain scholars perceive scientific and technological innovation as an intermediary variable and believe that the digital economy (Ding et al., 2021), environmental regulations (Li and Hu, 2021; Shi et al., 2023), green finance (Liu et al., 2021) and other means can act on scientific and technological innovation, promoting high-quality economic development by improving technological innovation capabilities. According to Wang's empirical research, it has been determined that technological innovation plays a crucial role in facilitating the high-quality development of regional economies. In order to enhance the level of regional technological innovation, it is imperative to focus on enhancing the endowment conditions and allocation efficiency of investments in technological innovation factors (Jianmin and Li, 2020). Various forms of marine scientific and technical innovation have distinct long-term and short-term effects on the high-quality development of the marine economy (Wu et al., 2020).

To summarize, previous studies on the advancement of the maritime economy and the influence of technical innovation on its progress have distinct features and have yielded valuable outcomes. These studies serve as significant reference materials for the present investigation. Nevertheless, there is a dearth of research regarding the correlation between technological innovation and the high-quality advancement of the marine economy, rendering it challenging to unveil the precise influence mechanism of technological innovation on the high-quality development of the marine economy. Additional investigation is still necessary. First and foremost, it is necessary to promptly ascertain the present state of technical innovation and the high-quality advancement of the maritime industry. Does technological innovation have a direct impact on the high-quality development of the maritime economy? Research urgently required: Does the green total factor productivity of the ocean and the structure of the ocean industry work as a mediator between technical innovation and the high-quality development of the ocean economy? What does the term "mediating effect" refer to? Additional investigation is still required. This article discusses the impact of technological innovation on the high-quality development of the marine economy, specifically focusing on the need to transform the growth mode from factor-driven and investment-driven to innovation-driven. Using panel data from 11 coastal provinces and cities in China spanning from 2006 to 2020, this study employs the PVAR model and mediation effect model to empirically examine the direct influence and mediating function of technical innovation on the high-quality advancement of the marine economy. Conduct research on the mechanism by which technological innovation drives the high-quality development of the marine economy. Examine the current state of marine technological innovation in China from both theoretical and practical angles. Analyze the impact of technological innovation on the high-quality development of the marine economy. Based on the research findings, propose policy recommendations that promote the high-quality development of China's marine economy. This research holds significant importance for the advancement of China's marine economy.

2 Theoretical mechanism analysis

2.1 The direct impact of scientific and technological innovation on the high-quality of marine economy

Currently, the marine economy of China is undergoing a gradual transition from a phase characterized by high-speed growth to one characterized by high-quality development. Progressively, the traditional marine economy is experiencing a decline in its growth momentum. Enhanced efficiency and sustainability in marine resource development have resulted from the scientific and technological innovation level of marine continuing to rise. The advancements in science and technology have presented novel prospects for the conventional fishery and marine aquaculture sectors, thereby fostering the modernization and expansion of the traditional marine industry. In addition, scientific and technological innovation contributes significantly to the preservation of the marine environment by facilitating the use of renewable energy technologies to reduce pollution and enhance the health of marine ecosystems. Consequently, scientific and technological innovation serves as a direct catalyst for the advancement of high-quality economic development.

Hypothesis 1: The high-quality development of the marine economy is significantly enhanced by scientific and technological innovation.

2.2 The indirect effects of scientific and technological innovation on high-quality development of marine economy

Based on the tenets of Western economic development theory, the attainment of economic growth may be accomplished via two primary mechanisms: augmenting factor input and enhancing the efficacy of component use. The crucial aspect in fostering economic growth of superior quality via technological innovation is in the optimization of resource allocation efficiency via technological advancements, thereby enhancing the degree of green total factor productivity. The promotion impact of scientific and technological innovation on the green total factor productivity of the marine economy may be primarily seen via three primary aspects: Firstly, by means of scientific and technological advancements, the efficacy of marine production elements, such as labor and capital, is enhanced twofold or substituted with intelligent alternatives, thereby facilitating the enhancement of marine green total factor productivity. Secondly, the efficiency of marine resource utilization is enhanced through scientific and technological innovation, leading to the attainment of energy conservation and emission reduction objectives. Furthermore, it is essential to enhance the use of marine resources by means of scientific and technical advancements, while concurrently advocating for sustainable marine production and consumption practices. Hence, it can be argued that scientific and technical advancements have a favorable influence on the overall efficiency of the marine economy in terms of environmental sustainability. Consequently, these advancements indirectly contribute to the enhancement of the marine economy's quality and development.

Hypothesis 2: Scientific and technological innovation serves as a driving force for the high-quality development of the marine economy, with the enhancement of green total factor productivity playing a crucial mediating role in this process.

Since the implementation of reform and opening up policies over four decades ago, the marine economy of China has seen significant and fast growth, accompanied by subtle transformation in the structure of its marine industry. Scientific and technological innovation plays a crucial role in driving the high-quality development of the marine economy. As a significant driving force, it progressively impacts the industrial structure of China's marine economy, steering it towards a more rationalized state. Firstly, scientific and technological innovation facilitates the adjustment and upgrading of the industrial structure of the marine economy from both the supply and demand perspectives; Secondly, the promotion of scientific and technological innovation fosters the emergence of correlation effects within different sectors of the marine industry. Thirdly, scientific and technological innovation expedites the amalgamation of marine industries, leading to the creation of new sectors within the existing industries, and facilitating the transformation and advancement of conventional marine industries. In addition, scientific and technological innovation have the potential to enhance the social division of labor, facilitate the migration of individuals employed in sea-related occupations, alter the composition of sea-related employment, and drive the progression of marine industrial structure. Hence, scientific and technological innovation can optimize the marine industrial structure to a certain extent, and indirectly promote the high-quality development of the marine economy.

Hypothesis 3: The optimization of industrial structure plays a crucial role in mediating the high-quality development of the marine economy, which is driven by scientific and technological innovation.

For the marine industry, enhancing green total factor productivity means optimizing the development and usage of marine resources, hence boosting resource efficiency and minimizing marine resource consumption. Green total factor productivity focuses on decreasing marine environmental pollution and ecological damage, as well as lowering its influence on the marine ecological environment via the employment of clean technologies and environmentally friendly production methods. The enhancement of green total factor productivity has to be realized via scientific and technological innovation. By implementing cutting-edge technologies and environmentally sustainable production techniques, the marine industry can transition from traditional resource development to knowledge-intensive sectors with high added value, thereby enhancing its competitiveness and capacity for innovation. Therefore, increasing the green total factor productivity of the marine industry can facilitate the conversion of conventional marine industries characterized by high energy consumption and pollution levels into green, low-carbon industries, stimulate industrial modernization, and optimize industrial structure. As a result, the enhancement effect of scientific and technological innovation on green total factor productivity can further facilitate the upgrading of the structure of the marine industry, thereby fostering high-quality development of the marine economy.

Hypothesis 4: "Improvement of green total factor productivity - optimization of industrial structure" plays a chain intermediary role in the process of high-quality development of marine economy driven by driven by scientific and technological innovation.

Figure 1 illustrates the impact mechanism via which scientific and technological innovation facilitates the high-quality development of the maritime economy.

3 Materials and methods

3.1 Variable declaration

3.1.1 Explained variable: high-quality development of marine economy

Following the principles of purposefulness, completeness, operability, independence, and importance, on the basis of the scientific meaning and fundamental features of high-quality development of the marine economy, in accordance with the five major development concepts and pertinent literature, develop a robust indicator system for the marine economy that takes into account the overall economic output and is directed by the five primary development principles. Given that the "Five Development Concepts" prioritize effective processes, while "Economy Ecology Society" prioritizes favorable outcomes, and considering that this study focuses on the influence of technological innovation on the high-quality development of the marine economy, if we create an indicator system for the high-quality development of the marine economy based on the five development concepts, then the indicators related to innovative development in the five development concepts will unavoidably overlap with the scientific and technological innovation indicator system constructed from the perspective of the innovation ecosystem in this article to some extent. This overlap, known as multicollinearity, will impact the results of the empirical test. Hence, we consult pertinent research and establish a top-notch development indicator system for the marine economy, encompassing three key dimensions: economy, ecology, and society. (as shown in Table 1). The attainment of a specific degree of comprehensive economic prowess serves as the bedrock for the high-caliber advancement of the marine economy. Indicators are carefully chosen from four key dimensions: economic magnitude, economic composition, economic returns, and international commerce. An optimal ecological environment and the sustainable growth of the marine economy are essential and widespread conditions for achieving high-quality development of the marine economy. These conditions can be evaluated based on three factors: availability of resources, preservation of the environment, and control of pollution emissions. The high-quality growth of the maritime economy aims to achieve social harmony and symbiosis. To measure this, indicators are chosen from four areas: urban-rural structure, regional coordination, resident life, and social welfare.

Furthermore, to determine the level of high-quality development (HQME) of China's marine economy, the comprehensive index of high-quality development of the marine economy is computed utilizing the entropy weighted Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method (Zhang et al., 2022), the comprehensive index results of high-quality development of marine economy are shown in Table 2.

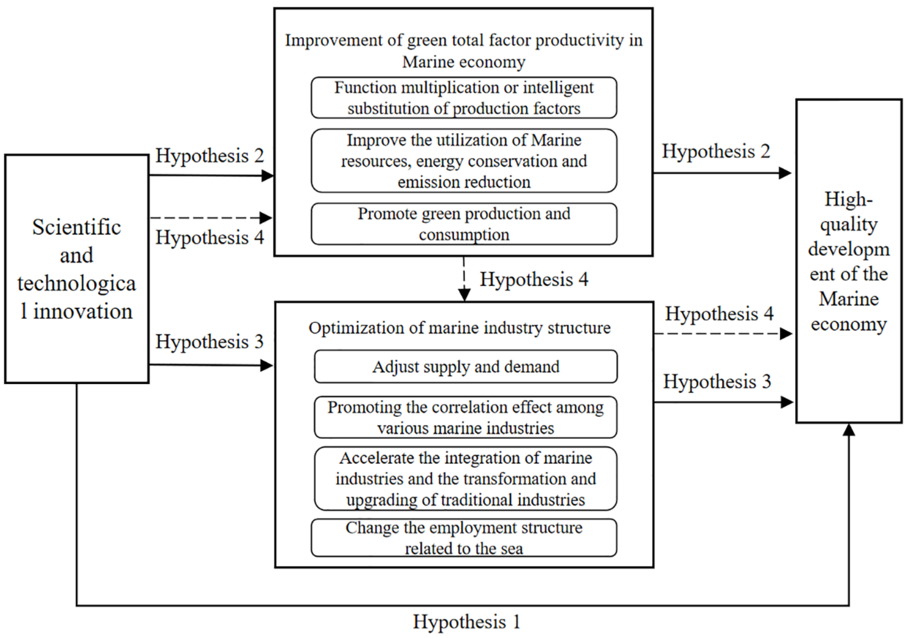

FIGURE 1
The impact mechanism of scientific and technological innovation driving high-quality development of marine economy.

TABLE 1 Evaluation index system of high-quality development of marine economy.

First level dimension	Secondary criteria	Specific indicators (attributes)
Economics	Economic Scale	Gross Ocean Product(GOP) (+)
		The Proportion of GOP to GDP (+)
		The Proportion of Marine Fishery Output Value to GOP (+)
		Added Value of Marine Industry (+)
	Economic Structure	The Proportion of Marine Secondary Industry in GOP (+)
		The Proportion of Added Value of Marine Industry to Gross Marine Product (+)
		Advanced Industrial Structure (+)
	Economic Benefits	Marine Labor Productivity (+)
		Growth Rate of Marine Economy(+)
	Foreign Trade	Ratio of Total Import and Export Volume to GOP (+)
		Proportion of Port Cargo Throughput to GOP (+)
Ecologically	Endowment	Per Capita Water Resources (+)
		Length of Coastal Wharf (+)
		Proportion of Class I and Class II Seawater in Nearshore Waters (+)
	Environmental Protection	Number of Marine Protected Areas (+)
		Investment in Pollution Control in Coastal Areas (+)
		Marine Type Protected Area (+)
		The Number of Wastewater Treatment Projects Completed in that Year (+)
	Environmental Disruption	Industrial Wastewater Discharge per Unit of Regional Gross Marine Product(-)
		Industrial Emissions of Sulfur Dioxide per Unit of Regional Gross Marine Product (-)
		Direct Discharge of Wastewater into Massive Amounts (-)
		Solid Waste Emissions from Coastal Industries (-)
Societies	Regional Coordination	Consumption Level Ratio of Urban and Rural Residents in Coastal Cities (-)
		Population Ratio between Urban and Rural Areas in Coastal Cities (+)
		The Proportion of Consumption Level of Residents in Coastal Urban Areas to the National Consumption Level (+)
	Resident Life	Engel Coefficient (-)
		Employment Situation of urban units (+)
	Social Welfare	Urban Per Capita Consumption Level (+)
		Number of Healthcare Institutions Per Capita (+)

[1]The attribute "+(-)" denotes that the evaluation indication is a benefit-based (cost-based) indicator, assuming a predetermined measurement technique. In this context, a higher (lower) attribute value is considered more favorable.

3.1.2 Explanatory variable: scientific and technological innovation

In order to assess the degree of scientific and technological innovation, this article develops a scientific and technological innovation evaluation index system from the innovation ecosystem's perspective. The index consists of twenty-one indicators, as shown in Table 3, and is based on the innovation ecosystem's three facets: innovation subjects, innovation resources, and innovation environment. Likewise, the comprehensive index of scientific and technological innovation is computed utilizing the entropy weighted TOPSIS method, with the purpose of assessing the degree of scientific and technological innovation in the marine sector of China, the comprehensive index results of scientific and technological innovation are shown in Table 4. To further explore the impacts of specific aspects of scientific and technological innovation on the high-quality development of the marine economy, the notion of marine scientific and technological innovation is dissected into three constituent elements: innovation subjects (IS), innovation resources (IR), and innovation environment (IE). This analysis is predicated upon the constituent components of the maritime innovation ecosystem. In addition, the entropy weighted approach is used to compute the respective indices for these components.

3.1.3 Mediating variables

(1) Marine Green Total Factor Productivity (MGTFP)

This study presents the construction of an input-output index system for measuring the total factor productivity of the marine economy. The resulting system is shown in Table 5. Additionally, the measurement of green total factor productivity is conducted using the super-efficiency SBM model, taking into account the non-expected output (Tone, 2002; Wang and Zhao, 2022).

(2) Marine Industrial Structure (MIS)

The optimization of the maritime industrial structure pertains to the ongoing process of enhancing the quality of the industrial structure and achieving the transformation from a low-level to a high-level state. Given the obvious characteristics of ocean service in the economic field, drawing on the approach of scholars such as Ma Jun (Ma and Wang, 2019), the ratio of added value of the marine tertiary industry to that of the marine secondary industry is chosen as an indicator to measure the degree of optimization of the marine industry structure.

3.1.4 Control variables

Drawing upon the scholarly work of previous researchers (Shi et al., 2020; Wilson, 2020; Khan and Ahmad, 2021; Yang et al., 2021;

TABLE 2 Results of the comprehensive index for high-quality development of marine economy.

Province	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Tianjin	0.193	0.193	0.192	0.194	0.202	0.207	0.209	0.239	0.255	0.242	0.230	0.240	0.248	0.275	0.278
Hebei	0.159	0.160	0.160	0.273	0.267	0.271	0.268	0.274	0.278	0.271	0.277	0.284	0.291	0.293	0.298
Liaoning	0.194	0.198	0.185	0.207	0.201	0.210	0.223	0.231	0.241	0.239	0.260	0.268	0.256	0.252	0.256
Shandong	0.249	0.265	0.329	0.310	0.323	0.338	0.356	0.374	0.441	0.429	0.499	0.501	0.477	0.467	0.480
Mean Value	0.199	0.204	0.216	0.246	0.248	0.256	0.264	0.280	0.304	0.295	0.317	0.324	0.318	0.322	0.328
Shanghai	0.345	0.339	0.343	0.327	0.335	0.344	0.347	0.405	0.412	0.415	0.443	0.453	0.449	0.458	0.469
Jiangsu	0.262	0.250	0.264	0.234	0.230	0.261	0.262	0.284	0.293	0.300	0.311	0.317	0.316	0.329	0.336
Zhejiang	0.195	0.204	0.212	0.214	0.206	0.226	0.231	0.245	0.265	0.260	0.298	0.301	0.296	0.312	0.321
Mean Value	0.267	0.265	0.273	0.258	0.257	0.277	0.280	0.312	0.323	0.325	0.351	0.357	0.354	0.366	0.375
Fujian	0.190	0.200	0.202	0.222	0.215	0.221	0.227	0.244	0.267	0.350	0.383	0.377	0.368	0.318	0.334
Guangdong	0.399	0.414	0.428	0.447	0.416	0.424	0.445	0.451	0.469	0.480	0.491	0.545	0.515	0.523	0.534
Guangxi	0.112	0.121	0.129	0.155	0.147	0.158	0.163	0.163	0.165	0.172	0.173	0.176	0.175	0.183	0.185
Hainan	0.213	0.225	0.217	0.223	0.208	0.213	0.216	0.218	0.215	0.221	0.227	0.234	0.219	0.240	0.240
Mean Value	0.229	0.240	0.244	0.262	0.246	0.254	0.263	0.269	0.279	0.306	0.319	0.333	0.319	0.316	0.323
China	0.228	0.233	0.242	0.255	0.250	0.261	0.268	0.284	0.300	0.307	0.327	0.336	0.328	0.332	0.339

Xu et al., 2022), this study incorporates five variables, namely economic development (ED), government participation level (GP), foreign investment utilization (FI), human capital (HC), and urbanization level (UL), as control variables in order to mitigate potential errors and minimize the influence of omitted variables. By including these variables, the model aims to enhance data fitting and improve the overall accuracy of the analysis, a more comprehensive and detailed analysis of the study findings is provided below. The following explanations outline the precise meanings and implications of each index:

(1)Economic development level (ED). The level of economic development serves as an indicator and reflection of the extent of development, pace of economic growth, and magnitude of a nation or territory during a particular period of time, and its value is in representing the economic prowess and degree of advancement of a country or region. The selection of per capita GDP as the indicator for measuring the degree of economic progress in this context has been made.

(2)Government participation level (GP).The government assumes a crucial and indispensable role in the facilitation of economic growth. By devising strategic economic development plans and policies grounded on scientific principles, allocating resources towards infrastructural development, fostering educational advancements and technical innovations, facilitating market-oriented services, and cultivating a conducive atmosphere for economic growth and development. The use of the ratio between local fiscal spending and GDP serves as a proxy variable to gauge the extent of government involvement.

(3)Level of foreign investment (FI).The process of attracting and incorporating foreign direct investment (FDI) into a country's economy is a significant avenue for the accumulation and development of national capital. The infusion of foreign finance has facilitated the augmentation of China's infrastructure building funds, stimulated firm growth, and enhanced its employment rate. Furthermore, the use of superior foreign technology has been instrumental in facilitating China's import and export commerce, therefore contributing significantly to the overall economic growth of the nation.

(4)Human capital (HC). Human capital is distinct from "material capital" in that it consists of the labor force's comprehensive knowledge, skills, and other economically valuable attributes; it serves as the primary impetus for economic growth. This article refers to the measuring methodology introduced by Chen et al (Chen et al., 2004), which use the average duration of schooling as a metric for assessing human capital.

(5)Urbanization level (UL). The level of urbanization serves as an indicator to measure the extent of urban development, playing a crucial role in evaluating the economic progress of a nation or area. This article use the urban population percentage in relation to the total population as a metric to gauge the degree of urbanization.

3.2 Econometrics model

3.2.1 PVAR model

This article employs the Panel Vector Autoregression (PVAR) model (Fengju et al., 2020; Sun, 2021) to examine the dynamic effects of technical innovation on the high-quality development of

TABLE 3 Evaluation index system for scientific and technological innovation.

First level dimension	Secondary criteria	Specific indicators (attributes)
Innovation Subject	Enterprise	Number of Enterprises above Designated Size with R&D Activities
	Higher Education Institutions	Number of Ocean Higher Education Institutions
	Scientific Research Institution	Number of Marine Research Institutions
Innovative Resources	Human Resources	Number of Employees in Marine Scientific Research Iinstitutions
		Number of People Engaged in Marine Science and Technology Activities
	Research Funding	Funding Investment for Marine Scientific Research Institutions
		Government Investment in Scientific Research Infrastructure
Innovation Environment	Technical Environment	Number of Scientific and Technological Projects in the Marine Field
		Number of Scientific and Technological Papers Published in the Field of Ocean Science
		Number of Patent Authorizations in the Ocean Direction
	Market Environment	Total Retail Sales of Social Consumer Goods
		The Proportion of Total Exports to Regional GDP
		Technology Market Transaction Volume
	Educational Environment	Number of Doctoral Research Points in the Ocean Field
		Number of Marine Majors in General Higher Education
		Number of Faculty and Staff in Marine Specialized Higher Education Institutions
	Social and Cultural Environment	Per Capita Financial Expenditure on Education
		Number of Students Enrolled in Higher Education Institutions
		Book Resources of Public Libraries Per 10000 People

the marine economy. The construction of the PVAR model is shown in Formula (1):

$$Y_{it} = \lambda_0 + \sum_{j=1}^{N}(\lambda_j y_{i,t-j}) + \xi_i + \theta_t + \mu_{it} \tag{1}$$

Among them, $Y_{it} = (HQME, STI, IS, IR, IE)$ is the fivedimensional vector composed of high-quality development of marine economy, scientific and technological innovation, innovation subjects, innovation resources and innovation environment; i=1,…,11, denotes 11 coastal provinces and cities; t = (2006, 2007,…,2020) denotes the year; λ_0 denotes the intercept term vector; The lag order of the endogenous variable Y_{it} is represented by **N**, while the coefficient matrix of the lagged variable is represented by λ_j. $y_{i,t-j}$ represents the endogenous variable's jth order lag term; ξ_i represents the fixed effect of 11 coastal provinces and cities, reflecting individual differences; θ_t represents the time effect, reflecting the impact of year changes on different provinces and cities; μ_{it} is a word for random disturbance.

Based on the above theoretical model, PVAR studied the impact mechanism of science and technological innovation on the high-quality development of marine economy. PVAR inherits the advantages of the VAR model, treating research variables as endogenous variables and treating each endogenous variable as a function of the lagged values of all endogenous variables in the system, thereby providing a rich structure and capturing more data features. In addition, the PVAR model allows for individual effects and heteroscedasticity in the data. Due to the presence of a large amount of cross-sectional data, this model allows the lag coefficient to vary over time, relaxing the requirement for data temporal stationarity.

3.2.2 Mediating effect model

In order to examine the indirect impact of technological innovation on the high-quality growth of the marine economy, specifically the role played by marine green total factor productivity and marine industrial structure in mediating the relationship between technological innovation and the high-quality development of the marine economy, this work utilizes the intermediate effect model proposed by Baron and Kenny (1986) as a reference for the design. The model is created in the Formulas (2)–(5):

$$HQME_{it} = \alpha_0 + \alpha_1 STI_{it} + \alpha_2 \sum C_{it}^{j} + \varepsilon_{it} \tag{2}$$

$$MGTFP_{it} = \beta_0 + \beta_1 STI_{it} + \beta_2 \sum C_{it}^{j} + \varepsilon_{it} \tag{3}$$

$$MIS_{it} = \delta_0 + \delta_1 STI_{it} + \delta_2 MGTFP_{it} + \delta_3 \sum C_{it}^{j} + \varepsilon_{it} \tag{4}$$

$$HQME_{it} = \eta_0 + \eta_1 MGTFP_{it} + \eta_2 MIS_{it} + \eta_3 STI_{it} + \eta_3 \sum C_{it}^{j} + \varepsilon_{it} \tag{5}$$

Among the variables considered, $HQME_{it}$ represents the level of high-quality development in the marine economy of a specific region i in a given year t. Additionally, $MGTFP_{it}$ and MIS_{it} are intermediate variables that represent the total factor productivity of the marine economy and the industrial structure of the marine economy in a specific region i and year t. C_{it} serves as a control variable in the analysis. Lastly, ε_{it} represents the random error term in the model.

3.3 Data description

This study utilizes panel data from 11 coastal provinces and cities in China spanning the period from 2006 to 2020 for the purpose of investigation. The data used in this study has been

TABLE 4 Results of the comprehensive index for scientific and technological innovation.

Province	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Tianjin	0.124	0.131	0.130	0.154	0.168	0.179	0.194	0.205	0.221	0.232	0.217	0.213	0.215	0.238	0.239
Hebei	0.134	0.139	0.142	0.146	0.148	0.155	0.160	0.164	0.167	0.171	0.178	0.188	0.204	0.209	0.218
Liaoning	0.123	0.127	0.135	0.173	0.182	0.200	0.218	0.239	0.278	0.370	0.259	0.265	0.267	0.281	0.279
Shandong	0.232	0.252	0.273	0.326	0.338	0.370	0.398	0.419	0.439	0.461	0.451	0.474	0.564	0.589	0.622
Mean Value	0.153	0.162	0.170	0.200	0.209	0.226	0.242	0.256	0.276	0.308	0.276	0.285	0.313	0.329	0.339
Shanghai	0.188	0.213	0.232	0.300	0.326	0.356	0.358	0.400	0.436	0.445	0.388	0.369	0.402	0.415	0.415
Jiangsu	0.171	0.191	0.237	0.269	0.289	0.325	0.364	0.377	0.412	0.432	0.422	0.443	0.463	0.531	0.547
Zhejiang	0.138	0.146	0.226	0.197	0.178	0.221	0.245	0.263	0.294	0.313	0.315	0.335	0.371	0.414	0.436
Mean Value	0.166	0.184	0.232	0.255	0.264	0.301	0.322	0.347	0.380	0.396	0.375	0.382	0.412	0.454	0.466
Fujian	0.113	0.119	0.125	0.140	0.145	0.154	0.165	0.168	0.196	0.195	0.207	0.215	0.235	0.251	0.263
Guangdong	0.227	0.244	0.265	0.294	0.309	0.339	0.378	0.380	0.416	0.564	0.579	0.680	0.756	0.843	0.913
Guangxi	0.078	0.079	0.083	0.089	0.098	0.103	0.108	0.109	0.133	0.138	0.126	0.131	0.150	0.153	0.160
Hainan	0.013	0.014	0.018	0.024	0.034	0.041	0.050	0.048	0.059	0.067	0.076	0.075	0.094	0.104	0.112
Mean Value	0.108	0.114	0.123	0.137	0.146	0.159	0.175	0.176	0.201	0.241	0.247	0.275	0.309	0.338	0.362
China	0.140	0.151	0.170	0.192	0.201	0.222	0.240	0.252	0.277	0.308	0.293	0.308	0.338	0.366	0.382

obtained from authoritative sources such as the China Statistical Yearbook, China Ocean Statistical Yearbook, and other regional statistical yearbooks. Table 6 presents the description and statistical information pertaining to each variable.

4 Results

4.1 Empirical results based on PVAR model

4.1.1 Panel unit root test

Prior to estimating the PVAR model, it is necessary to do unit root tests on each variable. This article employs a panel model and applies three test techniques, namely the Levin Lin Chu Test (LLC test), the Augmented Dickey Fuller test (ADF test), and the Im Esaran Skin Test (IPS test), to perform unit root tests on all variables. The test results are shown in Table 7. Based on the data shown in Table 7, it is evident that with the exception of the variable lnIS, all other variables exhibit non-stationarity. Consequently, a first-order differencing operation was conducted on all variables, followed by a unit root test on the resulting differentiated variables. All variables have successfully passed the significance level test, indicating that the original non-stationary variables have been transformed into stationary data via the process of first-order differencing. This stationary data may now be used for the subsequent estimate of the PVAR model.

TABLE 5 Input-output index system of green total factor productivity in marine economy.

Index type	Index description	Specific index	Unit
Input	Capital input	Marine capital stock	Million yuan
	Energy input	Total energy consumption of Marine economy	Tons of standard coal
	Labor input	Number of sea-related employment	Ten Thousands People
Expected output	Total Marine economy	Gross Ocean Product	Hundred million yuan
Undesirable output	Environmental Pollution	Marine industrial wastewater discharge	Ten thousand tons

4.1.2 PVAR model estimation results

In order to enhance the reliability of the estimate outcomes of the PVAR model, it is essential to first ascertain the most suitable lag order of the model during the construction process of the PVAR model. Table 8 displays the test results for each lag order based on various information requirements. This study indicates the ideal lag order of the PVAR model to be the first order lag, based on the criterion for choosing the lag order with the greatest minimum value among the three-information criteria BIC (Bayesian Information Criterion), AIC (Akaike Information Criterion), and HQIC (Hannan-Quinn Information Criterion).

Table 9 presents the estimate outcomes of the PVAR model. It is evident that the coefficient of the lagging technological innovation level's impact on the high-quality development of the marine economy is 0.4129, with a statistically significant confidence level of 1%. This finding confirms hypothesis 1 and demonstrates that scientific and technological innovation plays a significant role in driving the high-quality development of the marine economy. The impact coefficients of innovation subjects, innovation resources, and innovation environment on the high-quality development of

TABLE 6 The descriptive statistics for each variable.

Variable type	Variables	Sample size	Minimum	Maximum	Average	Standard Deviation
Explained variable	HQME	165	0.112	0.545	0.286	0.099
Explanatory variable	STI	165	0.013	0.913	0.256	0.158
Mediating variable	MGTFP	165	0.153	1.352	0.330	0.190
	MIS	165	0.457	4.601	1.416	0.692
Control variable	ED	165	8590	157279	55171.65	29889.92
	FI	165	0.002	0.121	0.028	0.028
	UL	165	0.392	88.7	11.739	23.225
	GP	165	0.081	0.449	0.173	0.067
	HC	165	7.670	11.810	9.242	0.875

the marine economy are all significantly negative, indicating that a single innovation dimension cannot promote the high-quality development of the economy from the perspective of the marine innovation ecosystem. To foster high-quality development in the marine dynamic economy, it is imperative that all innovation dimensions collaborate harmoniously to enhance the standard of scientific and technological innovation. The equation governing the level of scientific and technological innovation can be observed to exhibit a positive and statistically significant relationship between the lagged level of scientific and technological innovation in a given period and its current level. The estimated impact coefficient of 0.3534 suggests that the level of marine scientific and technological innovation possesses a self-promoting effect to a certain degree. Furthermore, it is worth noting that the high-quality growth of the marine economy has a notable and beneficial impact on scientific and technological innovation. This finding suggests that scientific and technological innovation and the high-quality development of the marine economy are mutually reliant and mutually reinforcing. Marine scientific and technological innovation serves as a perpetual catalyst for the high-quality development of the marine economy. Simultaneously, the high-quality development of the marine economy offers extensive opportunities for the growth and expansion of marine scientific and technological innovation endeavors. This symbiotic relationship facilitates the enhancement of the overall proficiency and effectiveness of marine technological innovation.

4.1.3 Stability test

Based on the analysis of Figure 2, it is evident that the eigenvalues of the adjoint matrix of the PVAR model are all situated inside the unit circle. This observation signifies that the created PVAR model exhibits stability and the estimate outcomes are deemed effective.

4.1.4 Granger causality tests

Subsequently, a Granger causality test was performed on the PVAR model in order to examine the presence of a Granger causation association between the high-quality development of marine economy and the scientific and technical innovation. Table 10 displays the results of the Granger causality test. Based on the findings, it is evident that, at a significance level of 1%, the level of scientific and technological innovation, along with its specific dimensions including the innovation subject, innovation resources, and innovation environment, serve as Granger causes for

TABLE 7 Unit root test results for each variable.

Variables	LLC Test	ADF Test	IPS Test	Results
lnHQME	-3.4452***	-0.4150	-0.2222	unstable
lnSTI	-3.6121***	0.9158	0.5970	unstable
lnIS	-6.9754***	-3.9528***	-3.3861***	stable
lnIR	-1.1993***	-1.1421	-0.8677	unstable
lnIE	-2.8180***	2.1425	1.5302	unstable
dlnHQME	-5.9937***	-4.6122***	-3.4510***	stable
dlnSTI	-9.9946***	-6.0825***	-4.9586***	stable
dlnIS	-12.9468***	-10.7979***	-8.5524***	stable
dlnIR	-5.0300***	-5.0457***	-3.9890***	stable
dlnIE	-4.5192***	-1.9675**	-1.5240*	stable

[1]The symbols *, **, and *** are conventionally used to denote statistical significance at the 1%, 5%, and 10% confidence levels, respectively.

TABLE 8 PVAR model lag order test results.

lag	BIC	AIC	HQIC
1	-278.0032	-85.96431	-163.6635
2	-172.1511	-44.99018	-96.43968
3	-79.37586	-17.09298	-42.29274

the high-quality development of the marine economy. The test term "all" has a P-value of 0.000, suggesting that the combination of all factors serves as significant Granger causes for the high-quality development of the marine economy. This suggests that changes in the extent of scientific and technological innovation will unavoidably result in modifications to the level of high-quality development in the marine economy. Furthermore, the high-quality development level of the marine economy serves as the Granger reason for innovation level, innovation subject, innovation resources, and innovation environment, at a significance level of 5%. This suggests that a reciprocal causal relationship exists between the degree of scientific and technological innovation and the high quality development of the marine economy.

4.2 Empirical results based on the mediation effect model

The estimated results of models (2) through (5) are presented in Table 11. Specifically, model (2) yields a significant coefficient of 0.4838 for scientific and technological innovation at the 1% level. This indicates that scientific and technological innovation promotes high-quality development of the marine economy in a significant way, once once again confirming hypothesis 1. The coefficient of scientific and technical innovation in model (3) is estimated to be 0.3912. Additionally, the product of this coefficient and the coefficient of green total factor productivity in model (5), which is 0.0693, yields a value of 0.0271. This value is found to be statistically significant at the 1% level. This finding suggests that advancements in scientific and technological innovation have the potential to enhance marine green total factor productivity. Furthermore, scientific and technological innovation can have a positive impact on the high-quality development of the marine economy by means of green total factor productivity. Specifically, for every 1 percentage point increase in the level of scientific and technological innovation, there is a corresponding increase of 0.0271 percentage points in the promotion of the high-quality development level of the marine economy. This finding provides support for hypothesis 2. The results obtained from the estimation of model (4) demonstrate that the coefficients associated with technological innovation and green total factor productivity are statistically significant at the 1% level when industrial structure is used as the explanatory variable. This suggests that enhancing the level of scientific and technological innovation and green total factor productivity can effectively facilitate the optimization and upgrading of industrial structure. Furthermore, the statistical analysis reveals that the mediating effect of scientific and technological innovation on the high-quality development of the marine economy through the optimization of industrial structure is 0.025. This finding is deemed significant at a confidence level of 1%. Consequently, it can be concluded that technological innovation plays a crucial role in facilitating high-quality development of the marine economy by stimulating the optimization and upgrading of industrial structure, thereby confirming hypothesis 3. The results obtained from estimating model (5) indicate that the regression coefficients of scientific and technological innovation, green total factor productivity, and industrial structure on the high-quality development of the marine economy are statistically significant at the 1% level. This suggests that enhancing the level of scientific and technological innovation, green total factor productivity, and optimizing and upgrading the industrial structure can all contribute to the high-quality development of the marine economy. At the 1% significance level, the scientific and technological innovation's chain mediating effect via enhanced green total factor productivity and industrial structure optimization is 0.0083. This indicates that scientific and technological innovation contributes to the enhancement of the marine economy's high-quality development level by increasing green total factor productivity and resulting in the optimization and upgrading of the industrial structure. Hypothesis 4 is supported by empirical evidence, indicating that a 1 percentage point rise in technical innovation level leads to a 0.0083 percentage point enhancement in the promotion of high-quality growth of the marine economy via the use of chain intermediates.

TABLE 9 PVAR model estimation results.

Variables	dlnHQME	dlnSTI	dlnis	dlnir	dlnie
L1.dlnHQME	-0.1665*** (0.0499)	0.3534*** (0.0888)	-0.7433*** (0.1748)	-0.3144** (0.1314)	0.3120*** (0.0735)
L1.dlnSTI	0.4129*** (0.0546)	0.2958*** (0.0762)	1.6350*** (0.2598)	0.9969*** (0.0978)	0.0861 (0.0618)
L1.dlnis	-0.0678*** (0.0140)	-0.0462** (0.0191)	-0.2819*** (0.0540)	-0.0355 (0.0360)	0.0026 (0.0161)
L1.dlnir	-0.0291*** (0.0065)	-0.0340** (0.0172)	-0.0606* (0.0340)	-0.0293 (0.0224)	-0.0293 (0.0179)
L1.dlnie	-0.4323*** (0.0584)	0.3012*** (0.0934)	-3.0403*** (0.2961)	-0.9157*** (0.1309)	0.5572*** (0.0777)

[1]The symbols *, **, and *** are conventionally used to denote statistical significance at confidence levels of 1%, 5%, and 10%, respectively. The standard deviations are shown in parentheses.

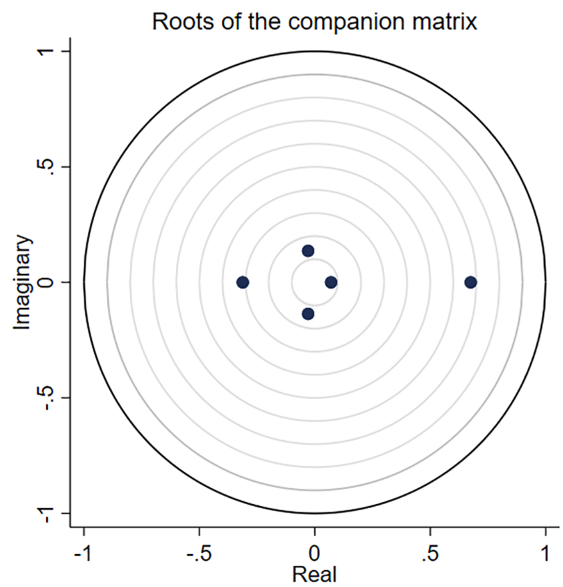

FIGURE 2
Stability test of PVAR model.

In order to strengthen the credibility of the study on the mediation effect, the Bootstrap test method was used to conduct 1000 random samples, therefore assessing the robustness of the dual mediation effect in the causal chain that involves enhancing green total factor productivity and optimizing industrial structure. The test results are shown in Table 12. The tabulated data demonstrates that both independent mediating effects and a chain mediating effect are present, as shown by the absence of a 0 value within the 95% confidence range for the mediating effect. Additional comparative analysis of the various types of effects stemming from scientific and technological innovation that propels high-quality development of the marine economy demonstrates that the overall effect is 0.4838. This effect is composed of 0.4234 for the direct effect, 0.0604 for the indirect mediating effect, and 12.48% for the mediating effect. Green total factor productivity is the most significant mediating variable among the indirect mediating effects, contributing 5.6% to the overall effect. Furthermore, it should be noted that the independent mediating effect of industrial structure as a mediating variable constitutes 5.17% of the overall effect. In addition, the chain mediated effect, which encourages the enhancement and modernization of industrial structure by means of augmenting green total factor productivity, exerts the least amount of promotion on the high-quality development of the marine economy, amounting to 1.72% of the overall effect. Figure 3 illustrates the mediating influence of scientific and technological innovation in facilitating the enhancement of green total factor productivity and the advancement of industrial structure, hence encouraging the high-quality development of the marine economy.

5 Conclusion and suggestion

This article uses panel data from 11 coastal provinces and cities (autonomous regions) in China from 2006 to 2020 to construct a PVAR model and a mediation effect model to study the impact of scientific and technological innovation on the high-quality development of the marine economy. The following conclusions are drawn:

Elevating the level of scientific and technological innovation has the potential to greatly facilitate the high-quality development of the marine economy. Concurrently, scientific and technological

TABLE 10 PVAR model estimation results.

Variables	Inspection item	chi2	P Value	Variables	Inspection item	chi2	P Value
dlnHQME	dlnSTI	57.183	0.000	dlnIS	dlnHQME	18.072	0.000
	dlnIS	23.401	0.000		dlnSTI	39.608	0.000
	dlnIR	19.947	0.000		dlnIR	3.185	0.074
	dlnIE	54.733	0.000		dlnIE	105.403	0.000
	ALL	69.075	0.000		all	155.670	0.000
dlnSTI	dlnHQME	15.858	0.000	dlnIR	dlnHQME	5.726	0.017
	dlnIS	5.838	0.016		dlnSTI	103.926	0.000
	dlnIR	3.883	0.049		dlnIS	0.975	0.324
	dlnIE	10.395	0.001		dlnIE	48.920	0.000
	ALL	33.134	0.000		ALL	138.174	0.000
dlnIE	dlnHQME	18.031	0.000				
	dlnSTI	1.938	0.164				
	dlnIS	0.025	0.874				
	dlnIR	2.670	0.102				
	ALL	42.671	0.000				

TABLE 11 Chain mediated effect model estimation results.

Variables	Model (2)	Model (3)	Model (4)	Model (5)
	HQME	MGTFP	MIS	HQME
STI	0.4838***	0.3912***	0.9487***	0.4234***
MGTFP			0.8***	0.0693***
MIS				0.0264***
Control Variables	YES	YES	YES	YES
Constant term	0.007	0.4325***	1.1305***	-0.0619
Sample size	165	165	165	165
R^2	0.6899	0.1839	0.5838	0.7284

[1]The symbols *, **, and *** are conventionally used to denote statistical significance at the 1%, 5%, and 10% confidence levels, respectively.

TABLE 12 Chain mediation effect test results based on bootstrap method.

Effect type	Path	Effect value	Boot SE	95% confidence interval	Effect proportion
Direct effect	Scientific and technological innovation → high-quality development of Marine economy	0.4234	0.0411	[0.3423,0.5045]	87.52%
Indirect effect	Independent Mediating effect 1: scientific and technological innovation →Improvement of green total factor productivity → high-quality development of Marine economy	0.0271	0.0170	[0.0052,0.0685]	5.60%
	Independent Mediating effect 2: scientific and technological innovation → optimization of marine industrial structure→ high-quality development of Marine economy	0.0250	0.0168	[0.0023,0.0637]	5.17%
	Chain Mediating effect: scientific and technological innovation → improvement of green total factor productivity → optimization of marine industrial structure → high-quality development of Marine economy	0.0083	0.0062	[0.0001,0.0229]	1.72%
	Population mediating effect	0.0604	0.0227	[0.3423,0.5045]	12.48%
Total effect	Scientific and technological innovation → high-quality development of Marine economy	0.4838	0.0414	[0.4021,0.5655]	–

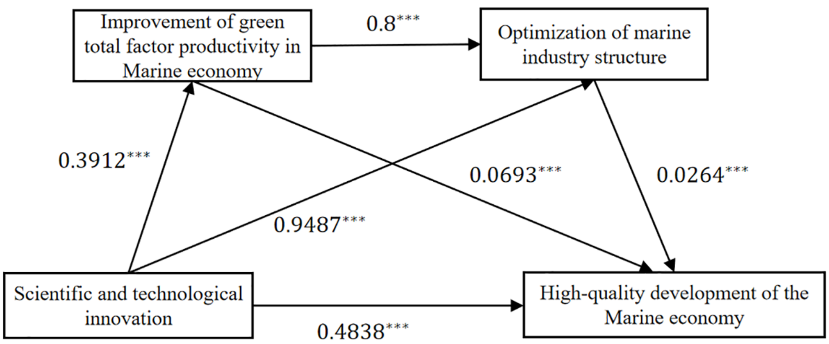

FIGURE 3
The chain mediation effect of science and technological innovation driving high-quality development of marine economy.

innovation can promote the high-quality development of the marine economy not only indirectly via two independent intermediary paths—improving green total factor productivity of marine and optimizing the marine industrial structure—but also via the intermediary path “promoting the upgrading of the marine industrial structure through improved green total factor productivity.” Specifically, scientific and technological innovation holds a significant role in both independent mediation and chain mediation effects. Among these effects, the independent mediation effect has the greatest contribution to the enhancement of marine green total factor productivity. Following this, the independent mediation effect of marine industrial structure upgrading holds the second highest impact. Lastly, the chain mediation effect of “improving marine green total factor productivity - promoting the upgrading of marine industrial structure” has the least influence.

Based on the aforementioned findings, this study proposes the following recommendations:

Encourage innovation entities, enrich innovation resources, improve the innovation environment, and give full play to the positive effects of technological innovation on the improvement of green total factor productivity, the optimization of industrial structure and the high-quality development of marine economy. From the standpoint of innovative entities, it is imperative to enhance collaboration between industry and university research, bolster cooperation among enterprises, universities, and research institutes, establish a robust mechanism for industry-university research alliances, facilitate the conversion and utilization of scientific research accomplishments, and foster the amalgamation and advancement of marine technology innovation and industry. Strengthen the construction of scientific research platforms, establish sound research institutions and experimental bases for marine science and technology innovation, improve the research and development capacity and innovation environment of all localities, encourage researchers to actively carry out research on cutting-edge technologies, and enhance the innovation capacity of marine science and technology. Strengthen policy guidance, establish a sound policy system for marine science and technology innovation, formulate fiscal, tax and financial policies to encourage marine science and technology innovation, and promote the development of marine science and technology innovation in an appropriate and differentiated manner according to the actual conditions of different regions.

Drive high-quality development of marine economy by increasing green total factor productivity and scientific and technological innovation. Based on the findings of the mediation effect model’s estimation results, it is evident that scientific and technological innovation, by enhancing green total factor productivity, is the most effective indirect pathway for promoting the high-quality development of the marine economy. The optimal use and exploitation of scientific and technological innovation should be pursued to effectively facilitate the advancement of green total factor production. By developing scientifically sound ocean management policies, fostering innovation in green ocean technology, enhancing the training of marine professionals, facilitating the movement of marine resources, and optimizing the efficiency of marine resource allocation and production. Enhancing scientific and technological innovation should generate a positive feedback loop with the expansion of environmentally sustainable total factor productivity, so as to more effectively address the requirements of the marine economy’s high-quality development.

Optimize the industrial structure, and promote the high-quality development of the marine economy by upgrading the marine industrial structure and improving the level of scientific and technological innovation. The results of the intermediary effect model show that the single intermediary effect and the chain intermediary effect through the industrial structure are very significant. Therefore, it is necessary to explore the promoting effect of the optimization and upgrading of the marine industrial structure on the high-quality development of the marine economy. Foster an industrial structure that is sustainable, diversified, and innovation-driven; abandon the conventional model of extensive production, which is characterized by high energy consumption, pollution, waste, and inefficiency; and support the growth of green emerging industries.

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 authors.

Author contributions

MF: Data curation, Software, Writing – original draft, Formal analysis. HG: Conceptualization, Methodology, Project administration, Writing – review & editing. YW: Data curation, Writing – original draft. YL: Validation, Writing – review & editing.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Publisher’s note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2024.1341063/full#supplementary-material

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