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The impact of digitalization on the green development of the marine economy: evidence from China's coastal regions

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Under the impetus of the new generation of technological revolution, digitalization offers new opportunities for the green development of the marine economy. Utilizing data from 11 coastal Chinese provinces and cities between 2011 and 2020, this paper constructs a comprehensive index system for the green development of the marine economy. Based on this, a fixed effects model is used to explore the impact of digitalization on the green development of the marine economy and its underlying mechanisms. The findings indicate that digitalization effectively promotes the green development of the marine economy, with this effect being more pronounced in regions bordering "the Belt and Road" initiative. Mechanism tests indicate that digitalization promotes the green development of the marine economy by raising the comprehensive development level of ports. When breaking down the components of port development, it is found that improving the port location quotient plays a more crucial role than port radiation intensity in how digitalization promotes the green development of the marine economy. Additionally, environmental regulation exerts a U-shaped moderating effect on the relationship between digitalization and the green development of the marine economy. Based on these findings, it is recommended to use digital technologies and data, expedite the development of marine big data platforms, integrate port resources, optimize port operations, and apply environmental regulation policies judiciously to promote efficient marine resource management and sustainable marine economic development.

KEYWORDS
digitalization, green development, marine economy, port development, environmental regulation

1 Introduction

As Earth's largest natural ecosystem, the ocean serves not only as a shared space for human survival and continuous progress but also as a treasure trove of resources for nurturing new industries and driving new growth (Jin et al., 2024). As the concentration of population and economic activities in coastal regions continues to intensify, the global marine economy is experiencing robust growth, demonstrating strong momentum and promising development prospects, increasingly highlighting its supportive role in economic and social development (Wang, 2020; Liu et al., 2023). China, a major maritime nation, is rich in marine resources, boasting a coastline of approximately 32,000 kilometers and a jurisdictional sea area of 3 million square kilometers. In 2023, China's marine economy reached a gross output of 9.9097 trillion yuan, constituting 7.9% of the national GDP, demonstrating significant resilience and potential. The importance of China's marine economy has increased with the implementation of its maritime power strategy and "the Belt and Road" Initiative (Chang, 2022).

However, the current state of China's marine economy still faces several challenges. Firstly, issues such as outdated production methods, inefficient use of non-renewable resources, and excessive exploitation of renewable resources are prominent (Fang et al., 2024). Additionally, development activities have led to deteriorating seawater quality, frequent marine disasters, and worsening marine ecological problems (Gao et al., 2024). Confronting the contradiction between limited resource supply and infinite resource demand, improving resource utilization efficiency and enhancing the marine ecological environment are urgent issues that must be addressed in transitioning the marine economy from extensive growth to green development.

Meanwhile, emerging digital technologies are continuously advancing. Digitalization has become an emerging force propelling economic growth, significantly contributing to optimizing resource allocation, innovating development models, and enhancing the flow of resources, thereby providing new avenues for the green development of the marine economy (Li et al., 2022a). On one hand, digital technology applications can increase the efficiency of marine production activities and reduce resource waste. For instance, intelligent fishing systems combined with real-time data analysis can accurately monitor fishery resource conditions, achieve sustainable management, and rationally use fishery resources, thereby promoting the green development of the marine economy. On the other hand, by establishing sophisticated monitoring systems, digital technologies enhance the capability for immediate surveillance and evaluation of marine environment, facilitating early detection and response to environmental issues such as pollution and ocean acidification (Xu et al., 2019; Glaviano et al., 2022). Furthermore, the advancement of digital infrastructure facilitates the removal of temporal and spatial limitations, optimizes the distribution of production elements and resources, modifies industrial structures, and strongly supports the environmentally sustainable growth of the maritime sector (Xu and Liang, 2023; Yao et al., 2023).

Ports, as core strategic resources for marine economic development, are crucial in building marine cities and developing the marine economy. Modern coastal ports serve as international logistics centers that integrate technology, capital, logistics, and information, constituting a significant component of the marine economy. The environmental issues arising from their development have become crucial in achieving sustainable economic development (Wang et al., 2021; Gu et al., 2023). Therefore, promoting the informatization and digitization of modern ports is imperative (Su et al., 2024). Citing the research of Lu et al. (2020), this paper further divides the comprehensive development level of ports into two dimensions: port location quotient and port radiation intensity. The port location quotient is an indicator that measures the degree of specialization of a port, highlighting its significance within the logistics network and its capacity to offer specialized services. Port radiation intensity refers to the extent of the port's economic influence and its stimulating effect on the surrounding hinterland economic regions (Chang et al., 2011; Khan et al., 2022).

Environmental regulation, serving as a pivotal instrument for catalyzing green development, exerts a significant influence on accelerating the economy's transition towards sustainability (Rugman and Verbeke, 1998). When pollution costs are relatively low, implementing environmental regulation increases compliance costs for businesses, diverting capital from digitalization and innovation, and thus inhibiting the digitalization process and the application of green technologies. However, once environmental regulation exceeds a certain threshold, sustained environmental pressure drives companies to adopt digital solutions to increase the effectiveness of resource allocation and lessen negative effects on the environment. At this stage, businesses in the maritime sector are more likely to employ digital tools like supply chain management software, intelligent monitoring systems, and big data analytics to optimize production processes, better utilize marine resources, and reduce pollution emissions, consequently moving the marine industry closer to sustainable and green development (Chang and Wang, 2010).

Therefore, exploring the pathways through which digitalization enables green development of the marine economy and formulating development strategies tailored to its characteristics have emerged as pivotal issues in promoting sustainable development of the marine economy. This paper addresses the following questions: (1) Can digitalization promote the green development of the marine economy? (2) Ports are core strategic resources for the development of the marine economy; will digitalization influence the green development of the marine economy by enhancing the comprehensive development level of ports? (3) Environmental regulation serves as an essential guide and constraint within economic development; will it act as a moderator in the relationship between digitalization and the green development of the marine economy? To answer these questions, this paper collects relevant data from 11 coastal provinces and cities in China from 2011 to 2020 and constructs a regression model to investigate the impact and mechanism of digitalization on the green development of the marine economy.

This paper makes contributions in the following two aspects: First, it broadens the research on digitalization and the green development of the marine economy. Although there is extensive literature on digitalization, discussions on the intersection of digitalization and the marine economy remain relatively underexplored. This paper incorporates digitalization and green development as key variables within a theoretical framework, analyzing their intrinsic connection. Second, it reveals the internal mechanisms by which digitalization empowers the green development of the marine economy. Previous research has primarily focused on the application of digitalization in technical innovation, industrial structure, and ecological monitoring. This paper, however, selects the comprehensive development level of ports and environmental regulation as mechanism variables to investigate the green development path of the marine economy in the context of digitalization.

The remainder of this paper is organized as follows: Section 2 reviews the literature and proposes research hypotheses. Section 3 constructs the models and describes data sources. Section 4 presents empirical results, including the spatial-temporal evolution of marine economy green development, baseline regression results, mechanism test results, and further research. Section 5 conducts robustness tests. Section 6 discusses the research findings. Section 7 summarizes the conclusions and offers policy recommendations.

2 Literature review and research hypotheses

2.1 Literature review

Digitalization represents a profound transformation that extends far beyond the mere application of digital technologies. It encompasses the comprehensive deployment of digital information and communication technologies to fundamentally restructure social and economic frameworks, enabling innovative approaches to value creation and capture (Creutzig et al., 2022). In the contemporary landscape, digital technologies and industries have become deeply interwoven with various sectors of society, positioning digitalization as a crucial catalyst for social and economic transformation. Current scholarly discourse on digitalization primarily emphasizes its economic implications through multiple dimensions. The first significant dimension relates to resource optimization and industrial structure enhancement, where digital technologies serve as a complementary force to existing production, operation, and control technologies. Through their integrative and reconstructive capabilities, these technologies facilitate the convergence of diverse elements across production, operation, and control domains, fostering innovation in both production methodologies and organizational models, thereby guiding industrial development toward more sophisticated levels (Zhang and Wei, 2019). The second dimension concerns the enabling effect of digitalization on innovation quality, fundamentally altering the decision-making processes of innovation participants. This transformation shifts from traditional reliance on limited information and personal experience to data-driven decision-making frameworks, effectively dismantling information silos and enhancing the capacity of innovation entities to access and utilize innovation resources (Neves and Sequeira, 2018). Within this context, digital finance emerges as a crucial component, providing sophisticated mechanisms for evaluating innovation project risks and predicting potential returns, thereby enabling more strategic allocation of funds toward high-value innovation activities (Xu et al., 2017). The third dimension highlights digitalization's pivotal role in environmental protection and green economic growth. He et al. (2022) discovered that the application of digitalization effectively improves resource utilization and reduces pollutant emissions, significantly enhancing ecological efficiency. Xin et al. (2023) indicated that digitalization could promote clean production and inclusive green economic growth by lowering energy use and carbon emissions.

The marine economy encompasses a complex ecosystem of industries and economic activities centered around the exploitation and utilization of marine resources. The concept of green development in this context advocates for harmonious coexistence between human activities and the natural environment, fundamentally grounded in adherence to natural laws and sustainable development principles. Within the marine economy, green development represents a sophisticated approach that seeks to optimize both economic benefits and environmental sustainability. The current research landscape in marine green economy remains in an exploratory phase, resulting in relatively limited findings. Existing scholarly work predominantly focuses on two critical aspects: measurement methodologies for green development and the identification of influential factors. In terms of measurement, scholars have largely adopted a framework that identifies "wastewater," "waste gas," and "solid waste" as undesirable outputs, employing Data Envelopment Analysis (DEA) techniques to construct comprehensive measurement indicators (Li et al., 2015; Zou et al., 2023). Advancing this methodological approach, Ding et al. (2020) introduced an innovative two-stage cooperative game network DEA model that explicitly accounts for the bidirectional relationship and interconnections between production processes and environmental treatment procedures, providing a more nuanced evaluation of marine circular economy performance in China's coastal provinces. Research has identified several key drivers promoting green development in the marine economy, including industrial structure upgrading, technological innovation, and trade openness (Du et al., 2020; Qin and Shen, 2020; Li et al., 2023; Zhao et al., 2023). Conversely, certain factors such as port trade dynamics and government industrial preferences have been found to potentially impede green development progress (Ye et al., 2021; Xia and Qiao, 2022). Recent studies by Sun et al. (2023) and Zhou et al. (2023) have emphasized that enhanced environmental regulation frameworks contribute positively to sustainable marine economic growth. Further investigations reveal that the impact of environmental regulation on marine economy green development exhibits variability depending on the specific types of regulations implemented and their duration (Lingui et al., 2021; Wu et al., 2023).

As digitalization continues to evolve and penetrate various sectors, scholarly attention has increasingly focused on examining the relationship between digitalization and regional economic green development. However, the literature specifically addressing the intersection of digitalization and marine economy green development remains relatively limited. Existing research primarily explores this relationship through several key aspects, including resource development, environmental monitoring, industrial structure, and technological innovation. Li et al. (2022b) posit that digital technologies serve as catalysts for continuous innovation in marine development, driving the marine industry toward more sophisticated forms of development characterized by green practices, integration, intelligence, and deep-sea capabilities. This transformation manifests in various ways, including green advancements in marine shipbuilding and the integrated development of marine engineering equipment. Through empirical analysis of European countries, Nham and Hoa (2023) demonstrated that digitalization significantly enhances the sustainability of marine mineral resources and overall blue economy performance. In the domain of marine environmental monitoring, the implementation of national carbon emissions trading markets leveraging digital technologies for online trading operations exemplifies how digitalization enhances governmental capabilities in carbon emission reduction management and supervision, facilitating smart carbon governance and strengthening national green competitiveness (Li and Song, 2023). Chen et al. (2021) highlighted the role of smart ocean systems in marine ecology protection, emphasizing how big data technologies effectively integrate various data sources, including marine measurement data, remote sensing data, and marine economic data, to enhance environmental monitoring and protection capabilities. Furthermore, evidence suggests that the upgrading of marine industrial structures and technological innovation amplifies the impact of digital finance on carbon emission reductions in the marine energy sector (Xu and Liang, 2023). Jian et al. (2021) argued that the evolution of digital technologies plays a crucial role in facilitating regional integration and dissemination of innovation resources, accelerating intra-industry connectivity and thereby improving production factor allocation efficiency, which particularly benefits the development of emerging sectors such as marine biopharmaceuticals and new marine energy.

While extensive research has examined both the socio-economic effects of digitalization and the various factors influencing marine economy green development from different academic perspectives, there remains a notable gap in literature that integrates these two domains within a unified research framework, particularly regarding the theoretical mechanisms underlying their relationship. This observation underscores the necessity of investigating the impact of digitalization on marine economy green development and its internal mechanisms through a comprehensive analytical approach.

2.2 Research hypotheses

As society enters a new digital era, data has emerged as a fundamental production factor, rapidly permeating across the entire spectrum of economic activities, including production, distribution, circulation, consumption, and social service management. This digital transformation has precipitated significant changes in the production materials and methodologies employed within traditional marine industries. From the perspective of production efficiency, the implementation of digital technologies has demonstrated considerable potential for enhancing marine production activities while simultaneously reducing resource waste (Li et al., 2022b). This is exemplified by intelligent fishing systems that integrate real-time data analysis capabilities to accurately monitor fishery resource conditions, enabling sustainable management practices and rational resource utilization, thereby promoting the green development of the marine economy. In terms of environmental monitoring, digital technologies facilitate the establishment of sophisticated surveillance systems that enhance capabilities for real-time monitoring and evaluation of marine environments, enabling early detection and response to environmental challenges such as pollution and ocean acidification (Chen et al., 2021). Regarding economic structure transformation, the advancement of digital infrastructure plays a crucial role in eliminating temporal and spatial constraints, optimizing the distribution of production elements and resources, modifying industrial structures, and providing robust support for environmentally sustainable growth in the maritime sector (Guan and Li, 2022). Based on these comprehensive analyses of digitalization's multifaceted impacts, this study proposes its first hypothesis:

H1: Digitalization can promote the green development of the marine economy.

The enhancement of port functionality and the cultivation of port advantages represent critical components in the development of marine cities and the broader marine economy. Contemporary coastal ports have evolved into sophisticated international logistics centers that integrate technology, capital, logistics, and information systems, constituting a fundamental pillar of the marine economy. The environmental challenges arising from port development have become increasingly significant in the context of achieving sustainable economic development (Sun et al., 2017). Consequently, the promotion of port informatization and digitization has emerged as an imperative strategy for advancing marine economic development (Wang et al., 2018). Drawing from the research framework established by Lu et al. (2020), this study conceptualizes the comprehensive development level of ports along two distinct dimensions: port location quotient and port radiation intensity. The port location quotient serves as a quantitative indicator measuring the degree of port specialization, reflecting its strategic importance within the logistics network and its capacity to deliver specialized services. Port radiation intensity, conversely, encompasses the breadth and depth of a port's economic influence and its catalytic effect on surrounding hinterland economic regions (Si, 2015). From the perspective of port location, digitalization enhances port operations through multiple mechanisms: optimizing operational processes, increasing efficiency through automation and intelligent technologies, reducing operating costs, minimizing pollution emissions, and strengthening specialized service capabilities. When examined through the lens of port radiation, digitalization facilitates the integration of information and resources across the supply chain, amplifying economic impact on hinterland regions through enhanced supply chain management practices. This integration strengthens logistics systems, promotes spatial agglomeration of industries in the hinterland, optimizes the allocation of port logistics resources to marine advantage industries, increases resource utilization efficiency (Meng et al., 2023), and reduces environmental costs per unit of output. Comprehensively, digitalization not only accelerates the development of smart ports, improving operational efficiency while reducing energy consumption and emissions to achieve both economic and environmental benefits, but also enhances the synergistic relationship between ports and their hinterland economies. Through the promotion of supply chain integration and optimization of resource allocation, digitalization provides substantial support for the green development of the marine economy. Based on these theoretical foundations, the following hypotheses are proposed:

H2a: Digitalization promotes the green development of the marine economy by increasing the port location quotient.

H2b: Digitalization promotes the green development of the marine economy by increasing port radiation intensity.

H2: Digitalization promotes the green development of the marine economy by enhancing the comprehensive development level of ports.

Environmental regulation has emerged as a crucial instrument for catalyzing green development, exerting significant influence on accelerating the economy's transition toward sustainability (Rugman and Verbeke, 1998). The relationship between environmental regulation and digitalization's impact on green development exhibits a complex, non-linear pattern. When pollution-related costs remain relatively low, the implementation of environmental regulations initially increases compliance costs for businesses, potentially diverting capital resources away from digitalization and innovation initiatives, thereby temporarily inhibiting the digitalization process and the application of green technologies. However, as environmental regulation intensifies beyond a certain threshold, sustained environmental pressure creates strong incentives for companies to adopt digital solutions as a means of increasing resource allocation efficiency and mitigating negative environmental impacts. During this advanced stage, businesses operating within the maritime sector demonstrate increased propensity to employ sophisticated digital tools, including supply chain management software, intelligent monitoring systems, and big data analytics, to optimize production processes, enhance marine resource utilization efficiency, and reduce pollution emissions. This technological adaptation ultimately drives the marine industry toward more sustainable and environmentally conscious development practices (Ye et al., 2021). Therefore, while the initial implementation of environmental regulation may temporarily constrain digitalization efforts, once regulatory intensity reaches a critical level, its positive effects begin to manifest, enabling digitalization to more effectively drive the green development of the marine economy. Based on these analytical insights, this study proposes its third hypothesis:

H3: Environmental regulation has a U-shaped moderating effect on the impact of digitalization on the green development of the marine economy.

The theoretical model of this paper is shown in Figure 1.

3 Models and data

3.1 Models

Drawing on the preceding theoretical discourse and considering the panel structure of our provincial data, we employ a fixed effects model to investigate the impact of digitalization on marine economy green development. This methodological choice is supported by the Hausman test results (χ^2 = 38.24, p < 0.01), which indicate the fixed effects specification is more appropriate than random effects for controlling unobserved provincial heterogeneity. The fixed effects model effectively addresses potential endogeneity concerns arising from time-invariant omitted variables such as geographical location and historical development patterns. Accordingly, our baseline regression model is specified in Formula 1:

$$MEG_{it} = \alpha_0 + \alpha_1 Digi_{it} + \alpha_2 Cons_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (1)$$

Among the variables considered, MEG_{it} is the explained variable, representing the green development level of the marine economy. $Digi_{it}$ is the explanatory variable, representing the level of digitalization. $Cons_{it}$ represents the control variables, μ_I and δ_t are individual and time fixed effects respectively, and ε_{it} is the random error term.

To further explore the pathways through which digitalization affects the green development of the marine economy and whether the transmission mechanism of Hypothesis 2 exists, the model is constructed in the Formula 2:

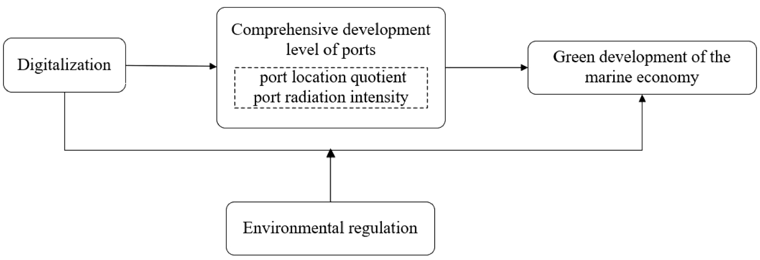

FIGURE 1
Diagram of theoretical model.

$$Med_{it} = \beta_0 + \beta_1 Digi_{it} + \beta_2 Cons_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (2)$$

Among the variables considered, Med_{it} is the mediator variable, which will be detailed later, and other variables are the same as in Formula 1. Following Jiang Ting's approach (Jiang, 2022), if the theoretical hypothesis section proposes mediator variables that are evidently consistent with economic theory and analyzes the relationship between the core explanatory variables, mediator variables, and the explained variable, then the link between the mediator variables and the core explanatory variables is all that has to be tested in the empirical portion. The following are the precise procedures for testing the mediation effect in this study. After the regression coefficient α in Formula 1 passes the significance test, the Formula 2 is constructed to test the relationship between the mediator variable and the explanatory variable *Digi*. If the regression coefficient β_1 in Formula 2 is still significant, then the mediation effect exists.

To verify Hypothesis 3, this paper adds the interaction term of digitalization and environmental regulation as well as the squared interaction term of digitalization and environmental regulation into Formula 1, thereby constructing model in the Formula 3.

$$MEG_{it} = \gamma_0 + \gamma_1 Digi_{it} + \gamma_2 Digi_{it} \times ER_{it} + \gamma_3 Digi_{it} \times ER_{it}^2 + \gamma_4 ER_{it} + \gamma_5 ER_{it}^2 + \gamma_6 Cons_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (3)$$

Among the variables considered, ER_{it} is the moderating variable representing environmental regulation. If the interaction coefficient $\gamma 3$ in Formula 3 is significantly positive, it indicates that environmental regulation exerts a U-shaped moderating effect on the relationship between digitization and green development in the marine economy.

3.2 Data

3.2.1 Explained variable: green development of marine economy

Green development efficiency of marine economy, which reflects how efficiently marine economic growth uses inputs and outputs within the limits of marine resources and the environment, is used to measure the level of the green development of marine economy (MEG). Following the study of Sun et al. (2023), this paper develops an indicator system and employs the non-oriented super-efficiency Slacks-Based Measure (super-SBM) model (Tone, 2002) to measure green development efficiency. Table 1 presents the input-output index system in full. Labor, capital, and energy are the three key input indicators. Labor input is quantified by the employment figures within marine-related sectors. For capital input, following the approach of Zhang et al. (2004), the capital stock of coastal regions is determined using the perpetual inventory approach, with 2000 as the base year. This is then adjusted by the ratio of gross marine product to GDP to determine the marine capital stock for each province and city. Energy input is similarly adjusted by the ratio of gross marine product to GDP to calculate the energy consumption of the marine economy for each province and city. The output indicators include both expected and unexpected outputs. The expected output is the gross marine product of each region, adjusted using the year 2000 as the base period. For the undesirable outputs, this study first adjusts marine industrial wastewater discharge, marine industrial sulfur dioxide discharge, and marine industrial solid waste by the ratio of gross marine product to GDP. These three indicators are then combined into a comprehensive value using the entropy method to obtain the undesirable output.

TABLE 1 Measurement of green development efficiency in the marine economy.

Indicators	Secondary Indicators	Specific Measure
Input Indicators	Labor Input	Number of Marine Employment Personnel
	Capital Input	Marine Capital Stock
	Energy Input	Energy Consumption (Marine GDP/GDP)
Output Indicators	Expected Output	Marine GDP
	Unexpected Output	Industrial Wastewater (Marine GDP/GDP)
		Industrial Sulfur Dioxide (Marine GDP/GDP)
		Industrial Solid Waste (Marine GDP/GDP)

3.2.2 Explanatory variables: digitalization

In accordance with the approaches of Li et al. (2024) and Zhao et al. (2022), this paper selects five indicators based on the connotations and characteristics of digitalization: the number of internet users per hundred people, the number of mobile phone users per hundred people, the proportion of employees in computer services and software industries relative to those in urban units, per capita telecommunications business volume, and the China Digital Inclusive Finance Index. Subsequently, the entropy method is used to calculate the digitization level of each region.

3.2.3 Mechanism Variable

3.2.3.1 Mediator variable: comprehensive development of ports

Following the methodology of Lu et al. (2020), this paper initially computes the port location quotient (Q) and port radiation intensity (Ri) using Formulas 4 and 5, followed by applying the entropy method to assess the comprehensive development level of ports in coastal provinces and cities.

$$Q = \frac{\frac{LTP}{WTP}}{\frac{LIE}{WIE}} \quad (4)$$

$$Ri = \frac{LTP - WTP \times \frac{LIE}{WIE}}{WTP} \quad (5)$$

where Q represents the port location quotient, Ri represents port radiation intensity, LTP represents the cargo throughput of coastal ports, WTP represents the total cargo throughput of coastal ports nationwide, LIE represents the total import and export volume of the coastal port location, and WIE represents the total import and export volume nationwide.

3.2.3.2 Moderating variable: environmental regulation

Referring to the study by Sun and Song (2019), this paper measures the intensity of environmental regulation using the ratio of environmental governance investment to GDP. This calculation method is derived from the formula "Environmental regulation intensity = (Environmental governance investment × the proportion of marine output value in the total value)/Total marine value".

3.2.4 Control variables

Following the academic work of Xia et al. (2019); Ye et al. (2021), and Zhang and Li (2023), this study adopts the following control variables to increase overall analytical validity and data fitting: (1) Foreign Direct Investment (FDI), represented by the proportion of total foreign investment to regional GDP; (2) Urbanization level (Urba), represented by the proportion of urban population to total population; (3) Government intervention level (Gov), represented by the proportion of fiscal expenditure to regional GDP; (4) Marketization level (Mark), represented by the marketization index from the "China Provincial Marketization Index 2018" compiled by Wang et al. (2019); (5) Sea area utilization level (SRL), calculated as the ratio of sea area use fees to the area of certified sea areas.

3.2.5 Data source

Due to the availability of Chinese marine economic data being updated only until 2020, this study selects data from 2011 to 2020 for 11 coastal provinces and cities in China as the research sample. The relevant data primarily come from the *China Marine Economic Statistical Yearbook*, *China Statistical Yearbook*, *China Tertiary Industry Statistical Yearbook*, *Peking University Digital Inclusive Finance Index*, and provincial statistical yearbooks. Missing data are filled in using the *National Economic and Social Development Statistical Bulletins* from various provinces and cities, the CSMAR database, along with other sources. Linear interpolation is used to fill in missing data for certain years.

4 Results

4.1 Spatial and temporal evolution of the green development of the marine economy

The evolution of the green development of the marine economy (MEG) in China is shown in Figure 2. As illustrated, the level of MEG in China exhibited an overall ascending trend punctuated by fluctuations over the period from 2011 to 2020. Specifically, it remained stable from 2011 to 2014, experienced a slight decline in 2015, began to recover in 2016, continued to develop steadily, and saw a significant increase in 2020. Further spatial analysis of the three major marine economic zones—North, East, and South—reveals significant regional disparities in the level of MEG. The overall trend in the Eastern Marine Economic Zone aligns with the national trend, maintaining a leading position in green development, while the Northern Marine Economic Zone remains behind. The observed disparity can likely be ascribed to the advanced economic status in the Eastern region, complemented by an established maritime transport infrastructure, pronounced marine industry structural advantages, a prevalence of high-tech sectors characterized by low pollution and energy use, and robust capabilities in environmental conservation and remediation. Conversely, the northern coastal areas, such as the Bohai Bay region, have historically been dominated by heavy industries. Although industrial restructuring has been undertaken in recent years, these regions still lag behind other parts of China, facing obstacles in balancing the growth of their maritime economies with that of the environment.

Figure 3 displays the level of MEG in China's coastal areas in 2020. As illustrated, most provinces and cities have not reached the national average level of MEG, with Shanghai ranking highest and

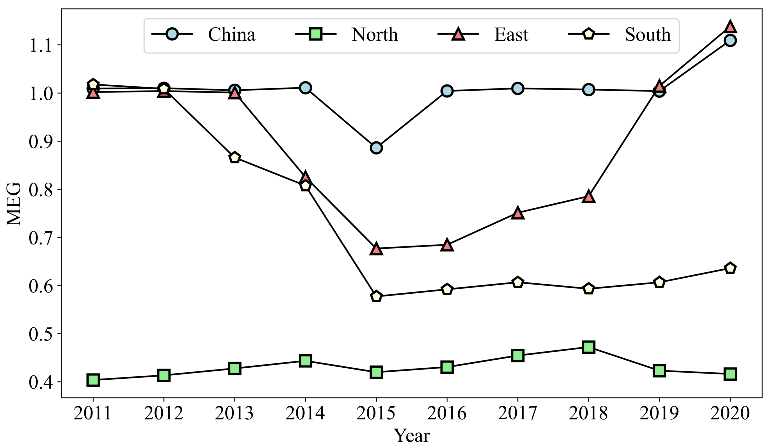

FIGURE 2
Green development trend of Marine economy from 2011 to 2020.

Guangxi lowest. This discrepancy may be because Shanghai's economy is relatively advanced, with numerous marine research institutions and comprehensive pollution management and ecological protection efforts in the Yangtze River estuary and offshore areas. Additionally, Shanghai has a well-established regional pollution joint prevention mechanism. Conversely, Guangxi has accepted the relocation of highly polluting and high-emission industries while developing marine salt chemicals, marine petrochemicals, offshore heavy industries, and coastal chemical industries. These industries typically suffer from outdated technology and extensive development models.

4.2 Baseline regression results

This paper utilizes a two-way fixed effects model for baseline regression to preliminarily assess the impact of digitalization on the green development of the marine economy (MEG). Table 2 presents the estimation outcomes. The results in column (1) indicate that, excluding control variables, the coefficient of digitalization is significantly positive at the statistical level of 5%, suggesting that digitalization actively promotes MEG. The results in column (2) show that after adding several control variables, the estimated coefficient of the explanatory variable increases from 0.748 to 0.838, and the explanatory power of the model also improves, indicating that the improvement in digitalization indeed supports MEG, thereby validating Hypothesis 1. Moreover, the extent of government intervention is found to significantly and positively influence MEG. This result is in line with the study conducted by Xia et al. (2019), suggesting that higher government attention in coastal areas leads to a higher level of MEG. Similar to the findings of Zhang and Li (2023), the regression coefficients for urbanization level and marketization level are significantly negative. This may be due to the rapid advancement of urbanization, which has increased pressure on the regional ecological environment, while a higher degree of marketization implies intensified market competition, leading to resource waste as enterprises pursue maximum self-interest, thereby inhibiting MEG. Although the regression coefficients for foreign direct investment and sea area utilization level are positive, they are not significant, indicating the need to further improve sea area utilization and actively attract foreign investment toward emerging marine industries.

4.3 Mechanism test results

To verify Hypothesis 2, this paper uses the mediation effect testing method proposed by Jiang (2022) to analyze how digitalization impacts MEG. Based on the sufficient demonstration of the rationality of the mediator variables in the previous section, this paper tests the effect of the core explanatory variable, digitalization, on the mediator variable, port comprehensive development level. The results in column (1) of Table 3 displays the regression results. The coefficient of digitalization is significantly positive, suggesting that digitalization has the potential to elevate the overall development level of ports. Further regressions dividing the port comprehensive development level into two dimensions, port location quotient and port radiation intensity, are shown in columns (2) and (3) of Table 3. The coefficients of digitalization are significantly positive at the 1% and 10% levels, respectively, implying that digitalization helps enhance both the port location quotient and port radiation intensity. Combining these results with the theoretical analysis in the research hypothesis section, it is evident that digitalization can promote MEG by improving the comprehensive development level of ports through the enhancement of port location quotient and port radiation intensity, thus validating H2a, H2b, and H2.

The results in column (4) of Table 3 test the nonlinear moderating effect of environmental regulation on the relationship between digitalization and MEG. As shown in column (4) of

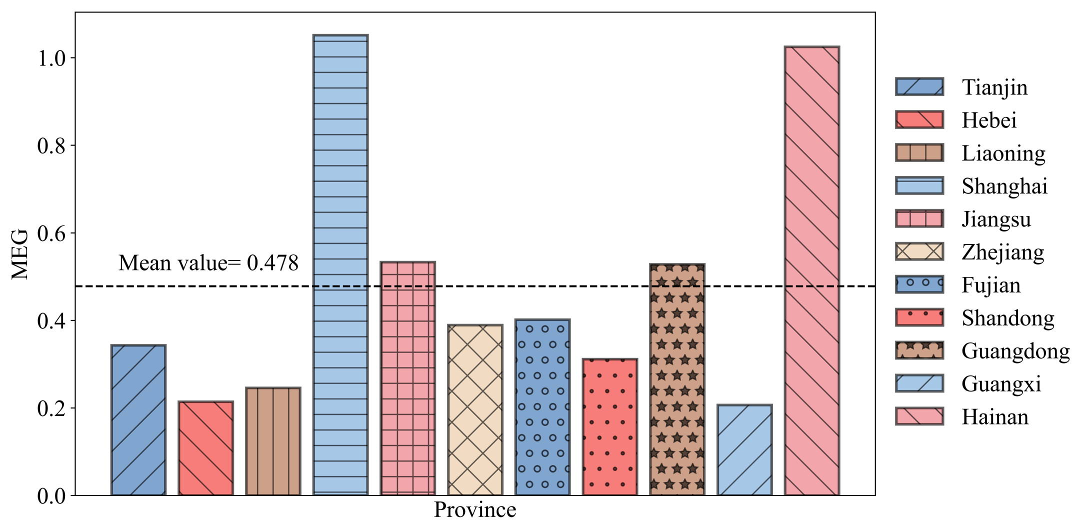

FIGURE 3
Level of green development of Marine economy in 2020.

Table 3, the interaction term between digitalization and the square of environmental regulation is positive at the significance level of 1%, suggesting that the impact of digitalization on MEG is moderated by environmental regulation in a U-shaped manner, thereby validating Hypothesis 3. The specific moderating effect is illustrated in Figure 4. From the figure, it is evident that when environmental regulation is less strict, it weakens the effect of digitalization in promoting MEG; as environmental regulation strengthens, it serves to bolster digitalization's affirmative contribution to green growth. When the intensity of environmental regulation is 1.27, the positive effect of digitalization on MEG is weakest, at 0.67.

4.4 Further research

Considering China's extensive geography and notable regional disparities in development, this paper delves deeper into the varied impacts of digitalization on MEG.

4.4.1 Temporal heterogeneity

In 2014, the "Chinese Government Work Report" first mentioned digitalization-related topics such as "next-generation mobile communications" and "big data.". Therefore, this paper divides the timeframe into two periods: the first stage from 2011 to 2014 and the second stage from 2015 to 2020. This division aims to discuss whether the impact of digitalization on MEG exhibits temporal heterogeneity. The results in columns (1) and (2) of Table 4 show that digitalization significantly promoted MEG at the 10% level after 2015, while this effect was not noticeable from 2011 to 2014. This may be because, since 2015, the growth of digitalization has received much more backing from the Chinese government due to policy guidance. With more investment and resource allocation, the information technology level of marine industries has been notably enhanced. This transition has not only promoted the modernization and intelligentization of the marine economy but also provided a solid technical foundation that can enable effective resource management and ecological environment preservation.

TABLE 2 The impact of digitalization on the green development of the Marine economy.

Variables	(1)	(2)
	MEG	*MEG*
Digi	0.748**	0.838**
	(0.375)	(0.379)
FDI		0.844
		(1.325)
Urba		-3.362***
		(0.744)
Gov		1.943**
		(0.775)
Mar		-0.056**
		(0.025)
SRL		0.001
		(0.000)
cons	0.153	2.375***
	(0.114)	(0.643)
Time	Yes	Yes
Province	Yes	Yes
N	110	110
Adj_R²	0.665	0.755

Robust standard errors are in parentheses and ** and *** respectively represent significant at the confidence level of 5% and 10%.

TABLE 3 The results of mechanism test.

Variables	(1)	(2)	(3)	(4)
	Q	*Ri*	*Port*	*MEG*
Digi	4.455***	0.076*	0.592***	1.673***
	(1.457)	(0.045)	(0.205)	(0.435)
Digi×c.ER				-1.556***
				(0.338)
Digi×c.ER²				0.608***
				(0.192)
ER				0.601***
				(0.135)
ER²				-0.185***
				(0.046)
FDI	-2.724	-0.018	-0.327	-1.089
	(4.010)	(0.085)	(0.517)	(1.129)
Urba	7.057***	0.266***	1.117***	-2.038***
	(1.962)	(0.047)	(0.249)	(0.612)
Gov	3.225	0.043	0.413	2.138***
	(2.206)	(0.044)	(0.259)	(0.746)
Mar	0.063	0.007***	0.016	-0.040*
	(0.073)	(0.002)	(0.010)	(0.022)
SRL	0.004**	0.000***	0.001***	0.001*
	(0.002)	(0.000)	(0.000)	(0.000)
cons	-4.814**	-0.251***	-0.327	0.982
	(2.029)	(0.048)	(0.517)	(0.592)
Time	Yes	Yes	Yes	Yes
Province	Yes	Yes	Yes	Yes
N	110	110	110	110
Adj_R²	0.974	0.877	0.981	0.819

*, ** and *** respectively represent significant at the confidence level of 1%, 5% and 10%.

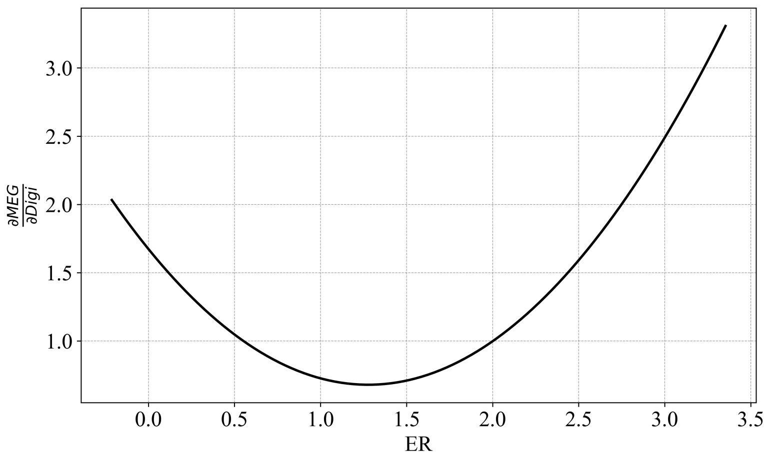

FIGURE 4
U-shaped moderating effect of environmental regulation.

4.4.2 Regional heterogeneity

Recently, China has been vigorously promoting the Belt and Road Initiative and the establishment of an all-dimensional, multi-level, and wide-ranging blue partnership. Accordingly, this paper splits the total sample into two sub-samples based on "the Belt and Road" initiative: regions along "the Belt and Road" and regions not along "the Belt and Road". The results in columns (3) and (4) of Table 4 show that digitalization significantly promotes MEG only in the regions along "the Belt and Road" initiative. The possible reason is that the regions along "the Belt and Road" initiative enjoy policy inclinations at the national strategic level. The government provides more funding, technology, and talent support to facilitate the deep integration of digitalization with the marine industry, improve resource allocation efficiency, promote the widespread application of environmentally friendly technologies, and thus accelerate the green transition of the marine economy.

5 Robustness test

5.1 Lagged regression of explanatory variables

Given that the impact of digitalization on MEG may not be immediate but rather lagged, this paper performs a regression by lagging the explanatory variable, digitalization, by 1-2 periods. The results in columns (1) and (2) of Table 5 show that the estimated coefficients of the explanatory variable lagged by one period and two periods are significantly positive at the 1% and 5% levels, respectively, underscoring the robustness of the findings and providing support for Hypothesis 1.

5.2 Removing outliers impact

To preclude the distortion of regression results by extreme outliers, this paper re-examines the data after performing 1% and 5% trimming on both sides of the explanatory and explained variables. The results are shown in columns (3) and (4) of Table 5. The coefficient of digitalization remains significantly positive, further demonstrating the robustness of the study's conclusions.

5.3 Instrumental variable regression

Measures such as restructuring the energy system, building a resource recycling system, promoting low-carbon technologies, and improving carbon data management efficiency are crucial for transitioning the marine economy to green development. However, these measures may also significantly increase the demand for digital technologies (e.g., intelligent ports, marine carbon sink monitoring), thereby promoting the development of digitalization itself. In order to lessen the possibility of an endogeneity issue resulting from this reverse causality, this study employs the instrumental variable (IV) method for endogeneity testing, ensuring the accuracy and reliability of the research results. Referring to the study by Huang et al. (2019), this paper selects the interaction term constructed by the number of internet users nationwide in the previous year and the number of post offices in each province in 1984 as the instrumental variable for digitalization. The model estimation is performed using 2SLS and LIML, and the regression results are shown in columns (1) and (2) of Table 6. Although the first-stage estimation results of 2SLS show a significantly positive correlation between the instrumental variable and the endogenous variable at the 10% level, the K-P Wald F statistic in the first stage of regression is lower than the critical value of 16.38 required for the weak instrumental variable test, indicating the presence of weak instrumental variable issues. A common solution to weak instrumental variable problems is to use the Limited Information Maximum Likelihood (LIML) method. Under large samples, LIML and 2SLS are asymptotically equivalent, but if the instrument is weak, LIML has better small-sample properties than 2SLS. Considering the small sample size in this

TABLE 4 The results of heterogeneity analysis.

Variables	(1) 2011-2014	(2) 2015-2020	(3) regions along B&R	(4) regions not along B&R
	MEG	*MEG*	*MEG*	*MEG*
Digi	0.010	1.040*	1.567***	-0.569
	(0.055)	(0.604)	(0.582)	(0.360)
FDI	0.402	-0.188	-1.659	-1.693*
	(1.265)	(1.917)	(2.400)	(0.891)
Urba	-1.572***	-4.914***	-3.127***	-0.503
	(0.375)	(1.293)	(0.885)	(0.601)
Gov	0.412	2.861***	3.178**	0.497
	(0.289)	(1.050)	(1.542)	(0.300)
Mar	-0.000	-0.092*	-0.029	-0.058***
	(0.005)	(0.052)	(0.042)	(0.018)
SRL	-0.000	0.000	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)
cons	1.213***	3.589***	1.519	1.251***
	(0.275)	(1.072)	(0.930)	(0.417)
Time	Yes	Yes	Yes	Yes
Province	Yes	Yes	Yes	Yes
N	33	77	70	40
Adj_R²	0.994	0.763	0.763	0.909

*, ** and *** respectively represent significant at the confidence level of 1%, 5% and 10%.

study, this paper adopts the methodology of Lin et al. (2022) and re-runs the regression using the LIML method. The results are shown in column (3) of Table 6. Compared to the 2SLS estimation results, the LIML and 2SLS estimation results do not differ significantly, implying that the weak instrumental variable issue has little impact on the estimation results of this paper. The conclusion that digitalization promotes MEG remains robust.

6 Discussion

Digitalization is guiding China's marine economy towards a greener and more sustainable development path. Compared with previous literature, this paper focuses on how digitalization influences the green development of the marine economy (MEG), providing a more macro and comprehensive perspective rather than just focusing on the impact of digitalization on specific marine sub-fields such as marine research and port logistics.

This study finds that digitalization significantly enhances MEG. Notably, this positive impact is more pronounced in regions along "the Belt and Road" initiative, suggesting that strategic policy initiatives can amplify the benefits of digitalization. The mechanism analysis reveals that improving the comprehensive development level of ports is a critical pathway through which digitalization promotes MEG. Within this framework, the enhancement of port location quotients plays a more crucial role than port radiation intensity. This finding indicates that while expanding the scope and connectivity of port operations is important, the specialized improvement of port functionalities yields more substantial environmental benefits. Moreover, the study identifies a U-shaped moderating effect of environmental regulation on the relationship between digitalization and MEG. At low levels of regulation intensity, environmental policies initially constrain digital and innovative capital investment, thereby dampening the momentum of green development. Nonetheless, with heightened regulatory intensity, firms embrace digitalization to improve operational efficiencies and diminish their environmental impact.

In terms of practical application, the findings provide important insights for advancing MEG. Through the integrated innovation of technologies such as big data analysis, artificial intelligence, and the Internet of Things, it becomes possible to predict marine environmental changes more accurately, respond promptly to various marine disasters, and ensure the sustainable use of marine resources. Port authorities can prioritize investments in digital technologies that enhance operational efficiencies and reduce environmental impacts. By integrating digital tools such as big data analytics, intelligent monitoring systems, and supply chain management software, ports can achieve significant gains in both cost-efficiency and environmental sustainability. Environmental regulators can take a more nuanced approach to policy design, ensuring that regulatory measures are stringent enough to drive innovation but also supportive of the digital transformation necessary for achieving green development goals.

Despite the findings, this study has certain limitations. First, the data used in this study mainly comes from China's coastal provinces from 2011 to 2020, which, although representative, could be further expanded in future research. Second, this study mainly focuses on factors such as digitalization, comprehensive development of ports, and environmental regulation. Future research could explore other potential influencing factors of MEG, such as policy environments and international cooperation.

In conclusion, digitalization emerges as a pivotal force in driving MEG. By enhancing port operations and resource management, digital technologies offer a pathway to sustainable economic growth. Policymakers, port authorities, and regulators must collaborate to harness the full potential of digitalization, ensuring that the marine economy evolves in a manner that is both economically viable and environmentally sustainable.

7 Conclusions and recommendations

7.1 Main conclusions

This study comprehensively investigates the relationship between digitalization and the green development of China's marine economy, yielding several significant findings. The research reveals that digitalization plays a fundamental role in promoting the green development of the marine economy, with this effect becoming particularly pronounced after 2015 when China began implementing targeted digital transformation policies. The impact manifests more strongly in regions along "the Belt and Road" initiative, highlighting the importance of

TABLE 5 The results of robustness tests.

Variables	(1) Lag one period	(2) Lag two period	(3) Taper 1%	(4) Taper 5%
	MEG	*MEG*	*MEG*	*MEG*
L.Digi	1.363***			
	(0.442)			
L2.Digi		1.483**		
		(0.601)		
Digi			0.801**	0.606*
			(0.398)	(0.353)
FDI	0.675	0.185	0.661	0.299
	(1.488)	(1.709)	(1.345)	(1.111)
Urba	-3.768***	-4.127***	-3.255***	-1.705***
	(0.897)	(1.140)	(0.780)	(0.424)
Gov	2.157**	2.357**	1.866**	0.982*
	(0.827)	(0.913)	(0.787)	(0.582)
Mar	-0.062**	-0.063*	-0.048**	-0.027
	(0.029)	(0.033)	(0.023)	(0.020)
SRL	0.001	0.000	0.001	0.001
	(0.000)	(0.000)	(0.001)	(0.001)
cons	2.517***	2.743***	2.264***	1.312***
	(0.765)	(0.935)	(0.670)	(0.445)
Time	Yes	Yes	Yes	Yes
Province	Yes	Yes	Yes	Yes
N	99	88	110	110
Adj_R^2	0.772	0.773	0.749	0.9763

*, ** and *** respectively represent significant at the confidence level of 1%, 5% and 10%.

TABLE 6 The results of instrumental variable regression.

Variables	(1) 2SLS I	(2) 2SLS II	(3) LIML
	Digi	*MEG*	*MEG*
Digi		6.053*	6.053*
		(3.595)	(3.595)
IV	0.000*		
	(0.000)		
FDI	0.862**	-3.597	-3.597
	(0.416)	(3.452)	(3.452)
Urba	0.009	-2.161*	-2.161*
	(0.214)	(1.225)	(1.225)
Gov	-0.352*	3.754**	3.754**
	(0.195)	(1.579)	(1.579)
Mar	-0.012	0.022	0.022
	(0.008)	(0.068)	(0.068)
SRL	-0.000***	0.003*	0.003*
	(0.000)	(0.002)	(0.002)
cons	-0.305	-0.825	-0.825
	(0.358)	(2.458)	(2.458)
Time	Yes	Yes	Yes
Province	Yes	Yes	Yes
K-P Wald F	3.053		
N	110	110	110
Adj_R^2	0.970	0.154	0.154

*, ** and *** respectively represent significant at the confidence level of 1%, 5% and 10%.

policy support in maximizing the benefits of digital transformation. Through detailed mechanism analysis, the study finds that digitalization enhances green development primarily by improving the comprehensive development level of ports, with port location quotient playing a more crucial role than port radiation intensity. This suggests that specialized enhancement of port functionalities yields more substantial environmental benefits than merely expanding operational scope. Furthermore, the research identifies a nuanced U-shaped moderating effect of environmental regulation on the relationship between digitalization and green development. Initially, when environmental regulations are less stringent, they may constrain digital innovation investments. However, as regulatory intensity increases beyond a certain threshold, it effectively catalyzes businesses to embrace digital solutions for improving operational efficiency and reducing environmental impact.

7.2 Policy recommendations

Based on these empirical findings, several targeted policy recommendations are proposed to enhance the effectiveness of digitalization in promoting marine economic green development.

First, governments should strengthen the digital infrastructure foundation of coastal regions by increasing investment in next-generation information technologies. The implementation process should follow a phased approach: initial infrastructure deployment in major port areas, followed by comprehensive coverage expansion, and ultimately achieving full integration with port operations. Regular assessments of infrastructure performance and environmental impact should be conducted to ensure policy effectiveness.

Second, port authorities should prioritize the development of smart port systems that integrate advanced digital technologies. Implementation should begin with foundational automated systems and environmental monitoring networks, progressively advance to digital twin technologies and blockchain solutions, and culminate in establishing comprehensive data sharing platforms. Performance metrics should focus on operational efficiency, energy consumption, and environmental compliance improvements.

Third, environmental regulators should adopt a graduated approach to policy implementation. The framework should establish baseline standards, implement tiered requirements with appropriate incentives, and progressively advance toward comprehensive digital integration. Regular evaluation mechanisms should be established to monitor regulatory effectiveness and environmental outcomes.

Finally, regions along "the Belt and Road" initiative should leverage their policy advantages through systematic implementation of demonstration projects. This includes establishing appropriate funding mechanisms, fostering international cooperation, and developing scalable models for broader application. Success should be evaluated through comprehensive assessment of digital transformation progress and green development indicators.

Data availability statement

The data analyzed in this study is subject to the following licenses/restrictions: Due to Chinese marine economic data availability being limited to 2020, this study uses data from 2011-2020 for 11 coastal provinces and cities. Data sources include the China Marine Economic Statistical Yearbook, China Statistical Yearbook, and other official statistical publications. The data presented in this study are available on request from the corresponding author. Requests to access these datasets should be directed to ML, 202230710218@stu.shmtu.edu.cn.

Author contributions

XJ: Writing – review & editing, Conceptualization, Funding acquisition, Methodology. ML: Data curation, Formal Analysis, Software, Writing – original draft, Writing – review & editing. XL: Visualization, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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