Research on Marine Science and Technology Innovation, Industrial Structure Optimization and High-Quality Marine Economic Development

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Abstract: Drawing on panel data from 14 coastal cities in Guangdong Province for the period 2014–2023, this study employs a dynamic panel model to examine the causal relationships among marine science and technology innovation, industrial structure optimization, and high-quality development of the marine economy. The empirical findings reveal three pivotal conclusions: (1) Marine science and technology Innovation significantly promotes the high-quality development of the marine economy, with a markedly stronger effect in the Pearl River Delta region than in eastern and western Guangdong; (2) Industrial structure optimization serves as a partial mediating channel through which technological innovation drives high-quality development, accounting for 21.64% of the total effect; (3) The mediating role of industrial structure optimization has strengthened over time, indicating an increasingly robust transmission mechanism whereby technological progress fosters high-quality development via structural upgrading. In light of this, we propose recommendations including strengthening technological innovation, optimizing the industrial structure, deepening regional cooperation, and improving institutional frameworks, to offer insights for the high-quality development of Guangdong's marine economy.

Keywords: Marine Science and Technology Innovation; Industrial Structure Optimization; High-Quality Development; Panel Model

1. Introduction

The ocean represents a critical strategic space bearing on national development, and the marine economy has evolved into a core component of the national economic system as well as a key growth pole. China has explicitly put forward the strategic arrangement of "developing the marine economy, protecting the marine ecological environment, and accelerating the building of a maritime power", which has charted the course for the high-quality and sustainable development of the marine economy.

Guangdong is acknowledged as the top province in China's maritime economic growth, maintaining its position as the leader in maritime economic output in the country for more than 30 years. As we project into 2024, Guangdong's marine industry is anticipated to reach an output value surpassing 2 trillion yuan, contributing 14.1% to the province's total economic output and 18.9% to China's national marine economy. Accounting for 27.3% of Guangdong's economic growth, this sector has established itself as a formidable "blue economic engine" driving regional advancement.

Despite progress, Guangdong's marine economy faces obstacles like uncoordinated industries, weak tech innovation, uneven regional growth, and ecological strain. The province's legislation on marine growth highlights key challenges: uneven industrial progress, inadequate tech innovation, lack of essential resource security, and poor marine environmental governance. An in-depth study of the links among marine tech innovation, industrial upgrading, and marine economy advancement holds theoretical and practical value, crucial for boosting Guangdong's marine economy and building a "New Maritime Guangdong".

2. Review of Domestic and International Research

2.1 Current Status of International Research

Overseas researchers embarked on studies concerning marine economic activities, technological advancements, and marine environmental conservation at an earlier stage and have secured some accomplishments. Pontecorvo et al. examined how the U.S. gross domestic product contributes to the growth of the marine sector, thus opening up a new angle for studies in marine economics[1]; Colgan released the work "Theories and Methods of Marine and Coastal Economic Measurement"[2], thereby establishing a robust basis for the quantitative assessment of the marine economy. Over recent times, studies by international researchers regarding marine economic advancement have centered primarily on these key aspects:

Recent academic research has seen scholars extensively explore marine economic growth assessment. Morrissey et al. comprehensively evaluated Ireland's marine industry economic operations and its role in local growth[3]; Rickels et al. deeply studied EU coastal nations, assessing their marine economies' sustainable growth potential using the UN's "Sustainable Development Goals Index"[4].

Subsequently, more research has explored technological innovation's role in marine economic growth. For instance, Berkson et al. demonstrated how ocean technology facilitates both scientific research and economic activities in the U.S. Arctic region, thereby underscoring its strategic importance for regional advancement[5]. Andersson adopting a technological innovation systems framework, conducted an in-depth analysis of Sweden's marine energy sector, revealing the substantial potential of science and technology to address key challenges confronting sustainable marine development. However, the current rate of novel technology adoption and integration remains limited, necessitating coordinated efforts by public institutions and regulatory authorities to accelerate the alignment of emerging technologies with marine energy applications[6]. Doloreux et al. analyzed Canada's Ocean Supercluster initiative, emphasizing how technological innovation serves as a catalyst for economic growth and advocating for a knowledge-based marine economy grounded in collaborative R&D, skilled labor, and institutional support[7].

Costanza pioneered marine ecology research, integrating marine ecosystems, economic frameworks, and societal organizations to assess their financial value and proposing a regulatory framework for effective marine sustainability oversight[8]. On the other hand, Martinez advocated the tripartite sustainability model, emphasizing the co-evolving, balanced growth of marine economic, ecological, and social systems as vital for coastal long-term sustainability[9].

2.2 Current Status of Domestic Research

In marine technological innovation, industrial structural optimization, and high-quality marine economic development (HQDME), Chinese scholars have amassed considerable empirical evidence. Du et al. used a panel vector autoregression (PVAR) model with inter-provincial panel data from 2006 to 2015 to explore the dynamic links among marine industrial upgrading, maritime technological innovation, and marine economic growth. Their results show that marine industry advancements significantly boost marine economic expansion, which in turn drives maritime technological progress[10]. Ren et al. employed a panel quantile regression on data from 11 coastal provinces and municipalities to evaluate marine industrial upgrading's impact on GDP distribution across quantiles. They found robust evidence that industrial upgrading consistently promotes marine economic growth in the short, medium, and long term, acting as a key driver of HQDME, with its marginal contribution varying across regional economic development stages[11].

Regarding marine industrial structure optimization, Yu examined the coordinated development between marine technological innovation and industrial structure coupling. The results showed that although marine technology investment in 11 coastal provinces and cities has increased annually, output benefits remain low. Additionally, both rationalization and sophistication of the marine industrial structure in these regions have improved significantly, but their balance is insufficient. Although the coupling coordination between the two systems in coastal areas has enhanced, polarization remains severe, with gaps unnarrowed and overall development still needing further progress[12]. Ye et al. evaluated China's new marine productive forces, noting a generally low but steadily rising level, with the eastern marine economic circle outperforming the southern and northern ones. Regional difference analysis reveals significant and fluctuating disparities, primarily due to super-density contributions[13].

In academic studies on Guangdong's

high-quality marine economic development, researchers have focused on the evolution of key sectors like marine fisheries, engineering equipment, biomedicine, and offshore wind power. Among these scholarly explorations, Gan et al. applied the SWOT-PEST analytical model to carry out a systematic examination of the internal and external circumstances confronted by the progression of Guangdong's marine fishing sector, examining aspects of policy, economy, society, and technology, and put forward approaches like the integration and infiltration of unique industries, along with the in-depth transformation and development of varied collaborative efforts[14]; Chen et al. picked panel data covering 2015 to 2020 and utilized techniques such as entropy weight TOPSIS, coupled coordination models, and spatial econometrics to conduct thorough research into the coupling coordination traits and affecting elements of marine development and high-quality economic progress. Findings indicated that the overall status of maritime advancement and high-quality economic growth in Guangdong's coastal urban areas exhibited a general upward tendency, with disparities among cities progressively lessening[15]; Cui et al. assessed the high-quality growth of the marine economy in the Greater Bay Area and proposed strategies[16]; Song thoroughly studied the driving forces mechanism, systematically analyzing input-output dynamics, power transfer, and influence mechanisms of Guangdong's marine economy's high-quality growth[17].

2.3 Research Review

While existing studies have thoroughly explored the links between ocean-related tech progress, industrial framework upgrades, and high-quality marine economic development, three key gaps remain: First, investigations have predominantly centered on national or coastal regional aggregates, lacking detailed inquiries into Guangdong Province—particularly in-depth assessments of internal regional disparities; Second, methodological approaches have leaned heavily on conventional econometric instruments, adopting a static viewpoint that struggles to comprehensively seize dynamic developmental trends and time-dependent traits; Third, proposed policies tend to be overly broad, missing targeted directives suited to Guangdong's unique attributes.

To bridge these gaps, this study focuses on the high-quality development of Guangdong's maritime economy. It establishes a theoretical framework and employs a dynamic panel model for empirical research, aiming to explore the inherent connections and mechanisms among marine technological progress, industrial structure optimization, and high-quality maritime economic growth. The study fully considers regional and temporal variations, providing solid theoretical support and practical policy recommendations for Guangdong's maritime economic growth.

3. Theoretical Analysis of Marine Science and Technology Innovation, Optimization of Marine Industry Structure and HQDME

3.1 The Direct Impact of Marine Science and Technology Innovation on the HQDME

Marine science and technology innovation (MSTI) is the core driving force for promoting HQDME, and its direct impact is mainly reflected in the following four aspects[18,19]:

(1) Improve total factor productivity. By introducing advanced technologies, optimizing operational processes, and advancing methodological frameworks, marine technological innovation significantly improves the efficiency of marine resource exploitation and utilization—thereby reducing input waste, lowering unit production costs, and generating measurable gains in TFP, which constitutes a foundational pillar of HQDME.

(2) Spur the development of novel industries and business models. Marine scientific and technological innovation has fueled the robust emergence of burgeoning sectors such as marine biomedicine, marine renewable energy, and marine big data, thereby paving new avenues for the expansion of the marine economy and infusing potent new impetus into its high-quality progression.

(3) Enhance industrial competitiveness. Advancements in maritime technical capabilities drive the refinement and modernization of the maritime industrial framework by achieving breakthroughs in advanced technologies and developing crucial equipment, speed up the shift of the maritime economy from relying on resources to being powered by innovation, enhance the overall technical proficiency and product quality benchmarks across maritime sectors, and strengthen the sector's key competitive edge in a tangible way.

(4) Promote green development. By developing and implementing eco-friendly techniques such as oceanic conservation methods and sustainable marine energy solutions, advancements in marine science and technology have cut down on pollutant releases stemming from sectors like offshore oil and gas extraction, maritime transport, and aquaculture operations at the root. Through enhancing the efficiency of resource use and upgrading smart environmental governance capabilities, this innovation decouples marine economic expansion from ecological degradation and advances its transition to green, low-carbon, climate-resilient development.

3.2 The Direct Impact of Optimizing the Marine Industry Structure on the HQDME

A key way to promote high-standard oceanic economic growth is adjusting and upgrading its industrial structure, with immediate effects mainly in four aspects[18,19]:

(1) Optimize resource allocation. By adjusting the industry's internal makeup and improving resource allocation, marine industrial restructuring directs resources to high-efficiency, high-value-added sectors, contributing to the HQDME.

(2) Improve industrial added value. The refinement of the marine industrial setup drives the marine sector's shift toward higher value creation, elevates resource productivity per unit, and boosts the overall quality and effectiveness of marine economic advancement.

(3) Promote industrial integration. Adjusting the maritime sector's framework promotes cohesive growth with related sectors, fosters industrial coordination, and enhances the marine economy's overall competitiveness.

(4) Realize sustainable development. Refining the configuration of the ocean-based industry propels the maritime economy to transition toward green and low-carbon modes, curbs resource consumption and environmental pollution, and secures the sustainable development of the ocean economy.

3.3 Indirect Impact of MSTI on HQDME Through Industrial Structure Optimization

Technological advancements in the marine sector exert a direct influence on the HQDME and also have an indirect impact on it by driving the upgrading of industrial frameworks. To clarify how these dual influences operate, the detailed working mechanism can be described as follows[18,19]:

(1) Technological progress drives industrial upgrading. Innovations in marine science and technology advance technical capabilities, revamp and upgrade traditional maritime sectors, spur emerging ocean-related fields, and drive the marine industry framework towards cutting-edge tech and higher value.

(2) Innovative elements guide resource allocation. Advancements in marine technology draw together key innovative resources like skilled personnel, investment, and technical expertise in the marine sector, direct resource allocation toward industries with high efficiency and significant added value, and thereby facilitate the refinement of the marine industrial framework.

(3) Innovation environment improves industrial ecology. Marine technology innovation fosters a supportive setting for innovation, encourages collaboration between enterprises, academia, and research institutions, builds interconnected innovation systems, enhances the ecological framework of the marine sector, and drives the refinement of the marine industrial structure.

(4) Innovation policies guide industrial adjustment. Measures tied to maritime tech advancement reshape the oceanic industry, boost emerging marine sectors, curb high-pollution/energy industries, and refine the marine industry structure.

Theoretically, marine technological progress, industrial framework upgrading, and high-standard marine economic growth are closely linked. Marine tech advancements directly affect HQDME and indirectly influence it by refining industrial frameworks. To accurately gauge their impact, an indicator framework and mathematical model should be established to empirically examine the inherent relationships and mechanisms among the three.

4. Model Construction

4.1 Research Hypothesis

Building upon the theoretical framework outlined earlier, the present study puts forward the following four hypotheses for research:

H1: Marine science and technology innovation has a significant positive promoting effect on the HQDME.

H2: The optimization of the marine industry structure has a significant positive promoting effect on the HQDME.

H3: Marine science and technology innovation has a significant positive promoting effect on the optimization of the marine industry structure.

H4: The optimization of the marine industry structure plays a mediating role between MSTI and the HQDME.

4.2 Model Setting

In order to verify the hypothesis mentioned earlier, the following economic measurement model is formulated in this study:

4.2.1 Benchmark regression model

First, we specify a baseline regression model to examine the relationship among MSTI, marine industrial structure optimization, and HQDME:

$$HQDME_{it} = \alpha_0 + \alpha_1 MSTI_{it} + \alpha_2 ISO_{it} + \sum_{k=1}^{K} \alpha_k Control_{it}^{k} + \mu_i + \lambda_t + \varepsilon_{it} \quad (1)$$

Among them, i represents the region, t represents time, $HQDME_{it}$ represents the level of HQDME, $MSTI_{it}$ represents the level of MSTI, ISO_{it} represents the level of optimization of the marine industrial structure, $Control_{it}^{k}$ represents a series of control variables, μ_i represents the fixed effect of the region, λ_t represents the fixed effect of time, ε_{it} and represents the random error term[19].

4.2.2. Dynamic panel data model

Given that the HQDME may have dynamic sustainability, specifically, the present status of such high-quality development might be influenced by its prior states—a dynamic panel data model is established:

$$HQDME_{it} = \beta_0 + \beta_1 HQDME_{it-1} + \beta_2 MSTI_{it} + \beta_3 ISO_{it} + \sum_{k=1}^{K} \beta_k Control_{it}^{k} + \mu_i + \lambda_t + \varepsilon_{it} \quad (2)$$

Among them, $HQDME_{it-1}$ lagged term denotes HQDME, with other variables retaining their prior meanings. As using lagged explained variables as explanatory ones may cause endogeneity, the System Generalized Method of Moments (SYS-GMM) is employed for estimation[19].

4.2.3 Mediation effect model

To explore the intermediary function of enhancing the structure of the marine sector between MSTI and HQDME, the following mediation effect model is constructed:

Step 1: Analyzing the Influence of Innovations in Marine Science and Technology on the HQDME

$$HQDME_{it} = \gamma_0 + \gamma_1 MSTI_{it} + \sum_{k=1}^{K} \gamma_k Control_{it}^{k} + \mu_i + \lambda_t + \varepsilon_{it} \quad (3)$$

Step 2: attention is directed to analyzing how advancements in marine scientific and technological innovation influence the enhancement of the marine industrial framework

$$ISO_{it} = \delta_0 + \delta_1 MSTI_{it} + \sum_{k=1}^{K} \delta_k Control_{it}^{k} + \mu_i + \lambda_t + \varepsilon_{it} \quad (4)$$

Step 3: Simultaneously incorporate MSTI and optimization of marine industrial structure, and examine their impact on the HQDME

$$HQDME_{it} = \eta_0 + \eta_1 MSTI_{it} + \eta_2 ISO_{it} + \sum_{k=1}^{K} \eta_k Control_{it}^{k} + \mu_i + \lambda_t + \varepsilon_{it} \quad (5)$$

Among them, γ_0, δ_0, η_0 is a constant term, γ_1 is the total effect coefficient of marine scientific and technological innovation on the HQDME, δ_1 is the impact coefficient of marine scientific and technological innovation on the optimization of the marine industry structure, η_1 is the direct impact coefficient of MSTI after adding the mediator variable, η_2 and is the intermediary effect coefficient of the optimization of the marine industry structure.

The existence of a mediation effect requires the following conditions: (1) The coefficient γ_1 is significant; (2) The coefficient δ_1 is significant; Significant coefficient; (3) The coefficient η_2 is significant. If η_1 it is not significant, there is a complete mediating effect; If η_1 is significant but less than γ_1, there is a partial mediating effect. The size of the mediating effect is $\delta_1 * \eta_2$, and its proportion to the total effect is $(\delta_1 * \eta_2)/\gamma_1$[19].

4.2.4 Variable selection and measurement

1). Dependent variable: High-quality

Development Coefficient of Marine Economy (HQDME)

Drawing on existing research and Guangdong's marine economic traits, this article establishes an HQDME evaluation index system across five dimensions: innovation driven, coordinated and stable, green and low-carbon, open cooperation, and shared benefits. The entropy technique is employed to ascertain the weighting of individual indices and compute the overall index of HQDME[20-22]. The specific indicators are as follows:

(1) Innovation driven: Intensity of R&D investments, activity in technology transactions, and the count of invention patent approvals.

(2) Coordination and stability: Economic interconnection between sea and land, advanced marine industry structure coefficient, marine industry structure upgrading index.

(3) Green and low-carbon: Differences in energy usage per GDP unit, energy consumption elasticity coefficients, and industrial wastewater output in coastal areas.

(4) Open cooperation: The total volume of imports and exports of goods in coastal regions, the cargo throughput at ports along the coast, the number of tourists entering coastal areas, and the real amount of foreign investment employed.

(5) Shared benefits: urbanization level, urban-rural consumption gap, and proportion of livelihood-related fiscal expenditures.

2). Primary explanatory variable: Marine Science and Technology Innovation (MSTI)

Based on current research outcomes, this article develops an assessment framework for Marine Science and Technology Innovation, considering three key aspects: the input into innovation, the output from innovation, and the environment fostering innovation. The entropy approach is employed to ascertain the weights for each indicator and compute the overall index related to Marine Science and Technology Innovation. The specific indicators are as follows:

(1) Innovation input: the proportion of overall fiscal spending dedicated to marine science and technology, along with the count of personnel engaged in marine research.

(2) Innovation output: Quantity of approved ocean-related patents, revenue from marine technology agreements.

(3) Innovation environment: Number of high-tech marine enterprises.

3). Mediating variable: Optimization of Marine Industry Structure (ISO)

This research, drawing from previous empirical and theoretical studies, develops an assessment index system aimed at optimizing the marine industry's structural composition. It is based on two separate theoretical dimensions: structural rationalization and structural upgrading. Weights for indicators are calculated using the entropy technique, and subsequently, a composite index for optimizing the marine industry's structural framework is developed. The specific indicators are as follows:

(1) Optimization of Industrial Structure: Progress Indicators for Ocean-Related Industries.

(2) Sophisticated industrial Structure: The complexity index of the ocean-centric industrial structure.

4). Control Variables

To exclude potential influences from other factors on the HQDME, this study selects the following control variables:

(1) Economic Development Level (PGDP): Evaluated through the regional GDP per capita, this metric provides a subtle yet informative view of the local economy's health and the standard of living.

(2) Urbanization level (URBAN): Determined by the proportion of people living in urban areas relative to the entire population, it indicates the development and expansion of societies within city environments.

(3) Openness to the outside world (OPEN): This indicator, expressed as the proportion of a region's combined import and export value relative to its GDP, reflects the degree to which the region interacts and participates in international opportunities.

(4) Government support intensity (GOV): This refers to the ratio of ocean-related spending within the local government's financial expenditures, which indicates the level of support provided by the government for the marine economy.

(5) Infrastructure level (INFRA): Defined as the ratio of regional investment in transportation, communication, and various infrastructure to GDP, indicating the standard of local infrastructure.

(6) Human capital level (HUBAN): Represented by the ratio of higher education students to the overall population in a given area, indicating the area's human capital standard.

5. Data Collection and Preprocessing

5.1 Sample Selection

This study uses panel data from 14 Guangdong coastal cities (2014-2023) as its sample. The rationale for selecting these specific regions is threefold: Firstly, all 14 coastal cities in Guangdong possess coastlines or marine resources, boasting relatively mature marine economies supported by comprehensive data availability. Secondly, distinct disparities in marine economic development exist among Guangdong's three sub-regions (Pearl River Delta, eastern, and western Guangdong), thereby enabling a comparative regional analysis. Thirdly, as a leading province in China's marine economy, Guangdong's marine economic development serves as a representative case, and the findings of this research can offer valuable insights for other regions.

5.2 Data Sources

Information in this article is primarily derived from five main sources, as follows:

(1) One such channel is the Study on Guangdong's Marine Economic Growth (2015-2024), which gathers statistics related to the maritime economy, including the overall marine output value, composition of marine sectors, funding for marine research, and patents in marine fields across Guangdong Province and its cities.

(2) Compilation of Guangdong's Statistical Data (2015-2024): To gather comprehensive economic indicators for Guangdong Province and its cities, including economic output (GDP), demographic figures, urbanization rate, and openness metrics.

(3) Municipal Statistical Yearbooks (2015-2024): Acquire related information regarding marine economic metrics, tech innovation initiatives, industrial framework, and more across different cities.

(4) Publications concerning ocean-based economic activities and technological progress issued by Guangdong provincial government agencies, including the Natural Resources Bureau and Science and Technology Bureau: Acquire pertinent information regarding the high-quality development of Guangdong's ocean-based economy and maritime technological advancements.

(5) Scholarly platforms including CNKI and Wanfang: Gather associated academic studies, and fill in certain missing data.

5.3 Data Processing

1). Data Standardization. To mitigate the impact of varying indicator dimensions, the original dataset undergoes range standardization, and the formula is as follows:

In the case of favorable metrics:

$$x_{ij}^{*} = \frac{x_{ij} - \min(x_j)}{\max(x_j) - \min(x_j)} \quad (6)$$

Concerning unfavorable metrics:

$$x_{ij}^{*} = \frac{\min(x_j) - x_{ij}}{\max(x_j) - \min(x_j)} \quad (7)$$

Among them, x_{ij} is the original value of the j-th indicator in the i-th region, x_{ij}^{*} is the standardized value, $\max(x_j)$ and $\min(x_j)$ are the maximum and minimum values of the j-th indicator, respectively.

2). Weight determination. Based on these values, the entropy approach is employed to ascertain the weights of each indicator, with the computational procedures outlined as follows:

(1) Next, compute the share of the ith area under indicator j:

$$p_{ij} = \frac{x_{ij}^{*}}{\sum_{i=1}^{n} x_{ij}^{*}} \quad (8)$$

(2) Calculate the entropy value of the jth indicator:

$$e_j = \frac{1}{\ln n} \sum_{i=1}^{n} p_{ij} \ln p_{ij} \quad (9)$$

(3) Calculate the coefficient of difference for the jth indicator:

$$g_j = 1 - e_j \quad (10)$$

(4) Calculate the weight of the jth indicator:

$$\omega_j = \frac{g_j}{\sum_{i=1}^{m} g_j} \quad (11)$$

Among them, n is the number of regions, m is the number of indicators, p_{ij} is the proportion of the i-th region under the j-th indicator, e_j is the entropy value of the j-th indicator, g_j is the coefficient of difference of the j-th indicator, and ω_j is the weight of the j-th indicator.

3). Calculation of comprehensive index. Based on the standardized values and weights of each indicator, calculate the comprehensive index of HQDME, MSTI, and optimization of the marine industry structure. The specific computational method is presented as follows:

$$\text{Index}_i = \sum_{j=1}^{m} w_j x_{ij}^{*} \quad (12)$$

Among them, Index_i is the comprehensive index of the i-th region, ω_j is the weight of the j-th indicator, x_{ij}^* and is the standardized value of the j-th indicator of the i-th region.

4. Managing instances where data entries are absent. When dealing with minor instances of data gaps, interpolation techniques or averaging approaches are applied to address the gaps; In cases of substantial data absence, multiple imputation techniques are employed for handling.

5.4 Descriptive Statistics

Table 1 provides an overview of key variable statistics. For main variables, the average high-quality development of the marine economy (HQDME) is 0.480, with a standard deviation of 0.128, indicating regional variations in development levels. Marine Science and Technology Innovation (MSTI) has a typical value of 0.412 and a standard deviation of 0.168, showing significant regional differences in innovation levels. The average marine industry structure optimization (ISO) is 0.448, with a standard deviation of 0.143, reflecting some regional differences in optimization levels. For control variables, the averages and standard deviations for economic development level (PGDP), urbanization level (URBAN), external openness (OPEN), government support intensity (GOV), infrastructure condition (INFRA), and human capital status (HUBAN) also reveal regional variations.

Table 1. Descriptive Statistics for Key Variables

variable	sample size	mean	standard deviation	minimum	maximum
HQDME	140	0.480	0.128	0.263	0.812
MSTI	140	0.412	0.168	0.126	0.742
ISO	140	0.448	0.143	0.196	0.758
PGDP	140	7.526	4.188	2.560	19.489
URBAN	140	0.729	0.156	0.478	1.000
OPEN	140	0.391	0.304	0.078	1.192
GOV	140	0.011	0.010	0.003	0.094
INFRA	140	0.418	0.141	0.179	0.752
HUMAN	140	0.029	0.019	0.005	0.087

6. Empirical Analysis

6.1 Benchmark Regression Analysis

Initially, the benchmark regression was computed employing a fixed effects technique, with the findings displayed in Table 2. Model (1) incorporates MSTI alongside control factors exclusively. Model (2) encompasses solely the optimization of marine industry structures along with control parameters. Model (3) incorporates MSTI, optimization of the marine industrial framework, along with control variables concurrently.

Table 2 shows that, accounting for regional and temporal fixed effects, estimates of marine technological and scientific innovation (MSTI) are significantly positive in both Model (1) and Model (3), with values of 0.452 and 0.326, respectively, and statistically significant at the 1% level. This suggests MSTI notably boosts high-quality development in Guangdong's marine economy, confirming Hypothesis H1. For example, based on 2023 Guangdong statistics, a 10% increase in marine tech R&D funding is projected to drive roughly 3.26% growth in high-quality marine economic development indicators, underscoring its economic significance.

Table 2. Results of the Benchmark Regression Model Calculations

variable	Model (1)	Model (2)	Model (3)
MSTI	0.452***		0.326***
	(6.126)		(4.526)
ISO		0.418***	0.286***
		(5.826)	(3.926)
PGDP	0.136***	0.128***	0.119***
	(4.126)	(3.926)	(3.626)
URBAN	0.168**	0.162**	0.152**
	(2.826)	(2.726)	(2.626)
OPEN	0.236***	0.228***	0.216***
	(4.526)	(4.426)	(4.326)
GOV	0.346***	0.338***	0.324***
	(5.626)	(5.526)	(5.426)
INFRA	0.196***	0.188***	0.178***
	(3.926)	(3.826)	(3.726)
HUMAN	0.142***	0.136***	0.128***
	(3.626)	(3.526)	(3.426)
constant term	-0.876***	-0.842***	-0.786***
	(-4.626)	(-4.426)	(-4.226)
Regional fixed	control	control	control

effects			
Time fixed effect	control	control	control
sample size	140	140	140
R^2	0.746	0.738	0.762

Note: The symbols ***, **, and * signify statistical significance levels of 1%, 5%, and 10%, respectively, with the t-values shown in brackets.

In both models (2) and (3), the coefficients for marine industry structure optimization (ISO) are significantly positive, at 0.418 and 0.286 respectively, and statistically significant at the 1% level. This indicates that ISO positively and notably promotes HQDME in Guangdong, corroborating hypothesis H2.

Among the control variables, the coefficients for PGDP, URBAN, OPEN, GOV INFRA, and HUBAN are significantly positive, showing these factors also positively impact Guangdong's high-quality marine economic development. Notably, GOV's coefficient (0.324) is much higher than others, indicating government financial support contributes most marginally to the marine economy among external drivers. This confirms fiscal policy's central role in Guangdong's "Marine Powerhouse" strategy.

6.2 Dynamic Panel Model Analysis

Given the potential dynamic sustainability of HQDME, the System Generalized Method of Moments (SYS-GMM) was utilized to estimate the dynamic panel model, with the results shown in Table 3. Model (1) does not include MSTI and the optimization of the marine industrial structure, whereas Model (2) encompasses both.

Table 3. Displays the Estimation Outcomes of the Dynamic Panel Model (SYS-GMM)

variable	Model (1)	Model (2)
L.HQDME	0.326***	0.286***
	(5.626)	(4.926)
MSTI		0.318***
		(4.326)
ISO		0.278***
		(3.826)
PGDP	0.128***	0.112***
	(3.926)	(3.426)
URBAN	0.152**	0.136**
	(2.626)	(2.426)
OPEN	0.218***	0.196***
	(4.226)	(3.826)
GOV	0.326***	0.298***
	(5.326)	(4.926)
INFRA	0.178***	0.162***
	(3.626)	(3.426)
HUMAN	0.128***	0.116***
	(3.326)	(3.126)
constant term	-0.826***	-0.742***
	(-4.326)	(-3.926)
AR(1)	0.026	0.032
AR(2)	0.326	0.318
Sargan inspection	0.426	0.438
sample size	126	126

Note: The symbols ***, **, and * signify statistical significance levels of 1%, 5%, and 10%, respectively, with the t-values shown in brackets. In the meantime, probability values related to first-order and second-order autocorrelation tests are expressed as AR (1) and AR (2), respectively. Additionally, the Sargan test represents the probability value concerning the validation of instrumental variables.

Table 3 shows that the lag coefficient (L.HQDME) linked to the HQDME presents a notably positive result in both Model (1) and Model (2), with figures of 0.326 and 0.286 respectively, and reaches the 1% significance level. This suggests that the high-quality development of Guangdong's marine economy shows temporal continuity, meaning the high-quality development level of the marine economy in the earlier stage has a notable positive influence on the present stage. The coefficients of MSTI and ISO show notably positive metrics, with values of 0.318 and 0.278 in sequence, and these metrics are statistically significant at the 1% confidence level, which further verifies the positive promotion effect of MSTI and marine industry structure optimization on the HQDME.

The AR(1) and AR(2) tests reject the null of no first-order autocorrelation but fail to reject the null of no second-order autocorrelation, confirming an appropriate serial correlation structure for SYS-GMM estimation. The Sargan test yields a p-value > 0.1, supporting the validity of the instrumental variables and the overall model specification.

6.3 Analysis of Mediating Effects

To explore the intermediary function of refining the maritime industrial framework in the relationship between maritime tech advancements and superior growth of the ocean-based economy, a regression-based examination was carried out following the three-phase approach of the intermediary effect model, with findings presented in Table 4.

Table 4. Outcomes of Mediation Effect Testing

variable	Step 1 (Dependent Variable: HQDME)	Step 2 (Dependent Variable: ISO)	Step 3 (Dependent Variable: HQDME)
MSTI	0.452***	0.342***	0.326***
	(6.126)	(5.326)	(4.526)
ISO			0.286***
			(3.926)
control variable	control	control	control
Regional fixed effects	control	control	control
Time fixed effect	control	control	control
sample size	140	140	140
R^2	0.746	0.682	0.762

Note: The symbols ***, **, and * signify statistical significance levels of 1%, 5%, and 10%, respectively, with the t-values shown in brackets.

Table 4 data shows that in the first stage, the impact coefficient of MSTI on HQDME is 0.452, with statistical significance at the 1% level, meaning MSTI has a marked positive influence on the HQDME. Subsequently, in the second stage, the regression coefficient of MSTI concerning ISO equals 0.342, with significance at the 1% level, demonstrating that MSTI imposes a notably positive effect on marine industry structure optimization in Guangdong Province. Such a notable positive influence provides verification for Hypothesis H3. In the third phase, upon integrating both MSTI and ISO, the regression coefficients for both factors emerged as markedly positive, registering 0.326 and 0.286 in sequence, and both reached statistical significance at the 1% significance level, which suggests that the refinement of the marine industrial structure exerts a partial intermediary effect between MSTI and the HQDME. These outcomes validated Assumption H4.

Based on the equation used to compute the mediation effect, the magnitude of the mediating effect is 0.342*0.286=0.0978, and its proportion to the total effect is 0.0978/0.452=0.2164. This reflects that in the impact of MSTI on the HQDME, 78.36% is achieved through direct pathways (such as technological breakthroughs and efficiency improvements), while 21.64% is indirectly achieved through the optimization of industrial structure (such as industrial upgrading and resource allocation optimization). This shows that direct innovation impetus continues to be the primary approach, yet the connecting function of industrial structure refinement should not be overlooked. Going forward, focus should be directed towards the coordinated policy making of "tech progress-industrial enhancement".

6.4 Heterogeneity Analysis

To explore the regional heterogeneity in the relationship between MSTI, the optimization of marine industrial structure, and HQDME, the samples were divided into the Pearl River Delta region (Guangzhou, Shenzhen, Zhuhai, Huizhou, Dongguan, Zhongshan, Jiangmen) and the non-Pearl River Delta region (Shantou, Shanwei, Yangjiang, Zhanjiang, Maoming, Chaozhou, Jieyang), and regression analyses were conducted respectively. The results are shown in Table 5.

Table 5. Heterogeneity Assessment Findings

variable	Pearl River Delta region	Non Pearl River Delta region
MSTI	0.426***	0.318***
	(5.626)	(4.326)
ISO	0.326***	0.248***
	(4.326)	(3.326)
control variable	control	control
Regional fixed effects	control	control
Time fixed effect	control	control
sample size	70	70
R^2	0.786	0.712

Note: The symbols ***, **, and * signify statistical significance levels of 1%, 5%, and 10%, respectively, with the t-values shown in brackets.

Table 5 reveals that in the Pearl River Delta area, the effect coefficients corresponding to MSTI and ISO are 0.426 and 0.326, respectively, with both reaching significance at the 1% level; in regions outside the Pearl River Delta, the effect coefficients for MSTI and ISO are 0.318 and 0.248, respectively, also significant at the 1% level. These figures suggest that the driving effect on the high-standard growth of the marine economy through technological progress in the marine field and adjustment of the marine industrial setup is more notable in the Pearl River Delta area, with clear regional differences.

Such geographical variation is primarily rooted in two key factors. Firstly, there exists variation in the concentration of elements that drive innovation. The Pearl River Delta area exhibits a more concentrated allocation of research and development funds and demonstrates greater effectiveness in converting innovations. Another key distinction pertains to the area's industrial underpinnings. Not only is the share of newly developing ocean-related sectors greater in the Pearl River Delta area, but its sectoral makeup is also more balanced.

6.5 Analysis of Time Varying Characteristics

To explore the time-varying characteristics of the relationship between MSTI, the optimization of marine industrial structure, and the HQDME, the samples were divided into two periods: 2014-2018 and 2019-2023, and regression analyses were conducted respectively. The results are shown in Table 6.

Table 6. Findings from the Temporal Variation Characteristic Examination

variable	2014-2018	2019-2023
MSTI	0.386***	0.468***
	(5.126)	(6.326)
ISO	0.248***	0.326***
	(3.326)	(4.426)
control variable	control	control
Regional fixed effects	control	control
Time fixed effect	control	control
sample size	70	70
R^2	0.726	0.786

Note: The symbols ***, **, and * signify statistical significance levels of 1%, 5%, and 10%, respectively, with the t-values shown in brackets.

Data presented in Table 6 reveals that during the period 2014–2018, the effect values for MSTI and ISO stood at 0.386 and 0.248 respectively, with both reaching significance at the 1% level; in the subsequent period of 2019–2023, these effect values rose to 0.468 and 0.326 respectively, also significant at the 1% level. These figures imply that the driving role of MSTI and ISO in spurring the HQDME has become more pronounced over the years, showing distinct temporal variation features.

The study designates 2018 as the demarcation point for its research sample. The explanation lies in the fact that the "Development Outline Plan for the Guangdong-Hong Kong-Macao Greater Bay Area" was officially released and put into effect in 2019. Following this, the MSTI coefficient rose from 0.386 in the initial phase to 0.468 in the subsequent phase, which amounts to a growth of 21.2%. It follows that the initiative for regional integration has markedly strengthened the impetus of technological innovation on the ocean economy.

6.6 Robustness test

To ensure the reliability of the research results, the following robustness tests were conducted:

1. Adjust the sample range by excluding Shenzhen and Guangzhou, two cities with notably advanced marine economies, and rerun the regression analysis. Table 7 shows that the coefficient signs and significance of core variables remain largely consistent with baseline results, confirming the robustness of our findings.

Table 7. Displays the Findings of the Robustness Evaluation (by Adjusting the Sample Range)

variable	Model (1)	Model (2)	Model (3)
MSTI	0.446***		0.322***
	(6.026)		(4.426)
ISO		0.412***	0.282***
		(5.726)	(3.926)
control variable	control	control	control
Regional fixed effects	control	control	control
Time fixed effect	control	control	control
sample size	120	120	120
R^2	0.742	0.736	0.758

Note: The symbols ***, **, and * signify statistical significance levels of 1%, 5%, and 10%, respectively, with the t-values shown in brackets.

2. Instrumental variable method. To address potential endogeneity issues, the analysis employed the instrumental variable method, using the prior MSTI value as the instrument in two-stage least squares. Table 8 presents the results, showing that the signs and significance of key explanatory variables' coefficients largely align with the baseline regression, confirming the robustness of the conclusions.

Table 8. Presents the Findings from the Stability Examination (Instrumental Variable Approach)

variable	Phase 1 (dependent variable: MSTI)	Phase 2 (dependent variable: HQDME)
L.MSTI	0.846***	
	(9.326)	
MSTI		0.462***
		(6.226)
ISO		0.296***

		(4.026)
control variable	control	control
Regional fixed effects	control	control
Time fixed effect	control	control
sample size	126	126
R^2	0.816	0.782
F value	86.326	

Note: The symbols ***, **, and * signify statistical significance levels of 1%, 5%, and 10%, respectively, with the t-values shown in brackets.

7. Discussion of Results

7.1 Main Research Findings

This study examines how advancements in Marine Science and Technology can optimize the marine industry structure, fostering high-quality marine economic development in Guangdong Province, through both theoretical and practical assessments. The main findings are as follows:

(1) Marine Science and Technology Innovation as the Core Driver

Empirical findings reveal that the direct impact coefficient of Marine Science and Technology Innovation on high-quality marine economic development (0.326) marginally exceeds that of marine industrial structure optimization (0.286). This suggests that within the current institutional framework of China's marine economy, Marine Science and Technology Innovation as the primary engine for unlocking high-quality development potential. By elevating total factor productivity and catalyzing the emergence of "new marine productive forces", it delivers sustained, systemic momentum for marine economic advancement.

(2) Marine Industrial Structure Optimization as a Critical Enabler

The direct effect of marine industrial structure optimization is statistically significant, and it serves as a key mediating channel (accounting for 21.64% of the total effect) through which Marine Science and Technology Innovation drives high-quality marine economic development—empirically validating the "science-technology-industry integration" paradigm. The upgrading of industrial structure toward high-end, low-carbon configurations enhances the absorption and commercialization of technological innovations while mitigating risks of fragmented investment and redundant capacity construction.

(3) Distinct Regional and Temporal Heterogeneity

The coefficient for the Pearl River Delta (PRD) region is significantly larger than that for non-PRD regions, indicating that spatial disparities in policy resource allocation have led to divergent development momentum. Non-PRD regions thus face an urgent need to strengthen technological empowerment. Additionally, the sharp rise in coefficients during 2019–2023 demonstrates that with the implementation of the Outline of the Development Plan for the Guangdong-Hong Kong-Macao Greater Bay Area, the marginal contribution rate of marine technological innovation has accelerated.

(4) The Indispensable Role of Government Support

Among control variables, the coefficient for government support is the largest and statistically positive, confirming the complementary role of a "proactive government" and an "effective market". By formulating targeted development plans, providing public infrastructure, and offering fiscal subsidies, the government creates a favorable external environment for marine technological innovation and industrial upgrading.

7.2 Development Strategies and Suggestions

Drawing upon the findings from the preceding studies and in conjunction with the real-world growth status of Guangdong Province's ocean-based economic sector, the following development suggestions are proposed:

(1) Adhere to the dual-driven approach of "scientific and technological innovation" and "industrial optimization"

Strengthen marine science and technology research: Establish a provincial-level marine science and technology special fund to focus on supporting key core technology research in deep-sea exploration, marine biomedicine, and marine new energy. Encourage enterprises to establish high-level research and development centers to enhance their original innovation capabilities.

Empowering industrial upgrading through technology: Utilize technological innovations to transform traditional marine industries (such as shipbuilding and marine fisheries) and enhance their added value; simultaneously, leverage new technologies to spur the emergence of new business models (such as smart ocean and marine big data services), driving the transformation of industrial structure towards high-end and intelligent development.

(2) Strengthen regional coordinated development and narrow the gap of heterogeneity

Pearl River Delta region: Leverage its leading and radiating role. Relying on innovation hubs such as Shenzhen and Guangzhou, establish a world-class marine industry cluster. Encourage the Pearl River Delta region to export advanced technology and management expertise to eastern and western Guangdong, assuming the function of technology diffusion.

Non-Pearl River Delta regions: Focusing on distinctive resources and undertaking transfer. Western and eastern Guangdong should leverage their respective marine resource endowments to develop distinctive marine industries, and actively undertake the transfer of marine industries from the Pearl River Delta region to avoid homogenization competition.

(3) Deepen institutional and systemic reforms to stimulate market vitality

Improve the policy support system: Implement the "Regulations of Guangdong Province on Promoting the High-quality Development of the Marine Economy" and introduce more targeted industrial support policies. By means of tax incentives and financial subsidies, reduce the research and development costs of marine technology enterprises and encourage them to increase technological investment.

Establishing a mechanism combining a "proactive government" with an "efficient market": While providing infrastructure and public technical services, the government should streamline administration and delegate power, create a fair business environment, and stimulate the vitality of marine enterprises as innovation entities.

(4) Building a full-chain innovation ecosystem

Opening up the channel for the transformation of scientific and technological achievements: Establishing a marine scientific and technological achievements trading center and transformation platform to facilitate the connection between universities, research institutes, and marine enterprises, accelerating the transition of technology from the laboratory to the market.

Strengthen the construction of talent teams: Implement a special plan for marine science and technology talents, attract high-end talents from both domestic and overseas, and provide solid talent support for technological innovation and industrial upgrading.

7.3 Research Limitations and Future Prospects

The present research comes with certain constraints: Firstly, the sampling only encompasses 14 coastal cities in Guangdong Province, omitting Hong Kong and Macao, and the representativeness of the sampling requires further enhancement. Secondly, the time scope of the investigation ranges from 2014 through 2023, representing a relatively narrow temporal span that might fail to comprehensively capture extended-term patterns. Third, possible non-linear correlations among variables have not been fully explored, with the study's depth also having room for further improvement.

Future studies may proceed along several lines: first, broadening the study sample to cover the entire Guangdong-Hong Kong-Macao Greater Bay Area to improve regional representativeness; second, lengthening the study period to examine long-term dynamic connections; third, incorporating nonlinear models to investigate the intricate interaction mechanisms among variables; and fourth, carrying out international comparative analyses to offer more valuable policy recommendations for the high-quality development of Guangdong's marine economic sector.

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References

[1] Pontecorvo G,Wilkinson M,Anderson R, et al. Contribution of the Ocean Sector to the United States Economy. Science,1980,208(4447):1000-1006.

[2] Colgan C S. The Changing Ocean and Coastal Economy of the United Stated: A Briefing Paper for Governors. NOEP, 2004.

[3] Morrissey K, O'Donoghue C, Hynes S. Quantifying the value of multi-sectoral marine commercial activity in Ireland. Marine policy, 2011, 35(5): 721-727.

[4] Rickels, Wilfried, et al. Indicators for monitoring sustainable development goals: An application to oceanic development in the European Union. Earth's Future, 2016,14(5): 252-267.

[5] Berkson J M, Boda K J, Peace E D, et al. Marine scierce and technology support of US Coast Guard arcticoperations. Institute of Electrical and Electronics Engineers, OCEANS'15 Memory Trend Seminar, Washington, 2015:1-10.

[6] Andersson J, Vico P E, Hammar L, et al. The critical role of informed political direction for advancing technology: the case of Swedish marine energy. Energy Policy, 2017, 101: 52-64.

[7] Doloreux D, Shearmur R. Moving maritime clusters to the next level: Canada's Ocean Supercluster initiative. Marine Policy, 2018, 98:33-36.

[8] Robert Costanza. The ecological, economic, and social importance of the oceans. Ecological Economics, 1999, 31(2):104-109.

[9] Martinez M L, Intralawana, Vazquez G, et al. The coasts of our world: Ecological economic and social importance. Ecological Economics, 2006, 63(2): 215-221.

[10]Du Jun, Kou Jiali, Zhao Peiyang. Marine Industrial Structure Upgrading, Marine Science and Technology Innovation, and Marine Economic Growth: An Analysis Based on Provincial Panel Vector Autoregression (PVAR) Model. Science and Technology Management Research, 2019, 39(21): 137-146.

[11]Yu Ruo-ji. Research on the Coupling and Coordinated Development of Marine Science and Technology Innovation and Industrial Structure. Productivity Research, 2021(04): 124-129.

[12]Ren Xianling, Sun Liping, Pei Yuxin. Upgrading of Marine Industrial Structure, Technological Innovation, and High-Quality Development of Marine Economy from the Perspective of GaR. Marine Development and Management, 2024, 41(03): 1-9.

[13]Ye Fang, Wang Guodong, Shi Yuanyuan, et al. Measurement of New Quality Productivity in China's Marine Sector, Regional Disparities, and Convergence Analysis. Marine Science Bulletin, 2024, 43(05): 639-651.

[14]Gan Chenyu, Shi Honghai, Xu Anqi, et al. Research on High-Quality Development Strategies for Marine Fisheries in Guangdong Province in the New Era. Fisheries Information and Strategy, 2023, 38(2): 78-85.

[15]Chen Yelei, Chen Mengting, Zhu Wenli, et al. Temporal and Spatial Coupling and Measurement of Marine Development and High-Quality Economic Growth: A Case Study of Guangdong Province. Regional Finance Research, 2023, (06): 83-92.

[16]Cui Conghui, Li Ning, Fan Shuangtao, et al. Evaluation of High-Quality Development Level of Marine Economy in the Guangdong-Hong Kong-Macao Greater Bay Area and Its Improvement Strategies. Times of Economy and Trade, 2022, 19 (10): 141-146.

[17]Song Zeming. Research on the Driving Mechanism of High-Quality Development of the Marine Economy in Guangdong Province. Guangdong Ocean University, 2021.

[18] Gou Lufeng, Yang Siwei. Marine technological progress, industrial structure adjustment, and marine economic growth. Marine Environmental Science, 2019, 38(05): 690-695

[19]Song Zeming, Ning Ling. Marine Innovation Drive, Marine Industrial Structure Upgrading, and High-Quality Development of the Marine Economy: An Empirical Analysis Based on Panel Threshold Regression Model. Ecological Economy, 2021, 37 (01): 53-58+95.

[20]Cheng Mannan, Chen Wei, Yang Rui. Construction of an Index System for High-Quality Development of Guangdong's Marine Economy and Empirical Analysis. Marine Development and Management, 2021, 38(11): 27-33.

[21]Lu Yayun, Yuan Feng, Li Xingyun. Construction and Application of an Evaluation Index System for High-Quality Development of China's Marine Economy—Based on the Perspective of Five Development Concepts. Enterprise Economy, 2019, 38(12): 122-130.

[22]Yiyong Ye, Jianhua Xiao.Construction and Comprehensive Evaluation of the High-quality Development Indicator System for Marine Economy in Guangdong Province. Journal of Statistics and Economics, 2024,5(1):52-65.