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Review

Research on the development strategy of China's marine fishery environmental monitoring system*

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Abstract The advancement of marine fishery constitutes a vital element in the endeavor to build a maritime power and safeguard food security. In light of the strategic requirements of the national marine fishery and marine ranching, In this article, three pivotal aspects are focused on: marine fishery environmental monitoring systems, core monitoring equipment, and key monitoring techniques. A feasibility assessment of the integrated implementation was conducted, probing into the interplay between the development of the marine economy and the marine fishery environment. Notably, the significance of establishing a sound marine fishery environmental monitoring system was underscored. Through in-depth analysis and systematic collation, a comprehensive understanding of the status of demands, industrial policies, technical capabilities, and future trends in the global marine fishery environmental monitoring system was analyzed. In addition, the core challenges and strategic approaches confronting the development of China's marine fishery environmental monitoring system were clarified. In the near future, by practical development requirements, an ecosystem with monitoring platforms and sensors will be gradually established. Novel organizational models will be explored with key technologies, and major scientific schemes and core tasks in this field will be put forward. In combination with relevant policies regarding fishery environmental monitoring, constructive suggestions for industrial development were provided, and future direction for its progress was outlined.

Keyword: fishery environment; marine ranching; monitoring system; monitoring technology; development strategy and recommendations

1 INTRODUCTION

The ocean covers approximately 71% of the Earth's surface and harbors crucial material bases and strategic resources vital for human survival, such as water, food, and minerals. The ocean is also an important region and connector for maintaining national sovereignty, developing the national economy, and building a community with a shared future for mankind (Wang et al., 2023). As the importance of marine resources and ecosystems grows globally, the

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imperative for robust marine fishery environmental monitoring has become increasingly urgent worldwide. The UN Food and Agriculture Organization's (FAO) *The State of World Fisheries and Aquaculture* 2022 (FAO, 2022) reports that the aggregate output from fisheries and aquaculture has hit an all-time high, with aquaculture's share surpassing half of the combined total. This trend highlights the growing prominence of aquaculture environmental monitoring within the global fishery sector and its increasingly vital contribution to global food security and nutritional supply. Current global priorities for fishery environmental monitoring focus on ensuring the sustainable use of fishery resources, strengthening ecosystem-based management, protecting biodiversity, and mitigating climate change impacts on fishery resources.

China, with a population exceeding 1.4 billion, faces the critical challenge of addressing food supply and ensuring food security. An integrated approach to food development is therefore imperative. Food should be sourced not only from land but also from the ocean. Cultivating the sea, advancing fish farming, and developing marine pastures and "blue granaries" (i.e., sustainable marine food production systems) are essential steps (Sun et al., 2023). Since China's reform and opening-up to the world, its marine fishery level has developed steadily, driven by the gradual improvement of fishery management systems and increased engagement of fishermen. However, with population growth, industrialization, and urbanization, the marine fishery is facing more and more threats, such as climate change, environmental pollution, and overfishing. The "Bulletin of Marine Ecology and Environment Status of China in 2015" pointed out that "coastal marine ecosystems in China that were in sub-health and unhealthy states accounted for 80% (Xu, 2016). When developing the marine economy, we must attach importance to the protection and governance of the marine fishery environment". Strengthening the monitoring and management of the marine fishery environment is very urgent.

The marine fishery environment is not only a vital ecosystem but also holds substantial economic significance (Ma et al., 2024). In 2021, China's marine economy accounted for 8.0% of the national GDP. Specifically, the marine primary, secondary, and tertiary industries accounted for 5.0%, 33.4%, and 61.6% of the total marine output value, respectively. The share of strategic emerging industries in the marine economy is continuously increasing. The Organization for Economic Cooperation and Development's *The Ocean Economy in 2030* (Organization for Economic Co-operation and Development, 2016) report forecasts that by 2030, the marine economy will contribute $3 trillion to the global GDP, with its value-added and job-creation performance outpacing the global economy overall. To develop the marine economy and fisheries and harness resources from the ocean, enhancing marine high-tech capabilities is essential for driving marine industrial growth. Strengthening marine fishery environment monitoring is the fundamental prerequisite for improving the ability to develop marine resources; and marine fishery environmental monitoring instruments and equipment are the core tools to achieve this goal.

Therefore, the marine fishery environment is crucial to the national economy and stability and public well-being. To safeguard the healthy development of marine fisheries, enhancing monitoring, supervision, and technological innovation are crucial approaches, which not only ensure the sound progress of marine fisheries but also impose higher standards for marine fishery environment. In this study, we attempted to establish a three-dimensional response system of "demand-technology-policy" for fishery environmental monitoring. Through an analysis of the demand, current state, and challenges encountered in fishery environmental monitoring, scientific issues and key implementation tasks were identified. Subsequently, policy and implementation recommendations were put forward in line with China's actual condition. These initiatives will offer novel directions for the advancement of China's fishery environmental monitoring. Moreover, they will furnish a policy foundation for the government to guarantee the safety of the fishery environment, thus ensuring the sound development of marine fisheries.

2 DEVELOPMENT DEMAND

2.1 Demand analysis of monitoring indicators

The fundamental task of marine fishery ecological environment monitoring is to comprehensively understand and accurately assess the environmental quality of marine fishery waters, as well as the intricate relationship between organisms and their environment. This monitoring effort is dedicated to safeguarding and enhancing the ecological environment of fishery waters, thus effectively promoting the sustainable development of the fishery industry (Ma, 2016). The monitoring area selected for marine fishery environment monitoring shall consider both economic and aquatic ecological values, as well as good representativeness. The *Fisheries Law of the People's Republic of China* stipulates that "fishery waters" as "spawning grounds (Ministry of Agriculture, Animal Husbandry and Fisheries, 1987), feeding grounds, wintering grounds, migration channels of fish, shrimps, crabs and shellfish, as well as aquaculture places for fish, shrimps, shellfish, algae and other aquatic animals and plants". Since the implementation of the "Outline of China's Aquatic Biological Resources Conservation Action", efforts to protect aquatic biological resources have been strengthened, and a number of national-level aquatic germplasm resource protection areas have been designated successively (Wu et al., 2023). These areas are also important fishery waters. When existing monitoring resources are insufficient to cover all fishery waters, priority should be given to fisheries-critical areas, such as key and sensitive zones with concentrated fishery resources, high economic value, and significance for aquatic resources and aquaculture (Ma, 2016).

Traditional marine fishery environment monitoring focuses on basic elements such as water quality, sediment quality, and biological communities. However, with the deepening understanding of the complexity of marine ecosystems, the monitoring content is also continuously expanding. Nowadays, in addition to basic ecological indicators, multiple aspects of monitoring such as ocean acidification, marine plastic pollution, and hydrometeorology have been added to understand and evaluate the health of the marine fishery environment more comprehensively. According to the experience of China's monitoring work in recent years, the conventional monitoring items of marine fishery ecological environment include the following aspects mainly:

1) Natural characteristic indicators: such as hydrology, meteorology.

2) The impact of coastal engineering and sewage discharge: effect on biological resources, spawning grounds, and habitats.

3) Water quality indicators: pH, suspended solids, dissolved oxygen (DO), inorganic nitrogen, active phosphate, chemical oxygen demand (COD), petroleum, heavy metals (Cu, Zn, Pb, Cd, Hg), and As.

4) Biological environment indicators: chlorophyll *a*, fish eggs (quantity and species), larvae (quantity and species), phytoplankton, zooplankton, and benthic organisms.

For phytoplankton monitoring, it includes the total amount of phytoplankton, the species, and the number of dominant species. Zooplankton monitoring includes the quantity of zooplankton, the species and biomass of dominant species, and the calculation of Shannon-Wiener biodiversity index (H').

5) Sediment indicators: petroleum, heavy metals (Cu, Zn, Pb, Cd, Hg), and As.

6) Biological residues indicators: Cu, Pb, Cd, methylmercury and inorganic As. The number of biological samples in each fishery water area should be representative.

Under favorable operational conditions, monitoring of indicators such as pyrethroid pesticides and polycyclic aromatic hydrocarbons (PAHS) can be conducted. Additionally, in conjunction with biological monitoring, analysis of the Fish Biotic Integrity Index (F-IBI) should be considered as appropriate.

The main analytical and evaluation methods adhere to a series of national standards issued by the Standardization Administration of China (SAC). DO, heavy metals, and petroleum hydrocarbons are assessed based *Water Quality Standards for Fisheries* (State Bureau of Quality and Technical Supervision, 1989); inorganic nitrogen and active phosphate in seawater, as well as COD, are evaluated according to *Seawater Quality Standards* (State Environmental Protection Administration, State Bureau of Technical Supervision, 1997), using Class I (for spawning, feeding, and protected areas) or Class II (for aquaculture areas) standards; marine sediments are evaluated based on *Marine Sediment Quality* (General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China, 2002) Class I standards.

2.2 Demand for monitoring equipment

Continuous monitoring of the marine fishery environment serves as the scientific cornerstone for assessing the health of the marine fishery environment. It also creates urgent demands and raises higher standards for new intelligent marine fishery environment monitoring systems. Marine environment monitoring equipment is not only a core component of the marine equipment industry, but also the fundamental means to meet the demands for real-time observation and prediction of basic environmental background conditions, such as marine meteorology, hydrology, geology, topography, and geomorphology, as well as the marine environment for the development of industries including fishery, resource exploration, biological resource utilization, transportation, and tourism. Particularly in the marine fishery sector, strengthening monitoring and supervision is foundational to safeguarding and protecting the healthy development of fisheries.

Marine fishery environment monitoring equipment replicates on-site sampling and laboratory testing process through sample collection devices and sensor detection arrays, and achieves a high degree of integration, intelligence, and miniaturization. It is also widely employed on various waterborne platforms such as vessels (ships), buoys, pontoons, and trestles. The equipment integrates new material technology, precision processing technology, fluid control technology, electrical automation technology, automatic detection technology, sensor technology, and marine fishery engineering technology. These technologies provide enhanced protection to core components like sensors and excels at resisting challenges met in marine fishery online monitoring, including biological fouling, ultraviolet aging, and vibrational impacts. Additionally, the application design of online monitoring technology is flexible, which supports modular expansion and platform adaptation. Beyond water quality monitoring, it can also be compatible with various types of equipment (e.g., meteorological stations, hydrological gauges, air quality detectors, and radiation sensors) by means of standardized interfaces (e.g., RS485, Ethernet) without major hardware modifications. This enables comprehensive observation and monitoring of marine fisheries. However, the marine fishery environments online monitoring service market remains fragmented and unregulated. It is essential to strengthen market supervision capabilities and raise entry thresholds, enabling technology-leading enterprises with advanced concepts, robust R&D capabilities, and sufficient talent reserves to access the market. This will actively drive the continuous development and advancement of marine fishery environmental online monitoring technologies.

As marine-monitoring technology advances, marine fishery environmental monitoring technology is also advancing in tandems. Functional nanomaterial-coated sensors are expected to detect microplastics at significantly lower concentrations than current capabilities. Buoys connected via 5G and low-Earth-orbit (LEO) satellites will not only relay compressed images and key sensor data in near-real time, but also enable the transmission of uncompressed high-definition video stream. Cloud platforms will integrate underwater acoustics, satellite optics and seismograph records to reveal interactions between current dynamics, temperature and fish migrations patterns. Meanwhile, artificial intelligence (AI) models will automatically classify and count the most common species in camera feeds. Together, these incremental yet significant advances will make fishery-environment monitoring more efficient and enhance support for the sustainable use of marine resources.

2.3 Demand for monitoring system

The marine fishery environmental monitoring system integrates core components including monitoring equipment, shipborne platforms, power supply equipment, communication equipment, data collection facilities, and data processing units. The system can monitor the operational status of equipment, transmit real-time online data, and process multi-source information in real-time. On March 16, 2016, the *Outline of the 13th Five-Year Plan for National Economic and Social Development of the People's Republic of China* (2016–2020) was promulgated (The Fourth Session of the 12th National People's Congress of the People's Republic of China, 2016). Notably, China's "Global Ocean Stereoscopic Observation Network" was incorporated into the country's national key marine projects. This network collects various types of data, including marine geospatial information, environmental parameters, ecological indicators, and resource data, and integrates cutting-edge ocean observation technologies and methodologies to achieve high-density, multi-parameter, all-weather, and fully automated ocean stereoscopic observation.

To conduct marine fishery environmental monitoring more effectively, countries worldwide are intensifying the construction of monitoring networks (Moltmann et al., 2019). A large number of monitoring stations have been established in coastal areas, and advanced communication technologies (e.g., 5G, satellite communication) are used to achieve high-speed data transmission and real-time sharing. This networked, integrated monitoring system significantly enhances the coverage and availability of monitoring data (Glaviano et al., 2022). According to the *2023–2028 In-Depth Analysis of China's Marine Environmental*

Monitoring Industry Market and Development Prospect Forecast Report (China Industrial Research Institute, 2023) by the China Industrial Research Institute, currently, China has established a four-level environmental monitoring network spanning central, provincial, municipal, and county administrations, with a total of over 4 800 professional and industry monitoring stations, including more than 2 200 environmental protection system monitoring stations and more than 2 600 monitoring stations across various industries. Among these, more than 300 institutions engaged in marine environmental monitoring, primarily affiliated with the Ministry of Agriculture and Rural Affairs (MARA), the Ministry of Natural Resources, the People's Liberation Army (PLA) Navy, and local provincial/municipal authorities.

Such a well-developed marine fishery monitoring system covering meteorology, marine physics, marine chemistry, and biology, can provide timely monitoring and early warning of marine environmental changes, thereby effectively mitigating associated risks (Tanhua et al., 2019).

The demand for marine fishery environmental monitoring has shifted from static status monitoring to dynamic process control, and from current-state assessment to early warning and forecasting, aiming to strengthen the real-time online monitoring and dynamic management capabilities of marine fishery authorities regarding the current state of the marine fishery environment, major pollution sources, marine fishery functional areas, environmental risk areas, and human activities. This shift is also critical to supporting the development of key areas, including marine fishery environmental pollution prevention, marine fishery ecological disaster early warning, coastal tourism, and aquaculture production.

3 DEVELOPMENT LEVEL AND TREND

The marine fishery environmental monitoring system offers crucial means and support for the effective management of the fishery environment. Developed countries have witnessed rapid progress in areas such as marine ranching construction and marine fishery environmental monitoring instruments and equipment, achieving abundant and practical results (Ru et al., 2023). In recent decades, China has also made breakthroughs in key technologies for marine fishery environmental monitoring. Some of these technologies are comparable to international counterparts, and marine ranching in China has also entered a stage of comprehensive development. Nevertheless, in the actual monitoring and application of the marine fishery environment, China has not yet established a complete marine fishery environmental monitoring system. The in-situ monitoring system is scattered, and the monitoring data lacks systematization. The procurement of monitoring instruments is still dominated by imported equipment, making it extremely difficult for domestic instruments to break into the domestic market. On data management and dissemination, China falls behind developed countries. Developed nations like the U.S. and Japan have built unified data platforms (e.g., NOAA's integrated fisheries environmental data systems) and institutionalized data disclosure, enabling standardized collection, real-time sharing, and transparent application of monitoring data. China has recently begun issuing national standards (e.g., HY/T 0342-2022) and pilot data-sharing protocols, yet they remain fragmented and unevenly implemented, so most monitoring data are still confined within departmental silos.

3.1 Policy and legislation on the monitoring system

Over the past half century of rapid advancement in marine science and technology, major developed countries worldwide have consistently emphasized marine exploitation and utilization. In the 21st century, international marine organizations, leading foreign marine powers, and China have successively released various strategic plans for marine, providing a policy foundation for the development of high-tech and equipment industries for marine monitoring. Regarding the sustainable and healthy development of the marine fishery environment, China has issued multiple documents, stressing the need to support and promote high-quality, sustainable development of marine fisheries, as well as intensifying efforts to protect the marine fishery environment.

The Central Committee of the Communist Party of China (CPC) and the State Council attach great importance to the construction of marine ecological civilization, a concept centered on marine ecological protection and sustainable development, and have made a series of decisions and arrangements. They bolster the protection of marine biodiversity and ramp up the conservation of marine fishery resources. In the top-level design of marine fishery-related systems, the protection and restoration of fishery resources in crucial fishery waters (such as coastal fishing grounds) have been incorporated into the planning process.

To enforce the *Fishery Law of the People's Republic of China*, the *Water Pollution Prevention and Control Law of the People's Republic of China*, and the *Marine Environmental Protection Law of the People's Republic of China* (Ministry of Agriculture and Rural Affairs, Ministry of Ecology and Environment, 2025), and to strengthen the ecological environment protection of fishery waters, the China's MARA established the National Fishery Ecological Environment Monitoring Network in 1985 to monitor the ecological environment of important fishery waters nationwide.

Using data from this monitoring network, the *Bulletin on the Status of Fishery Ecological Environment in China* (Ministry of Agriculture and Rural Affairs, Ministry of Ecology and Environment, 2025) is jointly issued annually with the Ministry of Ecology and Environment. Through the establishment of the national fishery ecological environment monitoring network and five sea-area and river basin-level fishery resources monitoring networks, China has monitored and assessed the status of fishery resources and the ecological environment of fishery waters, providing strong technical support for the conservation of aquatic biological resources.

In 2020, the Fisheries and Fisheries Administration Bureau under MARA developed the *National Fishery Ecological Environment Monitoring Network Conventional Monitoring Work Plan* (Fisheries and Fisheries Administration Bureau, Ministry of Agriculture and Rural Affairs (MARA), 2020) to comprehensively organize ecological environment monitoring for important fishery waters.

In 2013, China's State Council issued the *Several Opinions on Promoting the Sustainable and Healthy Development of Marine Fisheries* (State Council of the People's Republic of China, 2013), which actively promoted the construction and development of marine fisheries. The document clearly emphasized the need to strengthen the protection of marine fishery resources and their ecological environment. Specifically, it was pointed out that a comprehensive survey of fishery resources shall be conducted every five years, and monitoring and evaluation shall be carried out year-round. The focus shall be on investigating important fishery resources such as endangered species and aquatic germplasm, as well as important fishery waters such as economic biological spawning grounds, river estuaries, and the South China Sea. The construction of fishery resources survey vessels should be enhanced, the monitoring network improved, and the level of fishery resources survey and monitoring elevated. Additionally, the marine ecological environment monitoring system should be strengthened to boost monitoring capabilities. There should be strict control over the discharge of land-based pollutants into water, with a comprehensive sewage discharge control system implemented. Assessments of ecological environmental damage and biodiversity impact in fishery waters should be intensified, with remedial measures put in place. The density of offshore aquaculture should be controlled, the management of inputs such as feed and medication should be strengthened, and pollution from aquaculture should be reduced. Effective management of fishing in the 'Sansha' regions (Xisha, Zhongsha, and Nansha) should be enforced to protect the ecological environment. Furthermore, the management of waste discharge from fishing vessels (e.g., oil pollution, domestic waste) to reduce environmental pollution in offshore, nearshore, and high-seas areas.

In 2022, China's MARA issued the *Guidelines on Strengthening the Conservation of Aquatic Biological Resources* (Ministry of Agriculture and Rural Affairs of the People's Republic of China, 2022). The guidelines emphasize the need to conduct fishery resource surveys and monitor the ecological environment of fishery waters and call for establishing and improving of central-local collaborative mechanisms for survey and monitoring, as well as data-sharing systems. Reports on the status of fishery resources and the ecological environment are to be compiled regularly, with the delimitation and announcement of important fishery waters in batches. Local authorities are instructed to conduct comprehensive surveys of fishery resources every five years and implement year-round monitoring and assessment focusing on the status of key resources (rare and endangered species, aquatic germplasm resources) and the environmental conditions of critical fishery areas (spawning grounds for economic organisms, river estuaries, and the South China Sea). Relevant authorities and agencies are tasked using professional fishery resource survey vessels, expanding the survey and monitoring network, and upgrading the standards of fishery resources and environmental survey and monitoring.

Beyond strategic plans, developed countries have established robust legislation for marine fishery environmental monitoring. The U.S. *Magnuson-Stevens Fishery Conservation and Management Act* mandates standardized data submission as a prerequisite for quota and habitat management, while Japan's *Fisheries Basic Act* (2022-amended) legally requires in-situ monitoring of marine ranching areas (Fulton et al., 2016). By contrast, China's provisions remain fragmented across the *Marine Environmental Protection Law* and various departmental regulations; a dedicated statute specifying monitoring obligations, data standards and legal liabilities is still under development.

3.2 Development level of the monitoring system

3.2.1 Fishery environmental monitoring system

In the 1950s and 1960s, following the end of World War II, maritime countries increasingly sought to explore resources such as marine fisheries, minerals, and energy. Since the 1990s, developed maritime countries have experienced rapid advancements in marine monitoring instruments and equipment. With the emergence of new technologies, methods, materials, and processes, developed nations like the United States, Japan, Canada, and Germany have continuously innovated in the field of marine fishery environmental monitoring (El Mahrad et al., 2020). It is imperative to promote the transformation and upgrading of marine fisheries to be informative, intelligent, and modernized, establishing a comprehensive marine fishery environmental monitoring system.

Some countries have developed advanced marine observation technologies and integrated regional marine observation systems tailored to the needs of the marine economy. These systems have been successfully applied in marine fishery environmental monitoring (Zhai and Ni, 2018). For instance, the Centre for Environment, Fisheries and Aquaculture Science (CEFAS) marine observation system, jointly constructed by the CEFAS and the Met Office in the United Kingdom, includes 14 wave observation stations, 38 temperature and salinity observation stations, and 19 intelligent ecological monitoring buoys. This system initially served marine fisheries by providing real-time information on various fish schools, fish diseases, and predation (Morris et al., 2018). Similarly, the Poseidon monitoring and forecasting system in the Aegean Sea and the Irish Sea monitoring system provide substantial marine fishery monitoring information and data to relevant research institutions, fishery legislation departments, and fishery authorities in EU countries (Li et al., 2011).

The Ocean Biodiversity Observation Network funded by the National Oceanic and Atmospheric Administration (NOAA) and the National Aeronautics and Space Administration (NASA) in the United States, utilizes emerging technologies such as remote sensing, imaging, and molecular methods (eDNA and "omics"). It combines these with traditional research methods and collaborative experiments to observe marine organisms and ecosystems (Slater et al., 2017; Link et al., 2021). To date, five observation networks have been established in regions including the Arctic, the northwest Atlantic Ocean, the Gulf of Maine, and other areas. The "National Observer Program" implemented by NOAA features a comprehensive fishery data statistics and monitoring system. Observers monitor all U.S. coastal fishery activities and collect data for fishery protection and management statistics (Xu et al., 2009). Additionally, the independent non-profit Mote Center for Fisheries Electronic Monitoring (CFEMM) in Sarasota, Florida, has been enhancing fishery monitoring in the Gulf of Mexico since 2014. It employs GPS, sensors, and video-based electronic monitoring systems to strengthen fishery conservation and meet management objectives for all stakeholders (Neidig et al., 2024).

European and American marine observation systems and observational information directly serve the economic development and management of marine fisheries, which is valuable for China's efforts to advance its marine fishery sector. After decades of development, China has established a relatively comprehensive network of national, local, and regional marine fishery environmental monitoring stations. Through on-site sampling by survey vessels and laboratory-based manual analysis, it has achieved regular surveys of hydrological, meteorological, and biochemical elements in fishing waters (Li et al., 2024).

In the domain of molecular biotechnology monitoring for fishery environments, China has achieved notable advancements. A series of in-depth investigations have been carried out on techniques including environmental DNA (eDNA), loop-mediated isothermal amplification (LAMP), biosensors, DNA barcodes, and gene chips. China has successfully developed a methodology for estimating fish abundance and biomass in a specific region via eDNA analysis. Moreover, a breakthrough has been made in the rapid diagnosis of pathogens in aquaculture areas through LAMP and microfluidics (Zhou et al., 2021).

In recent years, with the rapid progress of fishery environmental monitoring sensor technology, in-situ real-time monitoring systems for marine ranching have been implemented in typical maritime areas. Environmental monitoring of marine ranching and real-time biological monitoring of underwater aquaculture are critical aspects in the development of marine ranching (Chen et al., 2021). In China, the construction of real-time monitoring systems for marine ranching is accelerating. At the national level, provinces and municipalities are strengthening their marine ranching monitoring systems. Several national-level marine ranching demonstration areas have installed multifunctional environmental resource monitoring platforms, realizing long-term, continuous, stable, and real-time online monitoring of ecological parameters and high-definition videos. The real-time online monitoring systems for marine ranching mainly fall into two categories: an automatic multi-environmental factor monitoring system based on buoys and an online monitoring system based on submarine cables.

The buoy-based system integrates telemetry terminals, water quality sensors, solar power systems, and anchoring systems to conduct in situ online monitoring and early warning of water quality. It is characterized by automatic continuous monitoring, self-cleaning, wireless data transmission, reagent-free operation, and unattended operation (Liu et al., 2019; Wang and Li, 2019).

The submarine cable-based online monitoring system offers a novel solution for nearshore submarine observations, consisting of three core components: shore-based control systems, submarine cables, and underwater observation systems (Du et al., 2014). The system integrates various instruments like current meters, wave meters, tide gauges, water quality meters, video cameras, hydrophones, and conductivity-temperature-depth (CTD) sensors. This integration facilitate the online and continuous observation of multiple marine elements, such as ocean currents, waves, water temperatures, salinities, tide levels, tsunamis, DO, chlorophyll, turbidity, underwater acoustic signals, and high-definition underwater videos (Chen et al., 2019). This system resolves the requirements for stable energy supply and long-distance, high-bandwidth data transmission in the context of needs for continuous marine environment observation through submarine cables. It innovatively employs on-site Controller Area Network (CAN) bus distributed modular integrated control technology, achieving distributed modular integration and intelligent control of underwater instruments (Zhai et al., 2020). Its simplified underwater plug-and-play design, optimized cable structure, and independent distributed modular control enhance the stability, reliability, and safety, while significantly reducing costs and maintenance efforts. This system has been extensively applied in more than 30 marine observation domains, encompassing the ecological environment monitoring of marine ranching, the online monitoring and protection of coral reef environments, the marine environment monitoring at river estuaries, the marine environment observation in petroleum and petrochemical areas of the "Blue Bay" remediation initiative, the regular marine environment monitoring at marine stations, as well as the scientific observation and research of the bottom boundary layer.

In Shandong Province's marine ranching, 24 sets of submarine cable online monitoring systems have been deployed, establishing the Shandong Marine Ranching Observation Network. This initiative has generated a total of 500 terabytes (TB) of data and video materials, which has led to the creation of the Shandong Marine Ranching Data Center. The data center has achieved a comprehensive effect of visibility, measurability, identification, and early warning (Guo et al., 2018). Despite these advancements, notable gaps remain in the maturity and comprehensiveness of China's marine fishery environmental monitoring system. It is essential to continue developing new marine fishery environmental monitoring technologies, to create independent and controllable localized equipment, to build a stable and reliable monitoring system, and to establish a scientific, advanced, and systematic modern marine fishery environmental monitoring technology system.

3.2.2 Fishery environmental monitoring equipment

Advanced fishery environmental monitoring equipment is essential for establishing a comprehensive marine fishery environmental monitoring system. Developed countries lead in marine fishery environmental monitoring technology and equipment, holding a dominant position in the international market.

Multi-parameter sensors, such as the YSI-EXO multi-parameter water quality instrument from the United States, RBR from Canada, and Aggreko from Japan, facilitate real-time and continuous monitoring of temperature, salinity, depth, DO, pH, turbidity, and chlorophyll in marine pastures and aquaculture areas. Notably, the measurement of DO is increasingly adopting photochemical principles, thus overcoming the limitations associated with traditional electrochemical methods. Fluorescence quenching-based DO measurement technology is widely applied, with devices like the G1100 fluorescence DO detector from HACH in the United States and the DO sensor from AANDERAA in Norway. The AAQ-RINKO fast optical DO sensor from JFE ADVANTECH in Japan boasts a response time of only 0.4 s and a continuous vertical section sampling rate of 0.5 m/s, making it a relatively advanced product. Recently, Sea-Bird in the United States has launched the SeaFET V2 pH sensor, which utilizes ion-sensitive field-effect transistor technology (ISFET), providing higher accuracy and better stability than the traditional glass electrode method.

Online measuring instruments for BOD, COD, total nitrogen, total phosphorus, and active phosphate, based on wet chemistry online monitoring technology (Guo et al., 2018), allow samples and reagents to enter the instrument through pumps and valves, mix and react in pipelines, and then enter the detector for real-time and continuous monitoring of water quality in fishery waters and aquaculture tail water. Foreign fishery water quality online monitoring instruments are comprehensive in function and variety, with representative companies including Sea-Bird and Wet Lab, YSI, AANDERAA from Norway, ALEC from Japan, and RBR from Canada.

Biosensors combine biological recognition elements (such as enzymes, antibodies, nucleic acids, and cells) with signal transducers (such as electrochemical, optical, and thermal sensors) to selectively recognize and quantitatively detect specific target molecules. In international fisheries environmental monitoring, the application of biosensor technology is becoming increasingly widespread. It can be used to monitor toxic substances such as heavy metals and organic pollutants and rapidly detect pathogens in aquaculture environments. For instance, Italian company SYSTEA has developed a biosensor based on luminescent bacteria that can perform fully automated online toxicity measurements of water samples (Li and Wang, 2023). Biosensors enhance traditional chemical analysis by providing insights into bioavailability and toxicity, while also reducing the dependence on hazardous chemicals, thus supporting the attainment of sustainable development goals (Huang et al., 2023).

Machine vision technology (based on optical images) and sonar technology have revolutionized underwater imaging, monitoring, and detection of marine fishery organisms. Tools such as underwater low-light cameras and 3D imaging sonar are now employed to monitor and detect the population distribution, dynamic changes, and living conditions of fish, shrimp, shellfish, and algae, markedly improving the efficiency of aquaculture and fishing operations. Given the limited light penetration in seawater, sonar detection technology offers a broader detection range compared to optical imaging. Acoustic cameras, leveraging deep learning, can continuously detect fishery organisms in low-light (nocturnal) or turbid water conditions. Underwater laser imaging technology further extends the reach of optical imaging. For instance, the range-gated underwater laser imaging system developed by Sperry Marine Co., Ltd. in the United States can observe up to 160 m in water with an attenuation coefficient of 0.1/m. Similarly, Sparta Corporation's underwater laser imaging system can achieve an imaging distance five times greater than that of a 500W bulb-based illumination system in port waters.

In recent years, marine scientific research and high-tech development have become a national priority, with investments in marine science and technology on the rise. This has led to a reduction in the gap between China's hardware construction and that of advanced nations, along with a marked improvement in the innovation capabilities of marine science and technology. China has made multi-spatial and multi-dimensional system technology breakthroughs in marine environmental monitoring equipment and technology, from offshore to far-reaching sea monitoring, and from in-situ sensor innovation to platform integration and big data mining. This has laid a solid foundation for the technical construction of a comprehensive marine fishery environment monitoring (observation) network system (Xue et al., 2022). Highly mechanized and automated technologies have improved the precision of artificial reef placement, marine pasture effect investigation and evaluation, and ecological harvesting. Acoustic, optical, and electrical technologies have been applied to efficiently control fish behavior, significantly enhancing the monitoring and evaluation of marine pasture resources. The integration of information technology, visualization technology, and satellite remote sensing has improved digital management and disaster early warning and prevention capabilities. Emerging equipment such as drones, unmanned boats, and underwater gliders have also demonstrated significant application value in marine pastures for automatic cruise monitoring (Schwing, 2023).

Since the "Ninth Five-Year Plan", with support from the National High-Tech R&D Program of China (commonly referred to as the "863 Program"), key R&D plans, National Natural Science Foundation of China (NSFC) Special Projects for Instruments, China's capabilities in R&D for fishery environmental monitoring and sensing technology have seen significant improvement (Ni et al., 2014). Chinese research teams have developed several independent fishery environmental monitoring sensor techniques that meet the international advanced level, narrowing the gap with the international advanced level. In response to the prevalent key issues and technical bottlenecks in real-time and efficient environmental monitoring of fishery waters, we have developed devices and technologies for the collection and separation of microplastic sample. We have established rapid detection methods for microplastics, and developed on-site rapid detection and screening technologies, along with portable instruments for various mixed pollutants such as heavy metals and antibiotics. Additionally, high-throughput rapid analysis technology for typical organic pollutants in fishery waters and multi-parameter in-situ online monitoring technology for the water quality and ecological environment in typical fishery waters have been developed. China strives to develop real-time rapid monitoring instruments, expand laboratory analysis technology, and improve the method system as part of research connotation, aiming to create a three-level monitoring technology system of "in-situ field laboratory". China aims to establish a practical comprehensive evaluation model of the fishery water environment, optimize it using three levels of monitoring data, and build a multi-parameter early warning and decision management support system for fishery water, safeguarding the green and healthy production, management, and high-quality protein supply of China's fisheries.

In general, the modern marine fisheries in China have substantial development potential, and the industry of marine fishery environment monitoring equipment also exhibits great considerable prospects. In the future, marine fishery equipment should persistently concentrate on modern technical equipment, tackling the "bottleneck" technical issues such as the development of high-precision monitoring equipment and special facilities. Through the integration and application of aquaculture technology, molecular biotechnology and the Internet of Things (IoT), the intensification, equipment, and intelligence of aquaculture in the vast open sea can be achieved.

In recent years, China has made remarkable advancements in the field of marine fishery environment sensor technology. There has been a consistent enhancement in innovation capacity and R&D potential, along with the emergence of novel sensors, which have promoted the development of marine fishery environment monitoring towards real-time, in-situ, fine, three-dimensional, and systematic capabilities. Nevertheless, the manufacturing and innovation level of localized sensor technology in China remains in the follow-up phase, and the long-term usability of domestic in-situ online sensors in fishery environmental monitoring requires improvement.

3.3 Development trend of the marine fishery environmental monitoring system

The Chinese government takes the lead in and vigorously promotes the modernization of fishery aquaculture. The application of sensor technology, molecular biotechnology, data transmission technology, and software technology in fishery water quality monitoring is experiencing rapid development, which is primarily reflected in water quality multi-parameter, data transmission, and intelligent decision-making systems (Guo et al., 2015). To facilitate the transformation and upgrading of marine fisheries towards informatization, intelligence, and modernization, efforts are actively made in the development of deep-sea aquaculture equipment and smart fisheries, with an emphasis on attaining intelligent, networked, cost-effective, and high-performance marine fishery environmental monitoring technology and equipment. Against the backdrop of the continuous development of industries such as materials, electronics, information, biology, and the global drive for green and low-carbon development, marine fishery environmental monitoring technology is also evolving towards low cost, high performance, and intelligence with independent intellectual property rights. In the future, the demand for long-cycle, low-cost, and multi-functional observation demand of the fishery environment will continue to expand.

With marine environmental monitoring technology and core equipment as the foundation, our objectives are multifaceted:

1) To devise a visualization- and information-based monitoring system for supervision and early-warning of marine fishery environmental problems.

2) To elevate the level of biological fine-grained monitoring in the marine fishery environment.

3) To institute a standardized and efficient approach for assessing the biological carrying capacity and conducting investigations on biological resources in the marine fishery environment.

4) To construct a real-time monitoring and evaluation information platform for the ecological effects of the marine fishery effects.

5) To track and offer feedback on the ecological environment and biological resources of the marine fishery.

6) To objectively summarize and evaluate the environmental status, thus providing a foundation for subsequent management, development, and utilization.

Tracking into account the construction and development models of different marine fishery regions in various sea areas, we shall further improve national, industrial, and enterprise standards for marine fishery environmental monitoring and assessment. Providing normative references from an ecosystem perspective, comprehensively evaluating the ecosystem service value of the modern marine fishery environment, and preventing ecological risks represent the crucial development directions and trends in the realm of marine fishery environmental monitoring in China (Liu et al., 2020).

4 KEY CHALLENGE

4.1 Gap between China and international counterparts

4.1.1 Lack of systematic and perfect monitoring system

The Western developed countries have established mature marine fishery environmental monitoring systems. In contrast, China's fishery environmental monitoring system developed relatively late, evolving from early sporadic and simple surveys of pollution sources and pollutant concentrations to the comprehensive monitoring systems in place today. Prior to the 1980s, China's fishery environmental monitoring was limited to regional, scattered efforts, primarily for environmental surveillance in certain maritime areas or basins, often associated with fishery resource surveys or stock enhancement activities. It was not until August 1985, when the National Fishery Environmental Monitoring Network was launched at its founding conference in Qingdao, that systematic fishery environmental monitoring was formally initiated in China. However, current routine monitoring still largely relies on vessel-based sampling and manual measurements. Key gaps persist, including a lack of in-situ real-time fishery environmental monitoring systems, insufficient top-level design for the national fishery environmental monitoring network, and the incomplete realization of an integrated land-sea-air monitoring network.

As data collection and storage technologies advance, marine fishery environmental monitoring system will increasingly prioritize data analysis and utilization. By leveraging big data analytics and AI, the monitoring system can more accurately predict key fishery resources indicators and environmental risk factors, ultimately providing scientific advice and decision support to reduce risks and improve efficiency .

4.1.2 Gap in the capabilities and technical level of monitoring

China has made significant strides in the development of marine monitoring technologies and equipment, laying a solid foundation for the establishment of a marine fishery environmental monitoring system. Despite these advancements, considerable challenges remain, including achieving independent and controllable precision monitoring of the fishery environment, as well advancing the digital transformation of monitoring technologies, and researching and simulating multi-scale marine fishery ecological monitoring systems.

In the field of high-precision, long-range marine fishery environmental monitoring, China has established a certain R&D foundation but still falls to meet product specifications for equipment, such as high-precision CTD sensors and high-precision acoustic Doppler current profilers (ADCPs), of which most remain dependent and rely on the imports.

In the area of underwater imaging monitoring and marine fishery biology detection, China has made breakthroughs in marine acoustic and optical detection sensor technologies. However, it still relies on imports for advanced equipment, including 3D imaging sonar, underwater low-light cameras, and online early warning instruments for toxic fish behavior and water quality detection. Notably, some items are embargoed by the Western countries, making them critical "bottleneck" products for China's marine monitoring capabilities.

In the monitoring of marine fishery environmental ecological parameters, China has broken through key technological bottlenecks for the online monitoring of seawater pH, DO, nutrient ammonia nitrogen, and COD-parameters essential for routine water quality assessments in marine pastures. However, notable gaps remain in stability and reliability compared to international technologies, with some core components or technologies still dependent on imports. Furthermore, in the area of water pollution parameters, including heavy metal monitoring, new pollutant monitoring, and algal toxin monitoring, China lags behind international standards in product R&D and advanced technology development.

To achieve the goal of "unmanned" operations encompassing breakthroughs in intelligent operation and maintenance, automated sampling and detection, smart facility management, and environmental perception, the aim is to drive the digital and intelligent transformation of traditional monitoring methods. Key measures include exploring the integration of AI technology in biodiversity assessment and complex fishery environmental perception, strengthening the application of new-generation sensing technologies and devices (e.g., remote sensing, advanced sensors) and advancing research on fishery resource quantity traceability technologies, as well as enhancing the use of optical feature recognition technology for pollution source tracing scenarios.

4.2 Technical and management challenge

4.2.1 Insufficient systematic R&D of monitoring system

Historically, our research in marine fishery environmental monitoring instruments has shown limited innovation in principles and methodologies, with most efforts concentrated on replicating foreign studies or established product technologies, a pattern common across multiple sectors. Compounded by a lack of specialized, forward-looking foundational planning, fragmented research funding, and dispersed research efforts, have resulted in a notably low level of independent innovation in China's marine monitoring equipment sector. Heavy reliance on external core technologies has led to a critical "bottleneck" constraint. There is an urgent need to promote independent innovation in fishery environmental instruments, to develop in-situ monitoring systems, and to establish a new generation of marine environmental monitoring systems propelled by indigenization, automation, intelligence, digitalization, and systematization. We aim to build an intelligent analysis and dynamic control system with real-time feedback, thereby striking a more effective balance between the economic benefits of the marine fishery industry and environmental sustainability.

4.2.2 Inadequate planning and infrastructure management

Building an intelligent, three-dimensional networked monitoring system is a complex, systematic engineering undertaking that requires comprehensive scientific planning based on preliminary investigations and in-depth studies. However, due to insufficient attention and funding constraints, a holistic plan to guide and standardize the development of intelligent fishery environmental monitoring systems is still lacking. The current marine fishery environmental monitoring systems that are established without thorough investigation, research, assessments, or a solid planning and design foundation, exhibit several flaws: incomplete monitoring parameters, limited surveillance areas, and discontinuous data that is not effectively utilized, thereby impairing the systematic and three-dimensional monitoring efficacy of marine fisheries. As such, there is an urgent need to address gaps in the scientific and standardized management of marine fishery environmental monitoring systems.

4.2.3 Inadequate information technology in monitoring data and limited data sharing

Fishery environmental monitoring data is essential for assessing the environmental status and pollution risks of fishery ecosystems, guiding fishery environmental conservation efforts, and supporting management decision-making. However, China's current fishery environmental monitoring data management system remains underdeveloped. There is an absence of robust national and provincial data resource platforms, as well as comprehensive data directories, integration mechanisms, and analytical frameworks. Inter-regional data sharing and exchange capabilities are Limited, and the application of innovation-driven productivity such as AI, blockchain, and the IoT, which are vital for fostering new productive forces, is insufficient. Furthermore, there is a lack of effective information technologies and intelligent tools to track real-time dynamic changes in the fishery environment, resources, and production. As a direct consequence, the development of a new generation of digital and intelligent fishery environmental monitoring technology systems is still in its nascent stages.

4.2.4 Challenge in the application of molecular biology techniques

Molecular biotechnology, including biosensors, eDNA technology, and LAMP shows great potential in fishery environmental monitoring. These techniques, valued for their rapidity, convenience, and high specificity, offer innovative tools for monitoring efforts (Zhao et al., 2024). Despite these advancements, the application of these technologies in China's fishery environmental monitoring still faces challenges. China initiated fishery ecological environment monitoring in the late 1970s, and has since established a national network (Shen, 2008). However, a notable gap exists in molecular biology technical support for monitoring. There is an urgent need to enhance real-time and large-scale monitoring capabilities for regional fishery biological resources. Furthermore, the monitoring of biological indicators such as microorganisms, toxins, and nutrients in the region requires immediate improvements to accuracy and timeliness.

5 PROSPECTIVE SCIENTIFIC ISSUE AND KEY IMPLEMENTATION TASK

5.1 Major scientific issue

To address the gaps in understanding and managing marine fishery environments identified in previous sections, an intelligent and comprehensive marine fishery environmental monitoring network and system ought to be established to enable on-site, real-time, online monitoring of key fishery waters. However, two core scientific issues remain to be resolved before this system can fully fulfill its function: first, how to effectively integrate multi-source monitoring data (e.g., from in-situ sensors, remote sensing, and laboratory analyses) to accurately delineate the spatiotemporal distribution patterns of diverse ecological factors within key fishery waters; second, how to clarify the dose-response relationships underlying the genetic, physiological, and biochemical impacts, as well as the mechanisms of pollutants (particularly endocrine disruptors) on economically valuable aquatic species and rare marine organisms.

5.2 Key task

5.2.1 Development of the monitoring system

Aligned with the comprehensive monitoring needs of China's fishery environment and targeting the gaps in systematic planning and integrated monitoring, we aim to construct a marine ranching monitoring network and an intelligent, information-based marine fishery environmental monitoring system. This initiative will elevate the precision of marine fishery environmental monitoring and ensure the visibility and management of marine ranching. Standardized and effective methods will be established for assessing the environmental carrying capacity and conducting resource surveys in marine fisheries covering key links such as habitat suitability evaluation and fishery resource stock estimation. Additionally, we will develop a real-time monitoring and evaluation information platform to track the health of the marine fishery environment, enhancing the accuracy of forecasts and the early warning capabilities for disaster events. By forming a comprehensive marine fishery environment monitoring industrial system, we will bolster the industrialization and application of monitoring instruments and systems, serving marine fishery activities including marine ranching and offshore aquaculture.

5.2.2 Enhancement of the monitoring technology

In response to both the distinctive requirements of marine fishery environmental monitoring (content, frequency, spatial coverage) and the inadequate systematic R&D of core technologies, there is a burgeoning innovation propelled by a suite of advanced technologies. These include next-generation information technology, AI, intelligent manufacturing, and big data analytics. We will actively explore the R&D, application, and integration of new principles, technologies, methods, materials, and energy sources to address the technical shortcomings in the core components and technologies of marine fishery monitoring equipment, such as low-cost high-precision sensors, anti-corrosion marine-grade materials, and energy-efficient power systems.

The low power consumption, longevity, stability, reliability, operational capability in complex marine environments, and effectiveness of monitoring data are key technical indicators of fishery environmental monitoring equipment. By increasing the automation and intelligence level of equipment, for example, integrating AI-driven adaptive sampling and self-diagnosis functions, we aim to achieve all-weather, uninterrupted real-time online monitoring of marine fishery resources and the environment.

Moreover, the cultivation of industrial capabilities, encompassing research and development, design, integration, testing, and maintenance, along with the facilitation of engineering, standardization, industrialization, and maturation, will augment the competitiveness of domestically manufactured fishery monitoring equipment in the international market.

6 POLICY AND IMPLEMENTATION RECOMMENDATION

An integrated, real-time, intelligent, visual, and information-based marine fishery environmental monitoring system should be established and improved. To advance this, we recommend incorporating the system into national and local marine fishery development plans and providing special policy funding to support its construction. This includes the development of independent and innovative fishery environmental instruments and equipment with policy incentives such as tax breaks for enterprises engaged in core technology R&D, and the promotion of in-situ monitoring system construction. Furthermore, accelerating the intelligent transformation of monitoring technology, enhancing the prediction and forecasting capabilities for fishery environmental quality and environmental risk monitoring and early warning, are the effective technical strategies to achieve high-level operational support.

Enhancing the overall coordination among multiple departments and commissions to facilitate the construction of a three-dimensional monitoring network that covers multiple layers and spatiotemporal scales, thereby promoting effective data sharing and improving intelligent decision-making capabilities. Specifically, a cross-departmental joint coordination mechanism should be established through policy stipulation, with a dedicated leading group to break down administrative barriers. Additionally, it is imperative to expedite the development of technical specifications and standard systems for fishery environmental monitoring, and to incorporate compliance with these standards into industry regulatory assessments, to lay a robust foundation for high-quality monitoring data acquisition. Simultaneously, the application of ecological compensation and international cooperation will achieve the technical goals of 95% detection coverage and a 90% prediction rate. Finally, through the dual-track guarantee of central special funds and network security level protection, a replicable Chinese-style ocean governance paradigm is formed, providing ISO standard output for the sustainable development of global fisheries.

7 DATA AVAILABILITY STATEMENT

All data generated and/or analyzed during this study are available from the corresponding author upon reasonable request.

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