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Spatiotemporal Differences in Marine Environment Quality in China and the Influencing Factors

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Abstract: Based on 2011–2020 panel data for China's coastal cities and provinces, this study used the entropy method and Theil index to measure marine environment quality (MEQ) and construct MEQ indicators. We used the Theil index to measure heterogeneity in regional MEQ and a geographic detector model to explore the driving factors of MEQ. Our study resulted in the following findings: (1) MEQ increased in waves, but the overall quality was relatively low, forming a spatial distribution pattern of high in the north and south, and low in the east. Moreover, MEQ was polarized between provinces. (2) Regional MEQ showed a distribution pattern of significant differences between the east and the north but small differences in the south. The regional gap was significant but gradually narrowing, with the contribution rate of intra-regional differences reaching over 90%. Meanwhile, interregionalinter-regional differences were relatively small and showed a balanced development trend. (3) Agricultural and aquaculture pollution were found to be the main factors affecting MEQ. The effect of marine engineering pollution was significantly increasing while that of environmental regulation intensity was relatively weak. The interaction between different driving factors mainly manifested as dual-factor enhancement and nonlinear enhancement.

Keywords: marine environment; spatiotemporal difference; regional difference; environmental quality; marine economic circle

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1. Introduction

The marine environment is an important foundation for human survival and sustainable development, playing an indispensable role in climate regulation, food security, economic development, and ecological livability. The ocean not only provides living space for fish, shrimp, algae, plankton, etc., but also provides oxygen, physical resources, and energy resources for human production and life. At the same time, the ocean provides a space carrier for employment worldwide. It is expected that by 2030, ocean-related industries will employ 40 million people. However, the quality of the marine environment is facing unprecedented challenges such as global climate change, pollution emissions, overfishing of marine fisheries, and the "plastic siege". According to the UN report The Second World Ocean Assessment (WOA II), "Over the past 50 years, the area of low oxygen seas worldwide has tripled, with nearly 90% of mangroves, seaweed, and wetland plants, as well as over 30% of seabirds facing extinction threats, weakening the ocean's role in regulating global climate". The number of "dead water zones" with extremely low oxygen content in oceans increased from over 400 in 2008 to nearly 700 in 2019. Economic losses caused by overfishing are as high as USD 88.9 billion per year [1]. According to 2022 data released by the UN Environment Programme, "Currently, nearly 100 million tons of plastic waste flow into the ocean every year, accounting for 85% of the total amount of marine waste. Marine plastic waste not only pollutes seawater but also pollutes the air in the sea, causing serious effects on the marine industry, resulting in economic losses of up to 8 billion US dollars" [2]. The continuous decline in marine environmental quality not only leads to ecological problems such as depletion of marine resources, acidification of seawater, abnormal marine biological structure, rising sea levels, and coral reef damage, but also causes development difficulties such as low efficiency of the marine industry, reduced resilience of the marine economy, intensified losses from marine disasters, and increased maintenance costs of the marine ecological environment. This has led to a vicious cycle of mutual constraints between the marine environment and economic and social development. Although countries and regions around the world are accelerating the governance of the marine ecological environment and promoting green and low-carbon development, the deterioration of marine environmental quality has not been fundamentally curbed. How to reduce marine pollution, reduce the damage of economic development to marine ecosystems, and solve the bottleneck of marine environmental quality development has become a common reality faced by countries and regions worldwide. Therefore, it is of great theoretical and practical value to deeply reveal the dynamic evolution of marine environmental quality, identify the core influencing factors of marine environmental quality, improve the level of marine environmental quality, promote the coordinated and integrated development of marine environment and economy, and achieve a win–win situation of high-level protection of marine ecology and high-quality economic development.

Recent research on marine environments has mainly focused on changes in marine water quality, the quality of marine biological resources, and the efficiency of the marine environment. Research methods mainly include GIS, fuzzy evaluation, grey relational evaluation, the water quality parameter method, and super-efficiency models for quantitative analysis [3–15]. Regarding changes in the water quality of the marine environment [16–20], Leifu et al. used the single-factor index method and the Nemero index method to analyze the pollution characteristics of seawater and surface sediment [21]. Wang et al. conducted a survey of the waters near Yalong Bay and analyzed the water quality and sediment environment [22]. Wang et al. analyzed the distribution characteristics of and changes in water quality and eutrophication in the Laizhou Bay area; they proposed a combination of "reducing emissions" and "increasing capacity" to control key pollutants and improve environmental quality in the area [23]. Du et al. measured the ecological security evaluation of marine ranching based on DEMATEL–Fuzzy comprehensive evaluation [24]. The European Union proposed an ecological assessment method for implementing the Water Framework Directive [25]. The "Clean Water Action Plan" of the US proposes an evaluation method for coastal waters [26]. Nabila Abid et al. studied Pakistan as the object and explored the relationship towards environmental sustainability by exploring the nexus among International Organization for Standardization (ISO) 14001, governance indicators, and green economy [27]. Marilena Sanfilippo investigated the spatiotemporal organic carbon distribution in relation to environmentally sustainable approaches and found different trends for all parameters, mainly related to different seasons and water exchanges with the sea [28].

Regarding the environmental quality of living marine resources [29–34], Wang et al. used GIS to evaluate the quality of the habitat environment for China's nearshore marine biological resources [35]. Jong evaluated the health of coastal ecosystems in the marine environment in 47 regions using the system analysis method of ecological quality objectives, as proposed in the Northwest Pacific Action Plan [36]. Han analyzed the similarities, differences, advantages, and disadvantages of marine environment assessment methods used in the US and the EU and proposed an assessment method for MEQ suitable for China's estuaries and coastal waters, as well as corresponding monitoring and management systems [37]. Song analyzed the diversity and long-term changes in major marine biological groups such as phytoplankton, zooplankton, and benthic organisms in Laizhou Bay [38]. Han used a variable fuzzy recognition algorithm to evaluate trends in MEQ changes in 11 coastal provinces and cities in China from 2006 to 2016 and conducted a spatiotemporal analysis [39]. Regarding marine environment ecological efficiency, Gaimei used a super-efficiency model to calculate dynamic changes in marine ecological efficiency in coastal provinces and cities in China [40]. Di Qianbin calculated spatiotemporal differences in China's marine ecological efficiency and explored its relationship with the response of the marine industry structure [41]. Sun evaluated the coordinated development of China's marine economy and environment by measuring the ecological benefits of the ocean, finding that the efficiency of China's marine ecology had improved, and its dynamic evolution was relatively obvious [42]. DEA is a systematic evaluation method first proposed by operations researcher Charnes A. et al. in 1978. It is a non-parametric statistical method for measuring the relative efficiency of multi-input and multi-output decision units (DMUs). DEA is mainly divided into CCR and BCC models. In terms of ecological efficiency research, the academic community mostly adopts the CCR model in DEA. Yang et al. calculated the efficiency of China's marine environment from 2008 to 2017 using a DEA model, explored its spatiotemporal evolution trends and regional differences, and analyzed the factors affecting the efficiency of the marine environment; they found that the marine industry structure and marine technology investment had a positive, significant effect on the efficiency of the marine environment [43]. Wang et al. calculated the natural resource endowment and ecological efficiency in China and found that regional eco-efficiency is low and the volatility is increasing [44].

Our review of the literature indicates that various empirical methods have been used to study MEQ in terms of seawater quality, biodiversity, environmental benefits, and carbon emissions. Such work provides theoretical foundations and research methods for the present study. However, previous studies have mostly focused on a single field or perspective, and there are omissions and areas for further development. The marine environment is a complex system, and research on its quality needs to be diversified. However, there are few theoretical or empirical studies of the evaluation and dynamic evolution of MEQ. What is the overall level of MEQ, and what are the characteristics and patterns of its spatiotemporal evolution? Is there heterogeneity in the quality of regional marine environments? What are the main factors that affect MEQ, and what are the interaction mechanisms between them? Such issues urgently need to be addressed to support the protection and governance of marine environments. This will not only help improve the quality and stability of marine ecosystems but also enhance the resilience of the marine environment. This study, therefore, took the MEQ of coastal provinces and cities in China as the research object, analyzed MEQ and its spatiotemporal evolution, and quantitatively measured the factors affecting MEQ. In this way, we hope to offer a new perspective for studying MEQ and provide a scientific reference for formulating sustainable development policies for marine environments. Our contributions are as follows: First, we selected multiple indicators of the marine water environment and marine ecological quality to construct an evaluation system for MEQ, thus enriching the connotation of MEQ. Second, we revealed the dynamic evolution laws and operational mechanisms of MEQ and explored the differences and coordination levels of regional MEQ. Third, taking China's MEQ as the research object, we calculated the level and evolution of its MEQ and analyzed the driving factors and interactions between factors that affect MEQ. Our results can serve as a typical case, providing a theoretical framework and decision-making support for other countries and regions to study MEQ.

2. Study Design and Methods

2.1. Study Area

We selected 11 coastal provinces and cities in China, including Liaoning, Tianjin, Hebei, Shandong, Jiangsu, Shanghai, Zhejiang, Fujian, Guangdong, Guangxi, and Hainan, as spatial scales, used relevant data to measure the comprehensive level of marine environmental quality, and focused on exploring the spatiotemporal evolution characteristics and driving factors of marine environmental quality. The study period was 2011–2022. The data sources included the China Marine Economic Statistical Yearbook (2012–2023), China Statistical

Yearbook (2012–2023), and China Marine Environment Bulletin (2012–2023). Missing data were obtained by linear interpolation or calculated by the authors.

2.2. Indicator System Construction

MEQ not only includes the quality of the seawater environment but also reflects the quality status of different environmental media, including the quality of marine sedimentary environment and marine biological quality. Based on the scientific nature of the research and the availability of data, we classified the level of MEQ into two levels: marine water environment quality (MWEQ) and marine ecological environment quality (MEEQ). Each level selects 5 indicators, resulting in a total of 10 measurement indicators, to construct a comprehensive evaluation system for marine environmental quality. Among them, the quality of the marine water environment was selected to be measured by indicators such as relative perennial changes in sea level, the proportion of nearshore Class I and II water quality, nearshore and coastal areas, seawater-rich oxidation index, and the annual average number of fecal coliform bacteria in water. And the proportion of nearshore Class I and II water quality and nearshore and coastal areas were used as positive indicators, while the seawater eutrophication index, the annual average number of fecal coliform bacteria in water, and the relative annual changes in sea level were used as negative indicators. The quality of the marine ecological environment was measured by indicators such as the proportion of the first type of marine sediment quality standard, the phytoplankton index diversity, the zooplankton index diversity, the benthic diversity index, and the coastal wetlands area, all of which were positive indicators. The specific indicators are shown in Table 1.

Table 1. Evaluation index system of MEQ level in China.

Target Layer	Rule Layer	Weight	Index Layer	Index (Positive/Negative)	Weight
MEQ level	Marine water environment quality (MWEQ)	0.4311	Relative perennial changes in sea level (millimeters)	Negative	0.0835
			Proportion of nearshore Class I and II water quality (%)	Positive	0.1039
			Nearshore and coastal areas (km^2)	Positive	0.1860
			Seawater-rich oxidation index	Negative	0.0451
			Annual average number of fecal coliform bacteria in water bodies (number/liter)	Negative	0.0126
	Marine ecological environment quality (MEEQ)	0.5689	The proportion of the first type of marine sediment quality standard (%)	Positive	0.0431
			Phytoplankton diversity index	Positive	0.0826
			Zooplankton diversity index	Positive	0.0370
			Benthic biodiversity index	Positive	0.1652
			Coastal wetland area (1000 hectares)	Positive	0.2409

Note: The weights in the table are calculated based on Formulas (3) and (4) of research method Section 2.3.2. The biodiversity index is a comprehensive expression of the distribution uniformity of the number of biological species and individual numbers among species, characterized by the Shannon–Wiener diversity index. The calculation formula is $H' = -\sum (P_i * \log_2 P_i)$. In the formula, P_i is the proportion of the i individual in the sample to the total number of individuals in the sample.

2.3. Research Methods

2.3.1. Data Standardization Processing

Due to the differences in dimensionality and the positive and negative directions of indicators used to measure the quality of the marine environment, it is necessary to standardize and eliminate the impact of dimensionality on each indicator datum. The specific handling method was as follows:

The positive indicators were as follows:

$$D_{ij}^{+} = \left[x_{ij} - min(x_{ij} \cdots x_{nj})\right] / \left[max(x_{ij} \cdots\cdots x_{nj}) - min(x_{ij} \cdots x_{nj})\right] \quad (1)$$

The negative indicators were as follows:

$$D_{ij}^{-} = \left[max(x_{ij} \cdots x_{nj}) - x_{ij}\right] / \left[max(x_{ij} \cdots\cdots x_{nj}) - min(x_{ij} \cdots x_{nj})\right] \quad (2)$$

2.3.2. Entropy Method

There are various methods for calculating weights, but the entropy method can effectively avoid the subjectivity of indicator weighting and has the advantages of strong objectivity and high accuracy [45]. Therefore, we selected the entropy method to calculate the weights and comprehensive scores of various indicators of MEQ.

Index entropy calculation:

$$\alpha_j = -\frac{1}{\ln k}\sum_{i=1}^{n} b_{ij}\ln\left(b_{ij}\right) \quad (3)$$

In the equation, $b_{ij} = D_{ij} \Big/ \sum\limits_{i=1}^{n} D_{ij}$, α_j represents the entropy value of the indicator $(0 \leq \alpha_j \leq 1)$; n represents the number of marine environmental quality indicators; and k is the total number of research subjects [46,47].

Indicator weight calculation:

$$\theta_j = \left(1 - \alpha_{ij}\right) / \sum\nolimits_{i=1}^{n}\left(1 - \alpha_{ij}\right) \quad (4)$$

In the equation, θ_j represents the weight of each indicator layer; θ_j' represents the weight of the criterion layer. The calculation formula is as follows:

$$\theta_j' = \sum\nolimits_{i=1}^{m}\theta_j \quad (5)$$

$$T = \sum_{j=1}^{n}\theta_j \times D_{ij} \quad (6)$$

In the formula, T represents the comprehensive score of MEQ.

2.3.3. Theil Index

Due to its good decomposability, the Theil index has been extended from its early use in studying income inequality to other fields, such as economics and ecology. It is mainly used to analyze regional overall differences, inter-regional and intra-regional differences, and the contribution of intra-group and inter-group differences to the total gap [48]. We used the Theil index to calculate the degree of difference in regional MEQ, and the specific formula is as follows:

$$M_{at} = \sum_{t=1}^{T} X_t \ln\frac{X_t}{N_t/N} \quad (7)$$

$$M_{bt} = \sum_{t=1}^{T} X_t\left(\sum_{i\in g_t}\frac{X_i}{X_t}\ln\frac{X_i/X_t}{1/N_t}\right) \quad (8)$$

$$M = M_{at} + M_{bt} \quad (9)$$

In the equation, M_{at} and M_{bt} represent the gap between regional groups and the gap within regional groups, respectively. N represents the total number of research subjects. The MEQ of N regions is divided into T groups, each group is $g_t(t = 1, 2, \cdots, T)$. The number of provinces and cities in group t and group g_t is N_t. X_i and X_t represent the MEQ of province and city i and the MEQ of group T, respectively.

2.3.4. Geographic Detector

The geographic detector is a spatial analysis model used to detect the relationship between a certain geographical attribute and its explanatory factors. It has been widely used in the study of the influencing factors of natural, economic, and social phenomena [49]. This method has the advantages of limited conditions, strong objectivity, and high credibility. This article mainly uses the factor detection and interactive detection modules of the geographic detector model to study the impact of each driving factor on the quality of the marine environment. The specific formula is as follows:

$$H = 1 - \frac{\sum_{i=1}^{m} T_i \sigma_i^2}{T\sigma^2} \tag{10}$$

In the equation, H is the explanatory power of the driving factor ($0 \leq H \leq 1$); $i(i = 1, \cdots, m)$ is the stratification of the detection factor X. T and T_i represent the total number of samples and the detection area, respectively. σ^2 and σ_i^2 are the variances in the whole and the detection area, respectively.

Interaction detection: Identify the interaction between different independent variables, that is, whether two explanatory variables enhance or weaken the explanatory power of the dependent variable Y during the interaction, or whether these independent variables have independent effects on the dependent variable Y. To conduct the measurement method, calculate the spatial difference explanatory power $H(X_1)$ and $H(X_2)$ of the two explanatory variables on the dependent variable, and then calculate whether the explanatory variable has spatial difference explanatory power $H(X_1) \cap H(X_2)$ on the dependent variable in the interaction.

The specific standards are shown in Table 2 below:

Table 2. Judgment criteria for interaction between variables.

Interaction Type	Judgment Criteria
Single-factor nonlinear attenuation	$Max[H(X_1), H(X_2)] > H(X_1 \cap X_2) > Min[H(X_1), H(X_2)]$
Double-factor enhancement	$H(X_1 \cap X_2) > Max[H(X_1), H(X_2)]$
Nonlinear attenuation	$H(X_1 \cap X_2) < Min[H(X_1), H(X_2)]$
Nonlinear enhancement	$H(X_1 \cap X_2) > H(X_1) + H(X_2)$
Mutual independence	$H(X_1 \cap X_2) = H(X_1) + H(X_2)$

3. Empirical Analysis

3.1. Analysis of Temporal Evolution of MEQ

We used the entropy method to calculate MEQ in China from 2011 to 2022. Table 3 and Figure 1 show the results.

As we can see in Table 3 and Figure 1, MEQ in China showed a wave-like upward trend, with an average increase of 25% from 0.454 to 0.569. Jiangsu and Shandong provinces have the highest levels of marine environmental quality, with averages of 0.693 and 0.659, respectively. Tianjin and Hainan had the highest growth rate of MEQ, with average annual growth rates of 7% and 4%. However, in terms of the development index, the average MEQ of China was only 0.493, indicating that the overall level of MEQ in China was not high, and the problem of MEQ has not been solved, reflecting an urgent need for improvement.

Table 3. Level of MEQ in China (2011–2022).

Province / Year	Liaoning	Tianjin	Hebei	Shandong	Jiangsu	Shanghai	Zhejiang	Fujian	Guangdong	Guangxi	Hainan	Mean Value
2011	0.609	0.216	0.427	0.671	0.608	0.339	0.340	0.362	0.628	0.429	0.363	0.454
2012	0.620	0.202	0.409	0.590	0.525	0.204	0.301	0.359	0.564	0.425	0.351	0.414
2013	0.648	0.182	0.370	0.600	0.659	0.263	0.382	0.518	0.660	0.416	0.353	0.459
2014	0.646	0.231	0.390	0.624	0.647	0.216	0.303	0.490	0.505	0.460	0.384	0.445
2015	0.681	0.259	0.411	0.647	0.702	0.271	0.376	0.510	0.520	0.442	0.371	0.472
2016	0.637	0.286	0.415	0.630	0.724	0.280	0.368	0.553	0.571	0.467	0.411	0.486
2017	0.580	0.311	0.473	0.683	0.735	0.337	0.382	0.536	0.587	0.522	0.462	0.510
2018	0.590	0.297	0.418	0.660	0.748	0.347	0.409	0.584	0.553	0.534	0.499	0.513
2019	0.562	0.433	0.496	0.692	0.755	0.347	0.372	0.537	0.669	0.529	0.521	0.538
2020	0.557	0.322	0.423	0.688	0.737	0.348	0.451	0.552	0.663	0.541	0.502	0.526
2021	0.598	0.350	0.507	0.699	0.712	0.312	0.417	0.577	0.684	0.535	0.512	0.537
2022	0.625	0.409	0.497	0.727	0.761	0.394	0.504	0.598	0.700	0.526	0.522	0.569
Mean value	0.613	0.291	0.436	0.659	0.693	0.305	0.384	0.515	0.609	0.486	0.438	0.493

Source: Calculated by the author based on the study data.

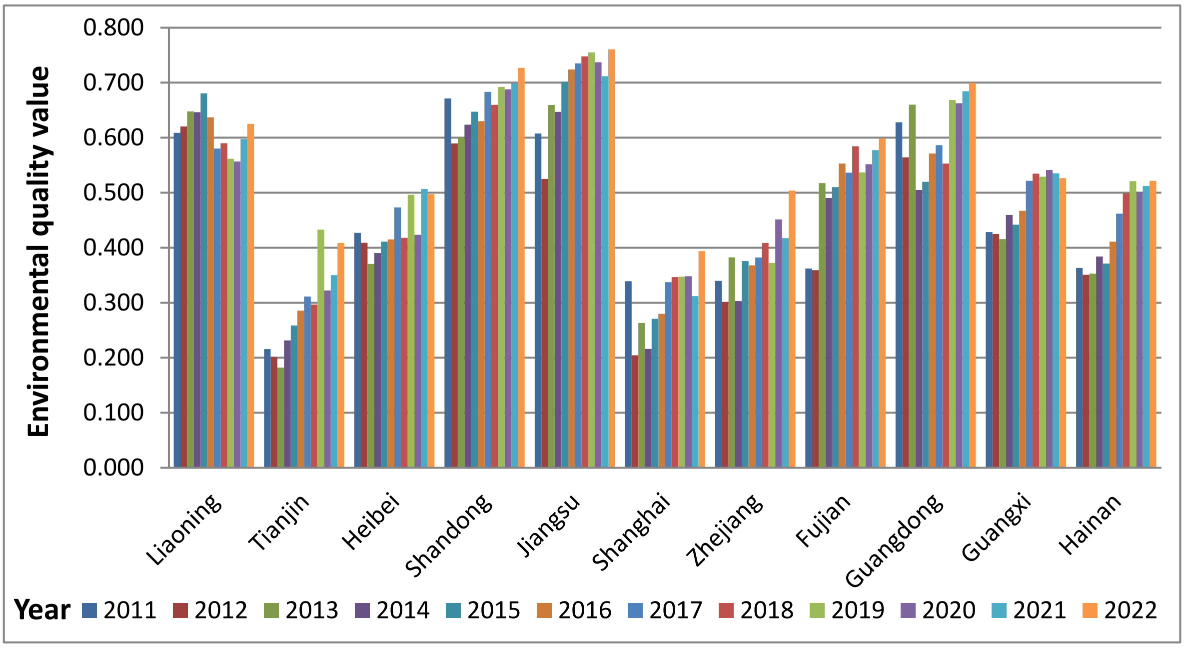

Figure 1. Mean change chart of MEQ in China (2011–2022).

In terms of time evolution, 2012 was a turning point. Most provinces in China experienced a significant decline in MEQ, which continued to fluctuate until 2014. During this period, Shandong, Jiangsu, Shanghai, and Zhejiang experienced the most significant fluctuations, with decreases of over 10%. This was mainly attributable to the relatively serious marine pollution accidents that occurred in neighboring countries in 2012, which greatly damaged the marine ecosystem, having especially significant effects on the Eastern Marine Circle of China. Between 2014 and 2017, MEQ showed a significant growth trend, with an average increase from 0.445 to 0.510. Another turning point was in 2017, when most provinces and cities in China experienced a significant decline in MEQ, with significant fluctuations that continued until 2020. Among them, Liaoning, Hebei, and others saw a significant decline in MEQ, with a decrease of about 5%. This was mainly attributable to the excessive exploitation of the ocean and the acceleration of industrial development in these provinces, which had a significant effect on MEQ, with the most typical manifestation being the frequent occurrence of red tides.

3.2. Analysis of Spatial Differences in MEQ

To more clearly depict the spatial evolution pattern of MEQ, we divided MEQ into six levels: $0.001 < T \leq 0.2$, ultra-low quality; $0.2 < T \leq 0.3$, low quality; $0.3 < T \leq 0.4$, medium-low quality; $0.4 < T \leq 0.6$, intermediate quality; $0.6 < T \leq 0.8$, medium-high quality; and $0.8 < T \leq 1.0$, advanced quality. T is MEQ. We selected typical years of MEQ levels for visualization (Figure 2).

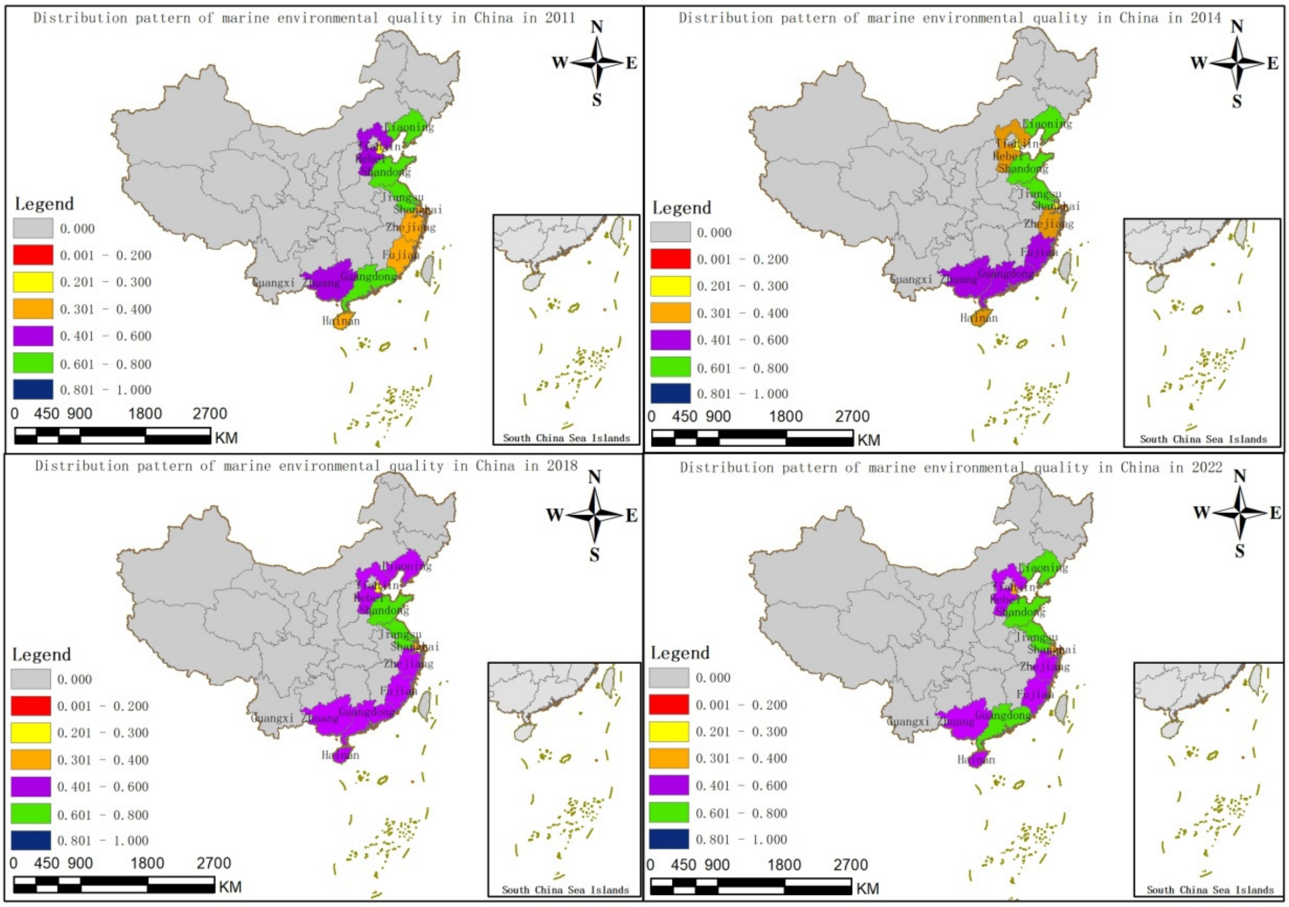

Figure 2. Spatial distribution pattern of MEQ in typical years.

We can see in Figure 2 that overall MEQ presents a spatial distribution pattern of high in the north and south, and low in the east. During the study period, the average MEQ in the northern and southern marine economic circles was relatively high, with averages of 0.50 and 0.51, ranking at medium-high quality. While only Jiangsu in the east reached medium-high quality, most other provinces were at intermediate quality, and the overall mean was 0.46. Looking at a typical year, in 2011, Tianjin's MEQ was relatively low. MEQ in provinces such as Shanghai, Zhejiang, Fujian, and Hainan was of medium-low quality. MEQ in Hebei and Guangxi was of intermediate quality, while in Shandong, Guangdong, Jiangsu, and Liaoning it was of medium-high quality. In 2014, MEQ in Tianjin was still low. MEQ in Shanghai decreased from medium-low to low quality, while MEQ in Hebei decreased from intermediate to medium-low quality. MEQ in Guangdong decreased from medium-high quality to intermediate quality, while in Fujian it increased from medium-low to intermediate quality. MEQ in other provinces and cities did not change. In 2018, there was a significant improvement in overall MEQ. MEQ in Hebei and Hainan increased from medium-low to intermediate quality. MEQ in Shanghai jumped from low to intermediate quality, while in Liaoning it declined from medium-high to intermediate quality. The MEQ of other provinces and cities significantly improved. In 2022, there was a significant change in MEQ. Among them, Tianjin's MEQ transitioned from low to intermediate quality. There were significant differences in MEQ between provinces, with Jiangsu having the highest average MEQ, reaching 0.693. The average MEQ in Tianjin was the lowest at 0.291, which is less than half the average MEQ in Jiangsu. At the end of 2022, the MEQ of Jiangsu, Shandong, and Guangdong reached 0.7, while in Tianjin, Shanghai, Zhejiang, and Hainan it was around 0.4, which is far below the average level. This indicates that the development of MEQ between provinces is extremely uneven, and there is a phenomenon of polarization.

4. Differences in Regional MEQ

To further clarify the differences in regional MEQ, we used the Theil index to calculate differences in MEQ within and between the three major marine economic circles (The Ministry of Natural Resources has divided the national marine economy into three circles: the Northern Marine Economy Circle, which mainly includes Liaoning, Hebei, Tianjin, and Shandong; the Eastern Marine Economy Circle, which mainly includes Jiangsu, Shanghai, and Zhejiang; and the Southern Marine Economy Circle, which mainly includes Fujian, Guangdong, Guangxi, and Hainan). Table 4 shows the results.

Table 4. Theil index of regional MEQ in China and its decomposition, 2011–2022.

Year	Group						Between-Column	
	Northern Marine Economy Circle		Eastern Marine Economy Circle		Southern Marine Economy Circle			
	Theil Index	Contribution Rate (%)	Theil Index	Contribution Rate (%)	Theil Index	Contribution Rate (%)	Theil Index	Contribution Rate (%)
2011	0.0290	57.15	0.0106	20.97	0.0100	19.71	0.0011	2.17
2012	0.0301	49.89	0.0169	28.03	0.0073	12.03	0.0061	10.05
2013	0.0340	52.88	0.0184	28.60	0.0108	16.82	0.0011	1.70
2014	0.0274	46.75	0.0260	44.40	0.0020	3.42	0.0032	5.42
2015	0.0248	49.83	0.0208	41.93	0.0031	6.18	0.0010	2.05
2016	0.0177	41.03	0.0216	49.99	0.0032	7.42	0.0007	1.56
2017	0.0138	42.98	0.0165	51.20	0.0013	4.17	0.0005	1.64
2018	0.0153	46.86	0.0157	48.12	0.0006	1.92	0.0010	3.11
2019	0.0056	21.48	0.0169	64.67	0.0021	8.13	0.0015	5.72
2020	0.0133	43.98	0.0133	43.78	0.0021	7.05	0.0016	5.20
2021	0.0107	35.27	0.0147	48.08	0.0025	8.21	0.0026	8.44
2022	0.0084	39.09	0.0100	46.65	0.0028	12.89	0.0003	1.37
Mean value	0.0192	43.93	0.0168	43.04	0.0040	9.00	0.0017	4.04

Source: Obtained by the author.

Table 4 shows that from 2011 to 2022, regional MEQ in China showed a distribution pattern of large differences between the east and the north and small differences in the south. The contribution rate of differences within regional groups reached over 90%. The mean values of the Theil index in the three major marine economic circles, from large to small, were the Northern Marine Economic Circle, Eastern Marine Economic Circle, and Southern Marine Economic Circle. Among them, differences within the Northern Marine Economic Circle gradually narrowed, with the Theil index decreasing from 0.029 to 0.0084, a decrease of 71%, and the contribution rate decreasing from 57.15% to 39.09%, showing a convergence trend. Differences within the Eastern Marine Economic Circle showed a downward spiral trend, with the Theil index rising from 0.0106 to 0.0216 and then decreasing to 0.010. The contribution rate increased from 20.97% to 64.67% and then decreased to 46.65%. There were significant fluctuations in MEQ in this region, but the overall trend was a slow decline. The difference within the Southern Marine Economic Circle was the smallest and showed a wave-like downward trend; the Theil index decreased by 70% from 0.01 to 0.0028. This indicates that differences in MEQ in the Southern Marine Economic Circle were accelerating toward becoming narrower. From the spatial distribution within the region, we can see that MEQ was gradually forming a pattern of high in the center and low in the surroundings.

Among them, the Northern Marine Economic Circle centers on Shandong, and the overall level of MEQ was in a leading position. The surrounding areas of Hebei and Tianjin were significantly lower. The Eastern Marine Economic Circle is centered in Jiangsu, and MEQ was significantly higher than that of surrounding provinces and cities such as Shanghai and Zhejiang, resulting in insufficient coordination within the region. The Southern Marine Economic Circle centers on Guangdong, with a leading position in MEQ. MEQ in Fujian, Guangxi, and Hainan was relatively low.

From the perspective of regional inter-group differences, the inter-group difference index was relatively small, showing a decreasing spiral trend. The Theil index decreased from 0.0011 to 0.0003, and the contribution rate decreased from 2.17% to 1.37%. This indicates that there were few regional differences in the quality of China's marine environment, with development transitioning from low-quality, disorderly development to high-quality, sustainable development.

5. Factors Affecting MEQ

5.1. Indicator Selection

Various factors affect MEQ. The main recognized sources are land-based pollution, sea-based pollution, and atmospheric pollution. Based on data availability for statistical indicators in the China Marine Environment Bulletin, China Statistical Yearbook, and Marine Economic Statistical Yearbook, we selected seven indicators to explore the driving factors of MEQ: (1) The area factor of aquaculture pollution. Aquaculture has destructive effects on the marine ecological structure; it is represented by the area of marine aquaculture. (2) Agricultural pollution factors. Agricultural non-point source pollution load generates a large amount of pollution and has serious effects on MEQ; it is represented by the amount of agricultural fertilizers used. (3) Industrial pollution factors. Industrial pollutants, sewage, and other pollutants have toxic, diffusive, cumulative, and persistent characteristics that have harmful effects on seawater and marine organisms; they are represented by the total asset index of industrial enterprises above a designated size. (4) Marine engineering pollution. A large number of marine vessels and engineering projects have disrupted seawater quality, marine ecological balance, and coastal landscapes; this is characterized by port cargo throughput. (5) The carbon emission index factor. Large amounts of carbon dioxide emissions damage atmospheric quality and cause climate change, leading to the warming and acidification of seawater; these are important factors affecting the marine environment. This is represented by carbon dioxide emission indicators based on Ning's estimation method guided by the IPCC's "Guidelines for National Greenhouse Gas Emissions Inventory" [50]. (6) The factor of marine scientific and technological capability. Good technological innovation capability can promote green economic development and improve MEQ; it is represented by the number of marine R&D projects. (7) The intensity factor of environmental regulation. Environmental regulations and marine environment governance policies can protect and improve MEQ; they are represented by the completion of investment indicators for industrial pollution control. Table 5 presents the indicators.

Table 5. Factors affecting MEQ.

Code Number	Influencing Factor	Driving Factors
X1	Aquaculture pollution	Marine aquaculture area (hectares)
X2	Agricultural pollution	Agricultural fertilizer usage (10,000 tons)
X3	Industrial pollution	Total assets of industrial enterprises above designated size (CNY 100 million)
X4	Marine engineering pollution	Port cargo throughput (10,000 tons)
X5	Carbon emission index	Carbon dioxide emissions (100 million tons)
X6	Marine technology capabilities	Number of marine projects R&D (items)
X7	Environmental regulation intensity	Completed investment in industrial pollution control (CNY 10,000)

5.2. Driving Factor Analysis

According to the needs of the data, we used the natural breakpoint classification method to discretize the data of each indicator. We divided each indicator into five levels and calculated the explanatory degree values of the various driving factors (Table 6).

Table 6. Detection results for the segmented driving factors of MEQ.

2011–2022			2011–2016			2017–2022		
Driving Factors	**H-Value**	***p*-Value**	**Driving Factors**	**H-Value**	***p*-Value**	**Driving Factors**	**H-Value**	***p*-Value**
X1	0.570	0.000	X1	0.707	0.000	X1	0.532	0.000
X2	0.594	0.000	X2	0.649	0.000	X2	0.674	0.000
X3	0.323	0.000	X3	0.312	0.000	X3	0.525	0.000
X4	0.295	0.004	X4	0.263	0.000	X4	0.483	0.000
X5	0.389	0.000	X5	0.443	0.000	X5	0.401	0.000
X6	0.435	0.000	X6	0.346	0.000	X6	0.667	0.000
X7	0.175	0.003	X7	0.221	0.010	X7	0.210	0.067

In Table 6, we can see that from 2011 to 2020, the *p*-values of the statistical tests for each driving factor passed the statistical significance test, and the explanatory power of the driving factors ranged from 17% to 59%. This indicates that MEQ is influenced by these driving factors, which is consistent with the expected values for indicator selection. Among them, the core driving factors affecting MEQ are agricultural pollution and aquaculture pollution, both of which have explanatory power exceeding 50%, indicating that land-based pollution and other factors have had serious effects on MEQ. The secondary factors affecting MEQ include the marine technology capability factor, carbon emission index factor, and industrial pollution factor, all of which had explanatory power exceeding 30%, indicating that atmospheric pollution and technological innovation have had significant effects on MEQ. Factors such as marine engineering pollution and environmental regulation intensity have had relatively low effects on MEQ. Among them, the explanatory power of the marine engineering pollution factor was 29.5%, and the explanatory power of the environmental regulation intensity factor was 18%, indicating that both marine engineering pollution and environmental regulation intensity have effects on MEQ. Comparing the dynamic changes in the driving factors in the two stages of 2011–2016 and 2017–2022, we can see that the explanatory power of aquaculture pollution factors decreased from 0.707 to 0.532, indicating that the green development of marine aquaculture has achieved certain results. However, the effect on MEQ is still significant, and there is an urgent need for further green, low-carbon transformation and development. The explanatory power of agricultural pollution factors significantly improved, reaching 67.4%, indicating that the effect of agricultural pollutants on MEQ has further intensified. Industrial pollution factors also showed improved explanatory power, at 52.5%, indicating that industrial pollution has not been fully curbed and is more severe. The explanatory power of marine engineering pollution factors sharply increased, nearly doubling to 48.3%, significantly enhancing their destructive effect on MEQ. The explanatory power of the carbon emission index factor gradually weakened but still reached 40.1%, indicating that although the effect of atmospheric pollution on MEQ has weakened, the situation is still severe. The explanatory power of the marine technology capability factor significantly improved, reaching 66.7%, indicating that China's marine technology innovation ability has had a more significant effect on MEQ of 21%; however, the environmental regulation intensity factor did not have significant explanatory power.

5.3. Driver Interaction Detection

Interaction detection is used to identify interactions between different driving factors—that is, to evaluate whether the joint action of two factors increases or weakens the explanatory power of the dependent variable, or whether these factors have independent effects on the dependent variable. Table 2 shows the judgment criteria, and Tables 7 and 8 show the interaction detection results for driving factors. There is an interaction relationship between each driving factor, and the explanatory power of the interaction on the H-value is significantly enhanced, with the interaction being greater than the explanatory power of a single driving factor. The main types of interaction are dual-factor enhancement and nonlinear enhancement, with no weakening or independent relationship, further indicating that each driving factor has a significant effect on MEQ.

Table 7. Interactive detection results for the driving factors of MEQ, 2011–2016.

	X1	Type	X2	Type	X3	Type	X4	Type	X5	Type	X6	Type	X7
X1	0.707												
X2	0.814	DE	0.649										
X3	0.849	DE	0.912	DE	0.312								
X4	0.903	DE	0.829	DE	0.746	NE	0.263						
X5	0.792	DE	0.789	DE	0.859	NE	0.633	DE	0.443				
X6	0.880	DE	0.908	DE	0.776	NE	0.735	NE	0.757	DE	0.346		
X7	0.825	DE	0.871	DE	0.4981	DE	0.615	NE	0.702	NE	0.783	NE	0.221

DE: double enhancement; NE: nonlinear enhancement.

Table 8. Interactive detection results for the driving factors of MEQ, 2017–2022.

	X1	Type	X2	Type	X3	Type	X4	Type	X5	Type	X6	Type	X7
X1	0.532												
X2	0.758	DE	0.674										
X3	0.821	DE	0.908	DE	0.525								
X4	0.933	DE	0.817	DE	0.863	DE	0.483						
X5	0.717	DE	0.810	DE	0.754	DE	0.753	DE	0.401				
X6	0.862	DE	0.920	DE	0.854	DE	0.862	DE	0.746	DE	0.667		
X7	0.710	DE	0.827	DE	0.704	DE	0.727	NE	0.652	NE	0.734	DE	0.210

DE: double enhancement; NE: nonlinear enhancement.

The driving factors with strong interactions between 2011 and 2016 were agricultural pollution and industrial pollution, aquaculture pollution area and industrial economic level, and agricultural pollution and marine technology innovation. The explanatory power of these interactions exceeded 90%, indicating that MEQ is the result of the joint action of various driving factors, and the interaction of land-based pollution had the most significant effect. The interaction between industrial pollution factors and environmental regulation intensity factors was the lowest, with an explanatory power of only 49.8%. This indicates that there are still significant shortcomings in marine environment governance, and the effect on the improvement in MEQ is relatively low. The interaction between environmental regulation intensity and industrial pollution factors and other factors was mainly nonlinear enhancement, and the explanatory power was significantly enhanced, indicating that the effect of environmental regulation intensity and industrial pollution on MEQ manifested as a synergistic effect with other factors.

Between 2017 and 2022, the driving factors with strong interactions still remained: aquaculture pollution area and marine engineering pollution, agricultural pollution and industrial pollution, and agricultural pollution and marine technology innovation. Explanatory power values exceeded 90%, and the explanatory power of interactions between other factors also exceeded 70.5%. This indicates that land-based pollution was still the main factor in MEQ pollution. The explanatory power of the interaction between aquaculture pollution area and marine engineering pollution significantly improved, reaching 93.3%. This indicates that the interaction between marine aquaculture and marine engineering pollution became increasingly evident, and the superposition of marine source pollution and aquaculture pollution increased the effect on MEQ. The interaction between the carbon emission coefficient factor and various factors significantly decreased compared with the past, indicating that the joint effect of atmospheric pollution and other factors on MEQ had weakened, but the degree of the effect was still relatively high.

6. Discussion

Measuring the quality of China's marine environment, we found that MEQ has spiraled upward, but the overall level is not high, and there is significant heterogeneity in regional MEQ. The main factors affecting MEQ were found to be land-source surface pollution and marine pollution. The first reason is that marine environmental pollution has not been controlled at its source; a forward-looking, systematic, and synergistic marine pollution prevention and control management system has not been established. Extensive development and an unreasonable industrial structure have posed serious threats to MEQ. The second reason is that the division of regional marine environment protection and governance is unreasonable, the economic relationship between land and sea is not coordinated, marine spatial planning lacks cohesion, and the coordinated regional management of land and sea and green development has not been formed. Previous studies have confirmed that the quality of China's waters has generally improved, but the Gulf ecosystem is mostly in an unhealthy state [30]. In recent years, the marine biodiversity index has shown an upward trend; however, it is still relatively low [33]. Such findings are similar to our results for the low overall quality of China's marine environment from 2011 to 2022, thus supporting existing research. Previous studies have also found that the excessive discharge of land-based pollutants such as industrial wastewater, domestic sewage, industrial and household garbage, pesticides, and fertilizers into the sea is the main reason for the deterioration of the marine environment [36,39]. This is similar to our calculations of the factors affecting MEQ. Specifically, we found that agricultural pollution, aquaculture pollution, and marine engineering pollution were the main factors affecting MEQ, especially agricultural pollution. We found that the effect of air pollution on MEQ had diminished. This could be attributed to China's strengthening of environmental regulations in recent years, as it seeks to achieve carbon peak and carbon neutrality, accelerate energy conservation and emission reduction, reduce air pollution, and promote green and blue carbon in the marine economy. Previous studies mainly focused on a single field in marine water quality and ecological diversity [16–22,26] or calculated the ecological efficiency of the marine environment [36–39,41–43]. We focused on analyzing MEQ, thus expanding the related research perspective and content. At the same time, we not only analyzed the spatiotemporal evolution of MEQ but also revealed the heterogeneity and coordination of regional MEQ. We found that the development of regional MEQ has been unbalanced and polarized. We should therefore accelerate the promotion of land–sea coordination and the coordinated management of regional marine environments. This could provide new research ideas and frameworks for the sustainable development of the marine environment.

The MEQ of different coastal countries and regions may form their own characteristics due to various factors, but how to improve the marine environmental quality and promote sustainable development of the ocean has always been a focus of global attention. Improving MEQ has been a long-term focus of many countries. The coast of South Africa, for example, is one of the world's most concentrated areas for oil tankers and bulk carriers. Factors such as oil spills, noise pollution, and alien species introduced by untreated ballast water discharge adversely affect marine habitats. After a storm surge on the eastern coast of South Africa, coastal erosion had effects 100 m inland, and such damage is likely to occur more frequently over the next decade [51]. Changes in ocean temperature, oxygen content, and ocean acidification indicate that negative changes are taking place in the EU's marine areas, further reducing the resilience of marine ecosystems, including resistance to climate change [52]. The European Environment Agency has suggested that the prospects for Europe's marine environment are not optimistic. Pollution from Southeast Asian marine vessels has caused oil to adhere to fish, algae, and plankton, leading to the death of marine organisms and the destruction of the living environment of seabirds, resulting in decreases in the seabird population. Oil pollution also reduces the quality of aquatic products and causes economic losses [53]. The analysis of seawater at depths of 10–15 cm in the Mediterranean waters of France, northern Italy, and Spain revealed that 90% of the samples contained plastic debris. It is speculated that there are about 500 tons of microplastic debris in Mediterranean waters [54]. Given that different regions face different marine environment problems, the scientific evaluation of MEQ can have great value for improving marine environment governance. Understanding the heterogeneity and evolution trends of regional MEQ can help other countries and regions evaluate the coordination of regional MEQ development; strengthen cooperation in regional marine environment protection, green aquaculture, defense against marine disaster, and spatial planning; construct diversified collaborative governance models tailored to local conditions; and adjust economic and environmental marine development policies [55].

Because of data availability, some indicators could not be included in this study's evaluation index system, which could have affected the accuracy of the results. For example, a quantity indicator for marine plastic waste was not included in the model because of an inability to obtain data. Meanwhile, our analyses of the spatial spillover of MEQ and the convergence of regional MEQ were weak, and we did not explore driving mechanisms and path selection for the coordinated development of regional MEQ. These issues can be addressed in future research.

7. Conclusions and Suggestions

7.1. Conclusions

Based on our calculations of the spatiotemporal evolution, regional differences, and driving factors of MEQ in China's coastal provinces and cities from 2011 to 2022, the following conclusions can be drawn:

China's MEQ has been rising in a wave but overall quality is relatively low. The average MEQ increased from 0.454 to 0.569, representing an increase of 25%. We identified a spatial distribution pattern of high in the north and south and low in the east. Most provinces in the northern and southern regions have achieved medium-to-high quality MEQ, while only a few in the east region have done so, with most reaching intermediate quality. Meanwhile, there are significant gaps between provinces. Jiangsu had the highest average MEQ, with an average of 0.69, while Tianjin had the lowest, with an average of only 0.29.

The distribution pattern of regional MEQ showed large differences between the east and north while the differences in the south were small. There are significant regional differences, with the contribution rate of differences within regional groups reaching over 90%. Regional MEQ has formed a pattern of high in the center and low in the surroundings. Regional differences are relatively small, showing a narrowing spiral trend, and the development of regional marine environments is evolving from being low quality and disorderly to being high quality and sustainable.

The main factors affecting MEQ were found to be agricultural pollution, aquaculture pollution, marine technology, and the carbon emission coefficient. The explanatory power of marine engineering pollution factors significantly increased while that of environmental regulation intensity was relatively weak. The interaction between different influencing factors mainly manifests in two types: dual-factor enhancement and nonlinear enhancement. Industrial pollution and environmental regulation intensity factors have a strong ability to synergistically affect the marine environment with other factors.

7.2. Suggestions

Our first set of suggestions focuses on improving the top-level design of marine environment governance as follows: (1) China should improve the institutional mechanism for marine environment governance; accelerate the formulation of sustainable development strategies for the marine environment and policies and regulations for marine ecological protection; compile and implement marine environment governance plans and clarify the goals, tasks, and division of labor for marine environment governance; establish an overall land–sea coordination mechanism to strengthen the coordinated, efficient management of the environments of river basins, coasts, and sea areas; further integrate environmental goals, policies, standards, and systems in coastal areas, rivers, and coastal waters; strengthen responsibility for the prevention and control of pollution and the ecological protection and restoration of regions, river basins, and sea areas, and establish a marine environment response mechanism [56]; improve the assessment mechanism for marine environment construction, the property rights system for marine environment resources, the trading system for pollutant discharge rights, and the marine ecological compensation mechanism and pollution compensation mechanism; and create a system for building a marine environment construction system with clear powers and responsibilities and multi-party governance [57]. (2) Improve the laws and regulations related to marine environment governance; accelerate the enactment of special laws on marine environment protection and construction, such as the Regulations on Marine Ecological Spatial Planning, Regulations on Wetland Protection, and Regulations on Ecological Compensation, aiming to clarify the main bodies, responsibilities, and standards for marine environment governance; and refine the laws and regulations on marine environment protection and their applicable rules, promote marine environment governance based on the rule of law, and impose punishments and penalties for marine environment violations [58]. (3) Strengthen publicity and guidance for marine environment protection; implement institutional policies related to green living and promote a civilized public approach to the sea; and open up ways for all types of social actors to participate in marine environment governance, build platforms and carriers, improve social supervision and reporting and feedback mechanisms, and broaden supervision channels for marine environment protection (see Figure 3).

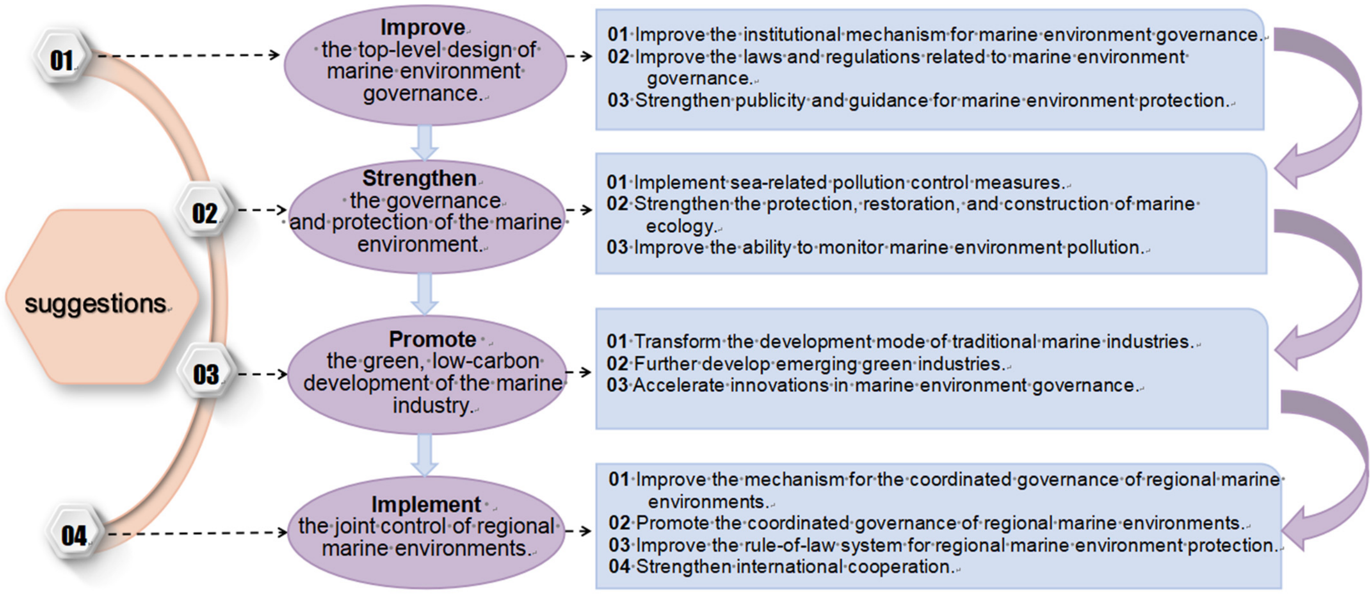

Figure 3. The mind map of suggestions.

Our second set of suggestions focuses on strengthening the governance and protection of the marine environment as follows: (1) Implement sea-related pollution control measures; strengthen the control of pollution from land-based sources; enhance the regulation and management of industrial, agricultural, urban, and rural wastewater and waste discharge, control the amount of sewage discharged into the sea, improve the rate of harmless treatment, and ensure that sewage discharged into the sea meets standards; construct marine ecological wetlands as well as fertilizer- and pesticide-interception systems to treat water entering the sea; strengthen the management of reclamation, delimit no-filling zones, clean up reclamation projects illegally occupying the red line area, remediate pollution in rivers entering the sea, and reduce the total amount of pollutants entering the sea; strictly control the space and capacity of mariculture, assess the environmental effects of mariculture, and implement the standardized treatment of wastewater and waste from aquaculture enterprises; explore aquaculture capacity management and landscape layout, promote deep-sea aquaculture, and reduce the total amount of air pollution; control emissions from industry, transportation, and construction, establish an inventory of emissions from pollution sources, improve the credit system for emissions, and implement the blacklisting and control of heavy-polluting enterprises; increase support for major projects and technological innovation in carbon dioxide emission reduction, and provide policy and financial support; improve the carbon emission trading market and use market-based methods to promote green, low-carbon development; strengthen the pollution control of ships and ports; strictly control emissions from marine engineering construction, and strengthen the management of marine engineering pollution prevention and control [59]; and the supervision of ship garbage, domestic sewage, oily sewage, sewage containing toxic and hazardous substances, exhaust gases, and ballast water discharged into the sea by ships must comply with laws and regulations, international treaties, and standards. (2) Strengthen the protection, restoration, and construction of marine ecology; reinforce the protection and utilization of coastal zones, implement an ecological red line system for coastal zones, and promote the protection and restoration of mangroves, coral reefs, seagrass beds, salt marshes, and other coastal zones; delineate marine environment buffer zones, strengthen the control of shoreline use, and ecologize the shoreline; establish marine natural reserves, coastal ecological protection zones, and wetland parks [60], and restore coastal wetlands that have been destroyed; strengthen the protection of marine biodiversity, improve the fishing moratorium and fishing system, construct offshore artificial reefs, and carry out fishery breeding and releasing; keep the coastal environment clean by promoting coastal cleaning actions, such as cleaning, transferring, and disposing of marine garbage; and accelerate the construction of green marine infrastructure, such as coastal green parks, green energy facilities, and blue–green infrastructure, to provide ecosystem services for marine environment protection. (3) Improve the ability to monitor marine environment pollution; strengthen the monitoring of pollutants entering the sea from rivers, fisheries, and aquaculture, as well as the monitoring of atmospheric sedimentation; establish an intelligent monitoring center for the marine environment, monitor the discharge of wastewater and waste exceeding standards, and establish a pollution management monitoring and evaluation system that connects the river basin, estuaries, and sea areas for joint governance; monitor marine organisms, beach vegetation, the spatial distribution of coastal wetlands, and the living environment; develop online monitoring, early-warning, and traceability systems for near-shore marine areas; and use a "data + sharing" model to save and utilize online monitoring data for the near-shore marine environment and thus achieve intelligent online monitoring [61].

Our third set of suggestions focuses on promoting the green, low-carbon development of the marine industry as follows: (1) Transform the development mode of traditional marine industries; eliminate outdated, inefficient, and surplus-based industries, and reduce or ban marine industries with high resource consumption and emissions; promote the green transformation and development of key industries, optimize the industrial layout and structure of marine and fishery industries, and transform the entire process into a cleaner, low-carbon one; promote the digital transformation of traditional marine industries and utilize technologies such as big data, the Internet of Things, artificial intelligence, and blockchain; and create intelligent fishing ports, sea ranches, and marine manufacturing to give full play to the multiplier effect of digital technology and reduce pressure on the carrying capacity of the marine ecosystem. (2) Further develop emerging green industries; promote marine-related new energy, new materials, biomedicine, intelligent tourism, and other green industries; promote the integration and innovation of new information technologies such as 5G and cloud computing with marine ecology and environmental protection, and explore "Internet+" green industry models to promote the green, low-carbon development of the marine industry; optimize green development patterns, upgrade the industrial structure, optimize the energy structure, and practice green, low-carbon living; use the market-based mechanism of carbon emissions trading in the marine industry, achieve green, low-carbon marine industry development, avoid the “locking” effect of high carbon on the ocean, and optimize the marine ecological space; promote eco-industrialization and develop eco-economies such as eco-fisheries, eco-marine tourism, and eco-marine industry; build green and intelligent ports and apply new energy and clean energy to port operation machinery to achieve electrification and intelligent development; and the marine industry and transportation sector should promote marine energy, hydrogen energy, and other renewable energy sources. (3) Accelerate innovations in marine environment governance; further apply technologies such as drones (boats), Virtual Reality, seawater purification, and ocean observation systems and improve the scientific and technological level of marine environment protection and governance; accelerate R&D on marine carbon sinks and carbon sequestration; and analyze pollutant traceability, pollution management, water linkage management, and ecological restoration, and strengthen the market transformation and application of technological products to provide scientific and technological support for marine environment management.

Our fourth set of suggestions focuses on implementing the joint control of regional marine environments as follows: (1) Improve the mechanism for the coordinated governance of regional marine environments; build a cross-regional, cross-sector coordination mechanism and unify the program planning, target indicators, and implementation of marine environment governance; establish regional ecological and pollution compensation mechanisms, strengthen joint supervision mechanisms for regional marine environments, and further refine and integrate regional marine environment management to help form a coordinated working mechanism for joint monitoring, joint law enforcement, and information sharing, both upstream and downstream of the river basin; improve upstream and downstream joint prevention and control for transboundary river basin pollution emergencies; and improve early-warning systems, pollution control, information notification, coordinated disposal, emergency response, and basic protection to mitigate major regional marine environment risks. (2) Promote the coordinated governance of regional marine environments; establish a sea area–watershed–land area corresponding to the spatial zoning control system and strengthen regional water, solid waste, and air pollution control; strengthen land–sea integration and implement estuarine and bay remediation to achieve the common management of regional marine ecosystems; implement regional marine ecological protection and restoration and environmental risk prevention, and strengthen the management of river–sea pollution; and jointly build regional marine environment infrastructure, including facilities for sewage collection and treatment, intelligent monitoring, disaster protection, emergency response, hazardous waste control, the port environment, and science and technology labs [62]. (3) Improve the rule-of-law system for regional marine environment protection; establish regional marine environment protection legislation and coordination mechanisms; unify regional marine environment enforcement discretion; increase the investigation and detection of transregional marine environment violations; and strengthen emission standards, product standards, technical requirements, and law enforcement norm docking. (4) Strengthen international cooperation; establish regional blue partnerships; strengthen collaboration in the fields of the blue economy, marine environment protection, disaster prevention and mitigation, marine science, and technology; jointly promote the improvement in the global marine environment governance system; advance bilateral and multilateral environmental protection in the regional marine field and strengthen the prevention and control of marine environment pollution; collaborate to promote regional marine environment pollution research and other activities; and in the process of cooperation, share experiences and improve the ability to prevent and control marine pollution.

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