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Review

The Characteristics and Advantages of Deepwater Ultra-Large Marine Ranches

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Abstract: Marine ranching is generally acknowledged to possess immense practical significance in the exploitation of marine resources across the globe. The term " Deep-sea " denotes waters situated more than ten kilometers away from the coastline or exceeding a depth of twenty meters. Furthermore, as a nascent frontier in the evolution of marine fisheries, Deepwater Ultra-Large Marine Ranches is currently demonstrating a dynamic and thriving trend. On a global scale, several countries that are pioneers in marine technology have spearheaded the construction of such ranches, and China is actively keeping pace, resulting in the development of new technologies that have significantly propelled the advancement of marine ranching. This article undertakes a comprehensive analysis of the current state of marine ranching and the development of Deepwater Ultra-Large Marine Ranches. It thoroughly compares traditional marine ranching with Deepwater Ultra-Large Marine Ranches in terms of economic efficiency, environmental friendliness, and technical sophistication, while highlighting their respective advantages. Additionally, it provides detailed descriptions of technologies such as the deployment of various ultra-large-scale net cages, their future prospects, and the challenges they pose. Moreover, the article delves into the structures of these net cages and the progress of related research. Lastly, it discusses the challenges currently faced by marine ranching and explores the future trends and technological advancements in its development.

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1. Introduction

The ocean is a treasure trove of resources, with abundant assets that have always been a focus of researchers. Marine ranching, as a widely studied sustainable resource acquisition method, has the advantages of ecological restoration, resource multiplication, and economic benefits. It boasts a clean, recyclable aquaculture environment and is a hot topic in the study of marine resource utilization. According to DNV data [1], from 1990 to 2020, the output of marine aquaculture increased by 5.8 times, reaching 29 million tons annually, and it is expected to grow to 74 million tons by 2050. However, traditional marine ranching still has negative impacts on the environment, including threats to local species and pollution of water bodies. With the advancement of science and technology, since the concept of marine ranching was first proposed by Chinese scientist Academician Zeng Chengkui, marine ranching has entered the 3.0 era [2].

In the 1.0 phase, the deployment of artificial fish reefs and resource enhancement stocking are the hallmarks, with a relatively basic technological level, focusing mainly on the construction of physical structures, yet lacking comprehensive assessment of the impact on the ecosystem [3]. The 2.0 phase is driven by ecological and informational advancements, dedicated to ecological balance and the sustainable use of resources, and significantly enhances the monitoring capabilities of the marine environment and biological resources through the introduction of information technology [4]. Building on this, the 3.0 phase further emphasizes intelligence, informatization, ecologicalization, and integration, integrating modern information technologies such as the Internet of Things, big data analysis, and artificial intelligence to achieve intelligent management. Additionally, the 3.0 phase integrates multiple functions, including fish farming, eco-tourism, scientific research, and environmental monitoring, to construct a multifunctional marine complex. It also leverages renewable energy technologies such as offshore wind power, wave energy, and tidal energy to achieve self-sufficiency in energy, elevating the efficient use of marine resources and the long-term protection of the marine environment to a new level [2].

The establishment of marine ranches is assuming a critical role in the stewardship and sustainable utilization of the world's marine resources. These ranches are pivotal in two respects: they are essential for the restoration of marine ecological environments and vital in countering the depletion of fishery resources, ensuring food security. By leveraging coastal regions, traditional marine ranches effectively foster the recovery of marine biodiversity through the construction of artificial reefs and the rejuvenation of seagrass beds. These ecological interventions provide a stable fishing ground for local fishermen and, to a significant extent, mitigate the impacts of marine pollution and ecological degradation.

However, as population growth and the demand for marine resources continue to escalate, traditional marine ranches are confronted with challenges such as finite resource capacity and mounting environmental stress. In this context, deep-water ultra-large marine ranches have come into being. Since the 1990s, fishery-advanced nations like Norway, Sweden, and the United States [5-6] have initiated attempts to develop the offshore aquaculture industry. Yet, due to the significant influence of marine wind and wave conditions on this industry, the advancement of offshore aquaculture has remained a formidable global challenge. At present, Norway stands at the forefront of the world in the development of offshore aquaculture, primarily focusing on the technologies of aquaculture vessels and large-scale deep-water net pens [7].

People are venturing into the vast and deep seas, utilizing advanced technological means and engineering facilities to construct large-scale and finely managed fishery ecosystems in the deep-sea environment. These marine ranches not only have stronger resource-bearing capacity and risk resistance but also achieve precise breeding and efficient management through intelligent monitoring and remote control. This ensures the supply of aquatic products while minimizing the impact on the marine environment. Moreover, the construction and operation of deep-sea ultra-large marine ranches also have a positive effect [8] on carbon sequestration, helping to mitigate global climate change.

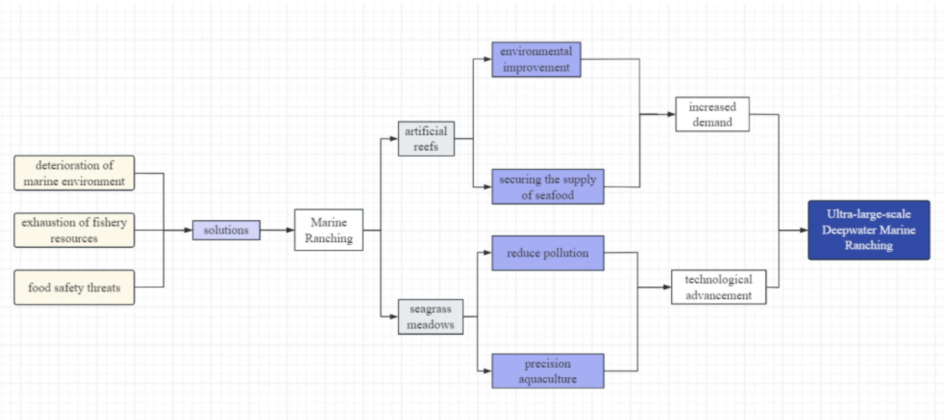

Figure.1. Mind Map of the Emergence of Deepwater Ultra-Large Marine Ranches

The process of aquaculture moving towards the deep sea represents a shift from traditional production methods to precise, efficient, and green practices. It signifies a transition from manual labor to machinery-based operations and from subjective experience-based judgment to intelligent decision-making backed by big data. For aquaculture companies, smart fisheries have evolved from being an optional project to a necessary one. The construction and operation of deep-sea marine ranches not only improve the sustainable use of fishery resources but also, through the carbon sequestration function of marine organisms, absorb atmospheric carbon dioxide and reduce greenhouse gas emissions, contributing to the global carbon cycle and the mitigation of climate change [9-10].

The construction of marine ranches in China began in the 1970s, with the first deployment of 26 experimental small individual artificial reefs along the coast of

Qinzhou, Guangxi, in 1979. Starting from 1983, various regions began deploying artificial reefs, albeit on a relatively small scale overall. Since 2002, the former Ministry of Agriculture has allocated special funds to support the construction of marine ranches, sparking a new wave of artificial reef construction in provinces such as Guangdong, Zhejiang, Jiangsu, Shandong, and Liaoning. Since 2015, efforts have been actively made to promote the standardized and scientific development of marine ranch construction. From 2015 to 2021, a total of 153 national marine ranch demonstration areas have been established in seven batches across the country, with an additional 16 in the seventh batch in 2022. As of 2024, the number of national marine ranch demonstration areas has reached 195, achieving remarkable economic, ecological, and social benefits [11].

In the construction of deep-sea marine ranches in China, multiple demonstration areas have been planned and established. It is anticipated that by 2025, the area of deep-sea waters involved will be significantly expanded, exceeding 2,500 square kilometers [2].

These areas are set to become important carriers for the transformation and upgrading of China's marine fishery industry, promoting the development of the fishery towards intelligence, greening, and sustainability. China's deep-sea aquaculture equipment industry is rapidly taking shape and growing, with the construction of large-scale aquaculture vessels, large deep-sea cages, and integrated deep-sea aquaculture platforms also underway. The technical level of the equipment is gradually entering the ranks of the world's advanced levels. However, unlike countries like Norway, China's coastal waters have a more complex and diverse natural environment. The frequent typhoons that strike China's coastal areas every year have a direct impact. Therefore, on the path of building marine ranches and developing deep-sea aquaculture, China must come up with a sustainable development "Chinese solutions”.

The "China Solution" for the sustainable development of marine ranching, as articulated by China, is a holistic approach that amalgamates technological innovation, ecological conservation, industrial synergy, policy incentives, and international collaboration. This comprehensive strategy is designed to steer the progression of marine ranching towards intelligence, environmental sustainability, and green practices. It encompasses initiatives such as intelligent breeding, ecological restoration, and the expansion of the industry chain to enhance the sector's ecological and economic efficiency. Furthermore, the strategy underscores the importance of bolstering international cooperation and fostering exchanges to collectively advance the sustainable development of global marine fisheries. By integrating these multifaceted elements, the "China Solution" aims to not only invigorate the domestic marine ranching industry but also contribute to the global effort in preserving marine ecosystems and ensuring the long-term viability of marine resources [12-13].

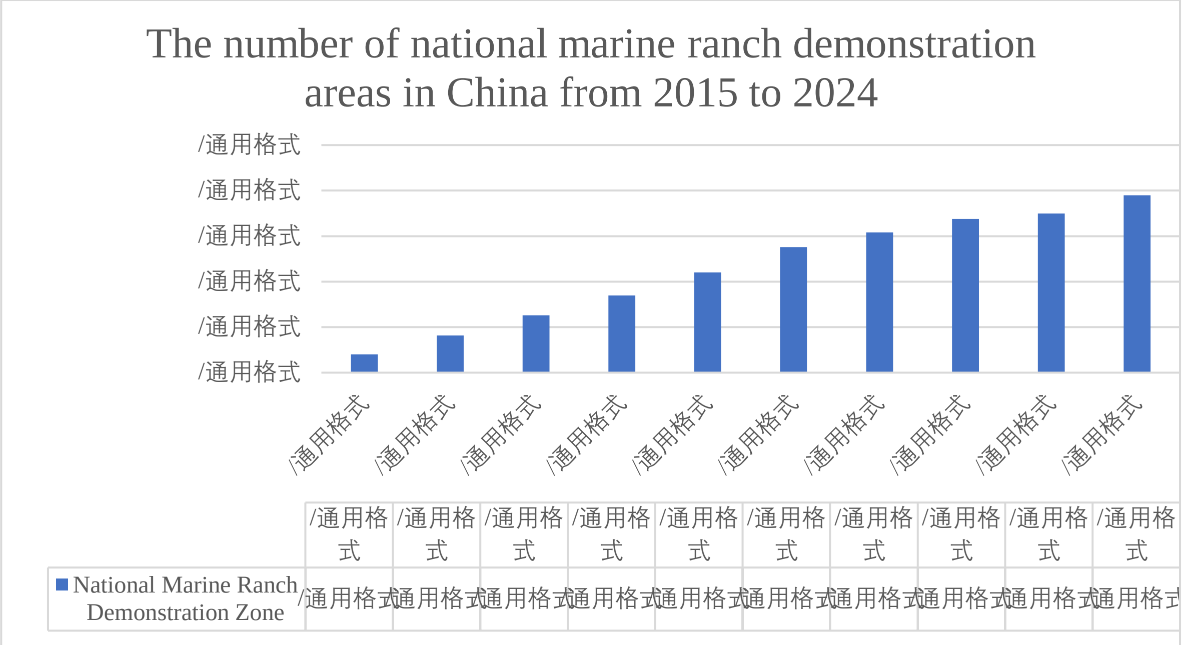

Figure.2. The number of national marine ranch demonstration areas in China from 2015 to 2024

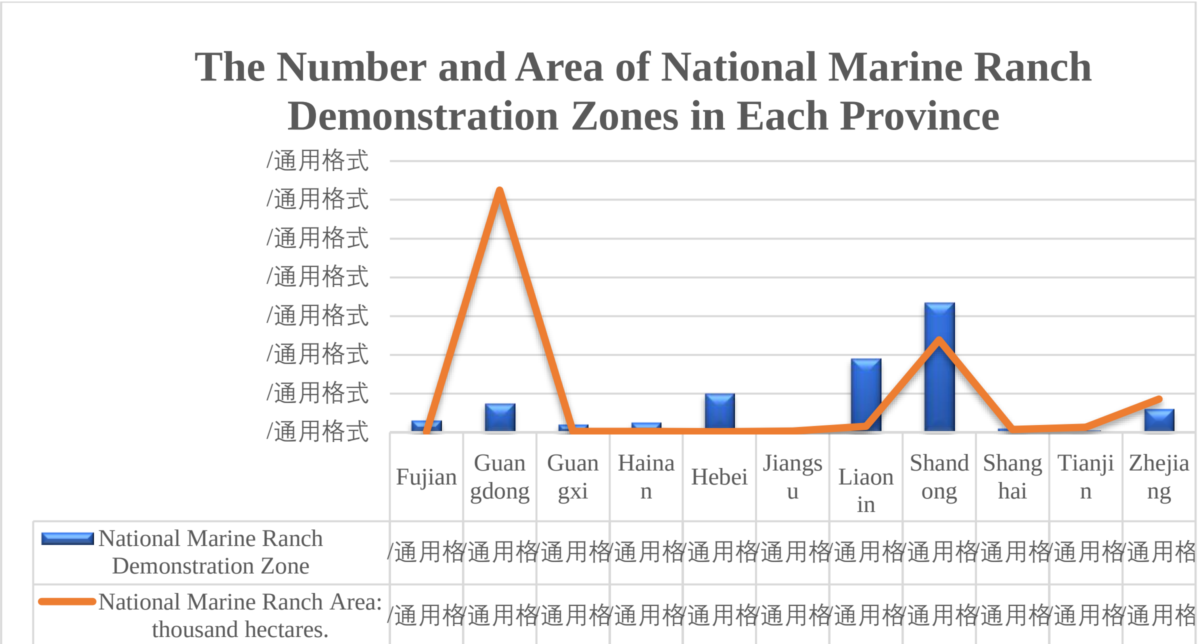

Figure.3. The Number and Area of National Marine Ranch Demonstration Zones in Each Province

2. Materials and Methods

2.1 Economic Comparison

2.1.1 Initial Investment and Cost Composition

In the pivotal process of marine ranch construction, the selection and planning of the site are of paramount importance. As elucidated in the seminal research by Chen et al., the initiation of marine ranches necessitates a thorough investigation into the marine ecological environment, resource endowment, transportation infrastructure, and regulatory compliance of the prospective sea area. The chosen maritime region should be amenable to the proliferation of marine life and concurrently facilitate effective management practices. During the planning phase, it is imperative to deliberate on the scale of operations, the species to be cultivated, the methodologies of aquaculture, and the strategic layout of facilities. This comprehensive consideration is essential to strike a harmonious balance between ecological preservation and economic viability. Post the site selection, it is equally crucial to undertake measures for the purification and safeguarding of the underwater and peripheral environments. Such actions are indispensable to mitigate the adverse impacts of environmental factors on the construction and subsequent operational phases of the marine ranch [14].

Subsequently, the deployment of underwater artificial reefs needs to be carried out. Artificial Reefs (ARs) are used in coastal areas around the world to attract fish, improve the environment, and support different activities. They started in Japan and have spread globally, with various materials and designs used depending on each country's needs [15]. Research shows that the goals of AR projects change over time, based on local concerns about fishing, protecting nature, and recreation. Future studies will look into how ARs can help with sustainable fishing, saving species, and restoring marine life. The Shenzhen Dapeng Ocean Ranch project in China has built three types of artificial reefs: rectangular concrete ones for farming fish (3.66m x 2.5m x 1.8m), rectangular concrete ones for planting (4m x 4m x 2.8m), and cubic concrete ones for attracting fish (3m x 3m x 3m). The project covers 49.0056 hectares of sea and cost 17.5 million yuan. It includes 20 farming reefs, 519 planting reefs, 149 fish-attracting reefs, and an underwater monitoring system. The total cost for the reefs and related facilities is 17.5 million yuan [16].

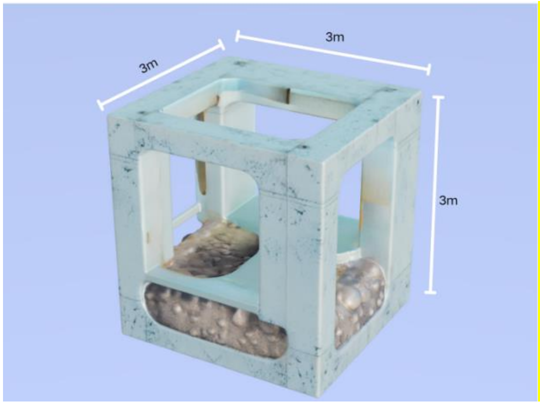

Figure.4. Cubic concrete ones for attracting fish

When considering the costs associated with the main species being farmed in a marine ranch, we can take the artificial reef coral seeding project in the Dapeng Bay National Marine Ranch Demonstration Area in Shenzhen as an example. The budget for this project is 14.45 million yuan, with plans to construct and deploy a total of 27,603.6 cubic meters of reef bodies, including various types and specifications of artificial coral reefs for subsequent coral seeding [11].

The Coral Ecological Online Observation System (CECO), developed by Xiamen University's Dongshan Taigu Ocean Observation and Experimental Station, exemplifies the forefront of marine observation technology. By utilizing optoelectronic networking and interface technologies, CECO ensures the stable operation of advanced sensors and underwater instruments through the provision of stable direct current voltage and optical communication channels to underwater junction boxes via optical-electrical composite cables. This system facilitates continuous, real-time, and long-term monitoring of marine environmental parameters and captures the growth status of coral communities in high-definition video. The convergence of these technologies has markedly improved the sophistication of marine environmental monitoring, positively influenced coral ecological conservation, advanced the realization of scientific aquaculture goals, and furnished invaluable data support for marine ecological conservation and research endeavors [18].

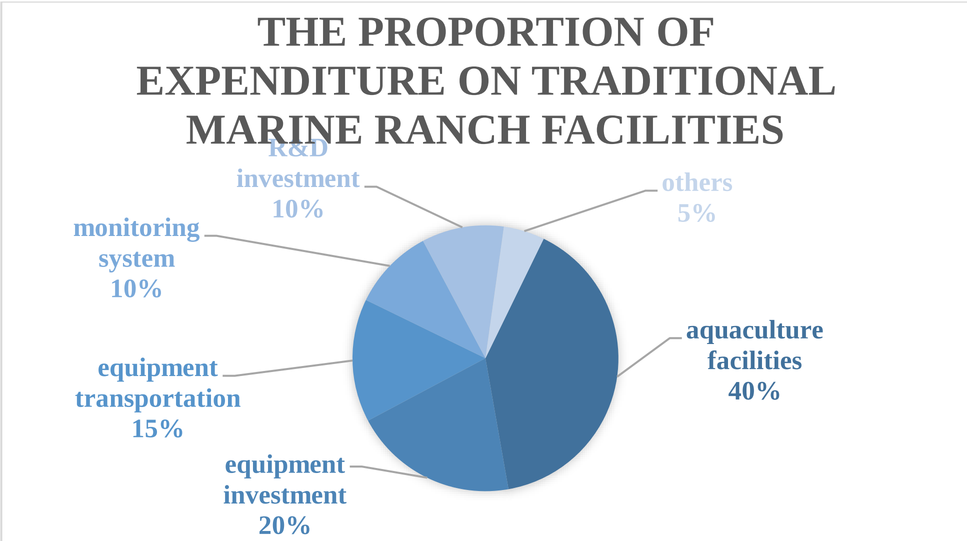

Figure.5. The facility cost of Ultra-large-scale Deepwater Marine Ranching

In the economic comparison, the distribution of expenditures for traditional marine ranching facilities is revealed. Among them, aquaculture facilities account for the largest proportion, constituting 40% of the total expenditures. This includes the costs of constructing and maintaining infrastructure such as cages, fish larvae, and artificial reefs. Next, equipment investment makes up 20%, covering the purchase and maintenance of necessary equipment for marine ranching. Equipment transportation accounts for 15%, referring to the logistics costs associated with delivering essential equipment and supplies to the marine ranch. Research and development investments and monitoring systems each constitute 10%, indicating a focus on innovation and monitoring while ensuring sustainable and efficient operations of marine ranches. Finally, 5% of the expenditures are categorized as "other," encompassing miscellaneous expenses such as administrative fees, insurance, and emergency funds. This distribution reflects a strategic emphasis on facility-related construction as the core operational need of marine ranches, while also acknowledging the importance of research, monitoring, and supporting services.

Compared to traditional marine ranches, the site selection for deep-water and ultra-large marine ranches differs greatly. In terms of water depth and offshore distance, deep-water and ultra-large marine ranches are typically constructed in deeper sea areas to leverage the broader space and richer marine resources. These ranches may be located in sea areas with isobaths of several tens of meters or even deeper, which facilitates the deployment of deep-sea cages and the arrangement of other required technical equipment, as well as integration with other technologies. In contrast, traditional marine ranches are closer to the coastline, generally at depths of about 10-15 meters and relatively shallow [18].

In terms of ecological environment and resources, deep-water and ultra-large marine ranches pay more attention to the protection and restoration of the ecological environment during site selection. They choose to construct in sea areas with good ecological environments, rich biodiversity, and suitable climates. These sea areas usually have relatively stable marine environments, clean water quality, and abundant original fishery resources. Additionally, deep-water and ultra-large marine ranches consider the sustainable utilization of marine resources to avoid overfishing and ecological damage. They choose to construct in traditional fishing grounds with good fishery resource bases or sea areas with abundant marine organism nurseries, in order to better fulfill the biological protection and restoration roles of marine ranches [19].

In terms of habitat construction, deep-sea marine ranches not only create fish reefs suitable for fish growth but also leverage the advantages of deep water and vast areas to create a systematic habitat on the seabed. This includes foraging areas, spawning grounds, overwintering sites, and migration corridors, integrating multifunctional habitats to meet the needs of marine life at different stages of their life cycles. This implies that the initial investment in infrastructure for deep-sea, ultra-large marine ranches will be substantial compared to traditional marine ranches. Similarly, when introducing fish fry and monitoring equipment, the same principle applies. Larger and deeper deep-sea, ultra-large marine ranches will require several times the processing capabilities and quantity of monitoring equipment compared to traditional marine ranches, significantly increasing the government's initial investment. In terms of equipment for marine ranches, the future, including deep-sea, ultra-large marine ranches, is moving towards a new stage of intelligence, unmanned operation, and ecologicalization [20]. Intelligent aquaculture platforms, represented by "Haiwei 1" and "Haiwei 2," leverage their truss structure and automatic draft control technology to provide a safe haven for fish populations. The construction cost of "Deep Blue 1" is up to 110 million yuan, while "Guoxin 1" is priced at 450 million yuan [21]. Unmanned operation equipment, such as autonomous feeding vessels, patrol boats, and underwater monitoring robots, has reduced labor costs and improved management efficiency. However, the initial investment required is also significantly increased. Deep-sea aquaculture vessels, like the "Jiuzhou No.1," integrate large-scale aquaculture, industrial facilities, and intelligent management, leading the new future of marine aquaculture [22]. All these equipment imply that the government needs to invest more in funding and technology, and at the same time, there must be a greater market demand for the products in order to successfully build deepwater ultra-large marine ranches.

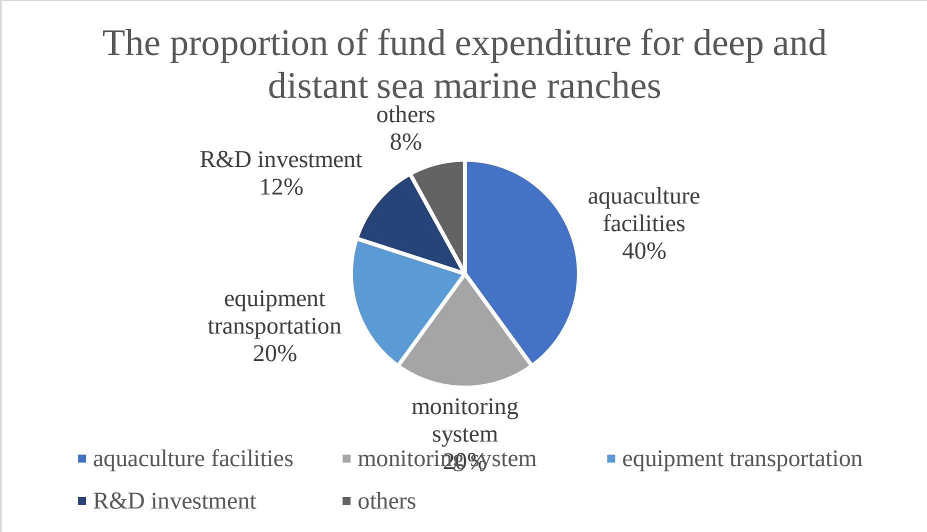

Figure.6. The proportion of fund expenditure for deep and distant sea marine ranches

The comparative analysis of the project's expenditure provides a detailed perspective on the allocation of investment in deep and distant sea marine ranches. The data presented in the chart show that aquaculture facilities account for a significant 40% of the investment, highlighting that the construction and maintenance of infrastructure represent the largest area of financial commitment in the establishment and operation of these ranches. The monitoring system claims 20% of the budget, which not only underscores the importance of surveillance of the marine ranch's environmental conditions and the growth of its biological populations but also plays a crucial role in ensuring the sustainable development of the marine ranch.

Equipment transportation also takes up 20% of the expenditure, a proportion that is closely linked to the unique geographical location of the deep-sea sites, leading to relatively higher logistics costs. R&D investment, though it constitutes a smaller portion at 12%, plays an indispensable role in enhancing the production efficiency and technological innovation of the marine ranch. Lastly, 8% of the expenditure is categorized as "others," covering miscellaneous expenses such as administrative costs, insurance, and emergency funds that are not explicitly listed in other categories

2.2 Operational Cost and Benefit Analysis

The daily maintenance and management of traditional marine ranches are crucial for ensuring the sustainable use of fishery resources and the balance of marine ecosystems. This complex and specialized task covers not only the meticulous maintenance of facilities and equipment and the scientific management of biological resources but also extends to environmental protection and the professional development of the team. At the level of facilities and equipment, marine ranches rely on a series of high-precision equipment to support various aspects such as data monitoring and harvesting. From stable offshore platforms to high-precision monitoring equipment, from net cages carrying biological mass to buoys guiding navigation and the status monitoring of underwater artificial reefs, each facility is the cornerstone of ensuring the normal operation of the ranch. Therefore, regular professional inspections, preventive maintenance, and timely updates and upgrades have become indispensable tasks, which require continuous investment and supervision from the government [23-24].

Secondly, the conservation and management of biological resources are one of the core tasks of marine ranches. In certain cases, it is necessary to formulate scientific stocking plans, select suitable species and reasonable stocking densities, aiming to restore and enhance the population numbers of fishery resources. In addition, effective disease prevention and control work relies on real-time monitoring, early warning, and prevention of pathogenic microorganisms, as well as reasonable medication guidance, to ensure the health and safety of biological resources [25-26].

Faced with the increasingly severe problem of marine pollution, marine ranches need to take a series of effective measures to reduce their impact on the marine environment. This includes but is not limited to optimizing breeding models to reduce waste emissions, implementing ecological restoration projects to restore damaged marine ecosystems, and strengthening marine environmental monitoring and assessment work to grasp trends in environmental changes. The implementation of these measures undoubtedly requires a large amount of data support and financial investment.

2.3 The maintenance costs, breeding efficiency, and market revenue of deep-water ultra-large marine ranches.

The maintenance costs of deep-water ultra-large marine ranches are significantly higher compared to traditional marine ranches, primarily due to the demand for more advanced and larger-scale facilities and equipment. For instance, Guangdong's "Dehai No.1" truss-type net cage has withstood the severe test of a Category 17 typhoon, with its structural safety performance continuously improving . Shandong's "Guoxin No.1" aquaculture vessel, which employs the "ship-carrying tank aquaculture" technology, provides innovative solutions for offshore aquaculture [21]. However, the construction and maintenance of these high-end facilities undoubtedly bring higher costs. In addition, offshore farming also needs to cope with more complex marine environments, such as strong wind and waves, which further increase its maintenance costs and bring higher risks and challenges [27]. Despite this, offshore farming is highly regarded for its market revenue potential, but it also inevitably faces the destruction of farming facilities by typhoons and other extreme weather, as well as the negative impact on fish growth.

However, from the perspective of breeding efficiency and profitability, deep-water ultra-large marine ranches have significantly improved breeding efficiency by adopting modern breeding techniques and equipment, such as automatic feeding, underwater and above-water video monitoring, real-time water quality monitoring, and so on. The use of automated equipment like intelligent cages, automatic feeding systems, and underwater video monitoring not only enhances breeding efficiency but also effectively responds to natural disasters through the automatic sinking and floating function of platforms like the "Hai Wei No.1" [28] intelligent breeding platform, ensuring breeding efficiency and the safety of the fish.

The higher quality water and faster currents in deep-sea areas provide a more suitable environment for fish growth, which helps to breed higher quality aquatic products to meet the market's demand for high-quality seafood, thereby bringing higher market returns. Products from distant sea breeding, such as large yellow croaker and golden pomfret that can avoid typhoons in specific breeding strata at depths of 14-15 meters, not only have higher economic value but also have a large market demand and higher prices, which can bring considerable profits to deep-water ultra-large marine ranches. At the same time, due to the high quality of their products, they are more likely to gain market recognition and achieve higher pricing.

Table 1. Economic Comparison Between Traditional Marine Ranches and Deepwater Ultra-Large Marine Ranches

Economic Comparison	Infrastructure Planning Construction	Habitat Restoration	Monitoring System	Scientific Research Investment	Others
Traditional Marine Ranching	Site Survey Aquatic Platform	Artificial reef Seaweed farm	Manual Monitoring Numerous Sensors	Lower	Low Maintenance Costs Low Income Average Quality
Ultra-large-scale Deepwater Marine Ranching.	Site Survey Floating Platform Underwater Station Fish Farming Vessel Aquaculture Platform	Deep-sea cage Large-scale Artificial reef	Highly Integrated Sensor System + AI Analysis and Control	Deep Cooperation with Enterprises and Universities	High Maintenance Costs High Level Automation Integration Good Quality Substantial Income

In terms of economic and operational dimensions, traditional marine ranches and ultra-large-scale deepwater marine ranches exhibit significant differences. Traditional marine ranches primarily rely on basic site surveys, aquatic platforms, artificial reefs, and seaweed farms, managed through manual monitoring and numerous sensors, with relatively low investment in scientific research, leading to lower maintenance costs and revenues, and average product quality. In contrast, ultra-large-scale deepwater marine ranches are equipped with more advanced infrastructure, including floating platforms, underwater observation stations, fish farming vessels, and aquaculture platforms, utilizing highly integrated sensor systems and artificial intelligence analysis and control technologies, engaging in deep cooperation with enterprises and academic institutions, and investing significantly in scientific research. These characteristics give ultra-large-scale deepwater marine ranches a clear advantage in automation, product integration, and quality control, despite higher maintenance costs, which are offset by substantial revenues. Overall, ultra-large-scale deepwater marine ranches hold the advantage in terms of technological advancement, level of automation, and revenue potential and future prospects, while traditional marine ranches are more competitive in terms of cost-effectiveness.

3. Environmental Comparison

3.1 the impact on the ecological environment

Traditional marine ranches, by deploying artificial fish reefs, constructing seaweed beds and seagrass beds, and implementing integrated measures such as biological restocking, not only significantly enhance biodiversity but also promote the sustainable use and recovery of fishery resources. In terms of artificial fish reefs, they can generate turbulence and upwelling [29], which encourages the upward migration of organic matter and nutrients from the seabed, increasing the reproduction and growth of phytoplankton in the euphotic zone, thereby enhancing the primary productivity of the sea area. This not only provides ample bait to attract fish aggregations [30], but also helps to accelerate the absorption and transformation of nitrogen and phosphorus in the aquatic environment, enhancing the self-cleaning ability of the sea area. Deep-sea areas with better water quality and faster currents provide a more suitable environment for fish growth, which is conducive to breeding higher quality aquatic products to meet the market's demand for high-quality seafood, thereby bringing higher market returns. Distant sea breeding products, such as large yellow croaker and golden pomfret, can avoid typhoons in specific breeding strata at depths of 14-15 meters, not only have higher economic value, but also have a large market demand and higher prices, which can bring considerable profits to deep-water ultra-large marine ranches. At the same time, due to their high product quality, they are more likely to gain market recognition and achieve higher pricing [2]. However, according to the tracking research on artificial fish reefs conducted by Wang Weiding and others, the deployment of artificial fish reefs may disrupt the original ecological balance. The engineering factors of fish reef deployment also disturb the marine habitat, and it is one of the factors leading to high levels of BOD5 and COD in the sea area. As a result, the fish reefs can have a short-term negative impact on the habitat, which after an adaptation period of 1-2 years, begins to shift from negative to positive effects [31].

In addition, the invasion of artificially propagated and released species may pose a threat to rare and endangered wild species resources. In the article by Zhang Yiyi and others, it was pointed out that the transplantation of seaweed and seagrass in suitable marine areas, whether it be the transplantation of young or mature individuals, can enhance the primary productivity of the seabed, provide food and habitat for fishery organisms, and accelerate the absorption and transformation of nutrients such as nitrogen and phosphorus in the aquatic environment, thereby improving the water quality and sediment environment of the maritime area [32]. However, the transplantation of seaweed or seagrass saplings may alter the original structure of the benthic plant communities in the maritime area, leading to a reduction in biodiversity and affecting the local ecological environment to a certain extent. Regarding the flow field effects of artificial reefs, Zou Tao and others have proposed that the layout pattern and spacing of artificial reefs have a significant impact on flow field effects [33]. The rational combination of permeable and impermeable reefs can effectively improve the flow field effects in their respective water areas, enhancing the disturbance between the lower and upper layers of the aquatic environment. Under different spacing and incoming flow velocity conditions, the impact of artificial reefs on upwelling volume, nutrient enhancement, and vertical eddy viscosity coefficient also varies [34].

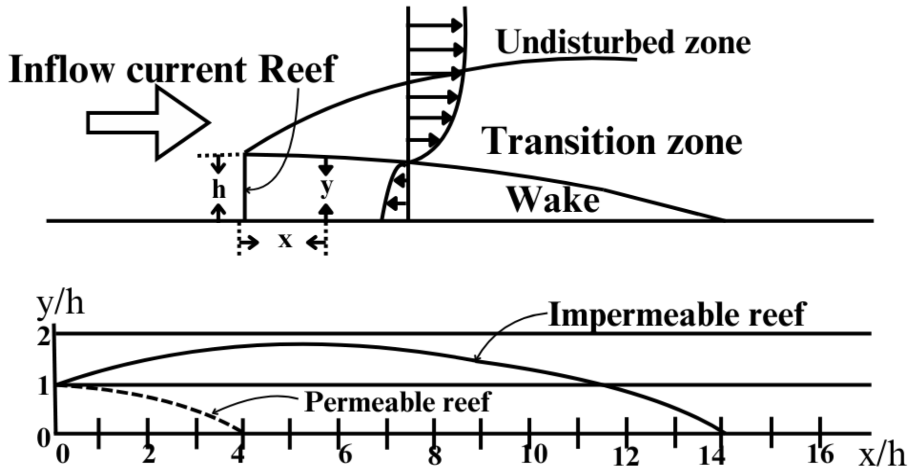

Figure.7. The impact of artificial fish reefs on the water flow environment

The seabed hydrodynamic characteristics diagram illustrates the hydrodynamic impact of artificial reefs on water flow characteristics. For impermeable artificial reefs, the flow velocity significantly increases upstream (x/h<1) due to the accumulation of water flow in front of the reef, while downstream (x/h>1) a wake region is formed, resulting in a significant decrease in flow velocity. This change is reflected in the flow velocity profile curve associated with impermeable reefs, showing a sharp rise followed by a rapid decline. In contrast, permeable reefs allow some water to pass through, leading to a more moderate change in flow velocity, which is depicted in the flow velocity profile curve as less dramatic fluctuations. The transition zone from the undisturbed area to the wake region is crucial for understanding the overall flow field dynamics. Changes in flow velocity and direction may have profound effects on the local marine ecosystem, including potential alterations in sediment resuspension, nutrient distribution, and the structure of benthic plant communities [35-36].

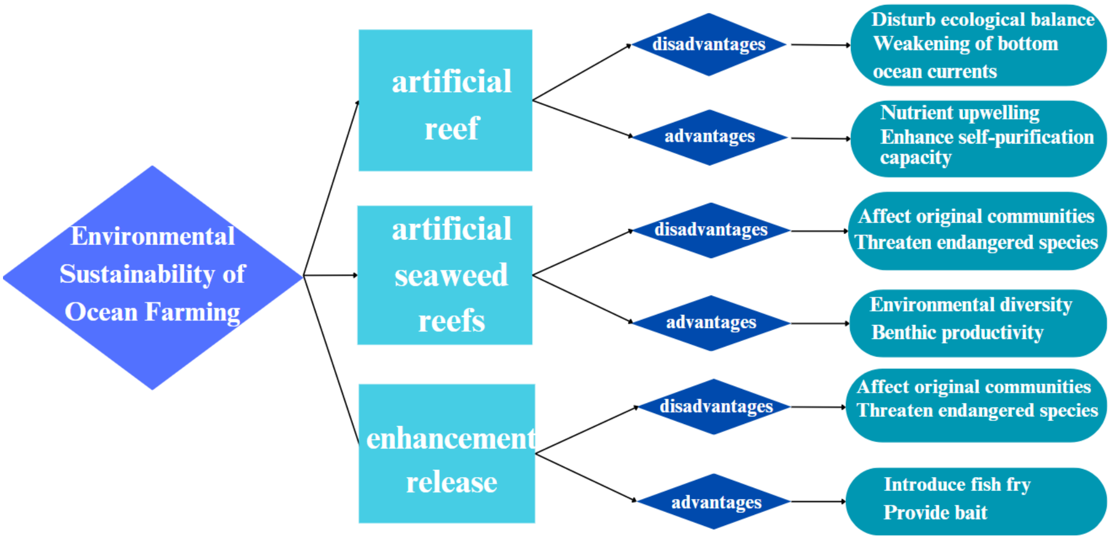

Figure.8. Environmental Sustainability of Ocean Farming

3.2. The impact of deepwater ultra-large marine farms and risk prevention and control measures.

Deepwater ultra-large marine ranches, as a form of aquaculture derived from traditional marine ranches, have a multifaceted impact on the marine ecosystem, and comprehensive risk prevention and control measures constitute a complex field. These impacts include but are not limited to changes in water quality, potential alterations to biodiversity, and disturbances to the natural habitats of the aquaculture area. At the same time, risk prevention and control measures need to cover technological innovation, environmental impact assessments, and the establishment and enforcement of policies and regulations. In terms of facility construction, deepwater ultra-large marine ranches significantly promote the richness of marine biodiversity through ecological engineering such as artificial fish reefs and seaweed beds. The design of these artificial ecosystems aims to mimic natural habitats, providing shelter and breeding grounds for marine life, thereby enhancing the structure and function of biological communities. In addition, by implementing refined stocking strategies and resource management plans, these ranches effectively achieve sustainable development of marine biological resources, while reducing the risk of environmental pollution caused by artificial feeding, ensuring the ecological safety of aquatic products, and reducing pollution in the area. However, in the expansion process of marine ranches, the increase in breeding scale and density may lead to the accumulation of feces and uneaten feed residues from cultured organisms in the aquatic environment, thereby negatively affecting water quality. If effective management measures are lacking, as seen in some marine ranches in the Guangdong region [37], this accumulation may further lead to eutrophication of the aquatic environment and even trigger ecological disasters such as red tides, posing a threat to the health and stability of the marine ecosystem. At the same time, the construction of marine ranches requires fixed facilities such as net cages and floats, which may physically disturb the habitats of benthic organisms, affecting the structure and function of benthic communities. In addition, the introduction of cultured species may compete ecologically or exchange genes with native species, which may disrupt the balance of the local ecosystem, leading to a decline in biodiversity and a loss of ecological service functions [38].

Regarding the impacts in these fields, improvements can initially be made from the perspective of artificial fish reefs. For instance, alternative materials such as oyster shell powder and biochar can be utilized, with the aim of reducing energy consumption and carbon emissions during the preparation process of traditional cement-based materials, thereby lowering the environmental footprint of artificial fish reefs [39]. Furthermore, according to the research by Chen, H, and colleagues, adjusting the chemical composition and physical structure of materials, such as the proportion of oyster shell powder, can enhance the bio-adhesion of artificial fish reefs and strengthen their ecological functions [40]. Additionally, reducing the pH value of the material's leachate can create a more suitable living environment for marine organisms. Meanwhile, deep-water ultra-large marine ranches often employ open net cage systems for aquaculture activities. The key structural forms of offshore marine ranches are divided into Open Net Cage Systems (ONCS) and Closed Containment Culture Systems (CCTS) to cope with extreme environmental challenges such as strong winds and large waves. Among them [37], the open net cage system is further refined into various types, with the Floating Flexible Cage (FFC) being the most widely used. In light of the significant economic losses and environmental impacts caused by the rupture of deep-sea net cages, the FFC, with its high adaptability, durability, structural diversity, and the cost-effectiveness of high-density polyethylene (HDPE) materials, ensures the stability and environmental friendliness of the structure. It has shown promising applications in many maritime areas around the world. However, in the design and operation process, the structural stability of FFC, construction access restrictions, and challenges in feeding system installation must be fully considered to ensure the long-term stability and operational efficiency of offshore marine ranch systems.

Table 2. Comparison of Advantages and Disadvantages of Various Deepwater Aquaculture Cages

Cage Type	**Advantages**	**Disadvantages**
Floating Flexible Cage	Good wave adaptability, long lifespan, low cost, diverse structures can be made	Large deformation in strong winds and waves difficult to install feeding systems
Floating Rigid Cage	Stable platform can integrate various machines	Heavy structure, high transportation costs, prone to damage in extreme conditions, high investment required
Semi-submerged Flexible Cage	Lightweight structure can reduce damage caused by fish	Requires underwater feeding systems small volume not suitable for large-scale aquaculture

Semi-submerged Rigid Cage	Long lifespan, can integrate feeding monitoring, offshore wind power systems less affected by external environment	Large and complex structure, high design difficulty, high capital investment, difficult to clean
Underwater Cage	Can be remotely controlled, unmanned operation, effectively isolated from surface storms	Poor visibility for operation, high maintenance costs
Closed Cage	Water quality replacement device can ensure ideal water quality inside the cage, isolated from external predators	High operating costs, greater environmental impact

As pivotal facilities in marine agriculture, deep-water aquaculture cages are categorized into various types based on structural design and functionality, including floating flexible cages, floating rigid cages, semi-submerged flexible cages, semi-submerged rigid cages, submerged cages, and enclosed cages. Floating flexible cages are favored for their exceptional adaptability to wave dynamics and cost-effectiveness. However, under extreme wind and wave conditions, significant deformation of the cages may occur, leading to a reduction in cage volume, which affects swimming space, increases stress on the fish, and may result in decreased growth or even mortality [41]. Additionally, this deformation poses challenges for the installation and maintenance of feeding systems [42]. In contrast, floating rigid cages offer a stable platform capable of supporting a variety of aquaculture machinery, yet their substantial weight leads to increased transportation costs, and their durability under severe marine conditions requires further enhancement, along with a significant capital outlay.

Semi-submerged flexible cages, with their lightweight construction, effectively mitigate physical damage to fish, but their design limitations preclude the deployment of underwater feeding systems and may not be suitable for large-scale aquaculture operations. Semi-submerged rigid cages are recognized for their extended lifespan and multifunctional integration capabilities [43], such as the incorporation of feeding monitoring and offshore wind power systems, despite facing challenges related to structural complexity, design intricacy, substantial capital investment, and the difficulty of cleaning and maintenance.

Submerged cages are designed to permit remote control and unmanned operation, effectively shielding them from the direct impact of surface storms, but the visibility issues during operation and relatively high maintenance costs cannot be overlooked. Closed cages maintain an optimal water environment within the enclosure through an internal water quality replacement system, providing a protective barrier against external predators. However, these cages have higher operational costs and may exert a greater environmental impact.

Finally, through an in-depth study on the microbial community structure on the surfaces of artificial fish reefs by Liu Weifeng and colleagues, the impact of additives such as biochar on microbial diversity and distribution, as well as their interactions

0with environmental factors, has been assessed [44]. This research lays a solid scientific foundation for evaluating the ecological effects of materials used in artificial fish reefs. These comprehensive strategies not only contribute to mitigating the adverse effects of artificial fish reefs on the marine environment but also offer innovative perspectives and approaches for the pursuit of sustainable marine ecological engineering.

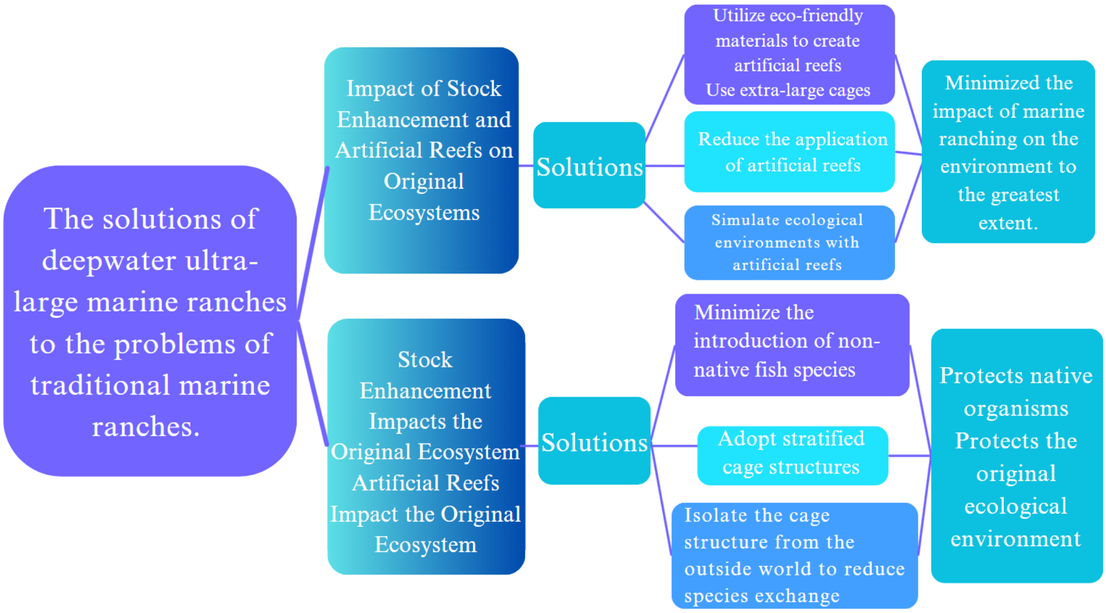

Figure.9. The solutions of deepwater ultra-large marine ranches to the problems of traditional marine ranches.

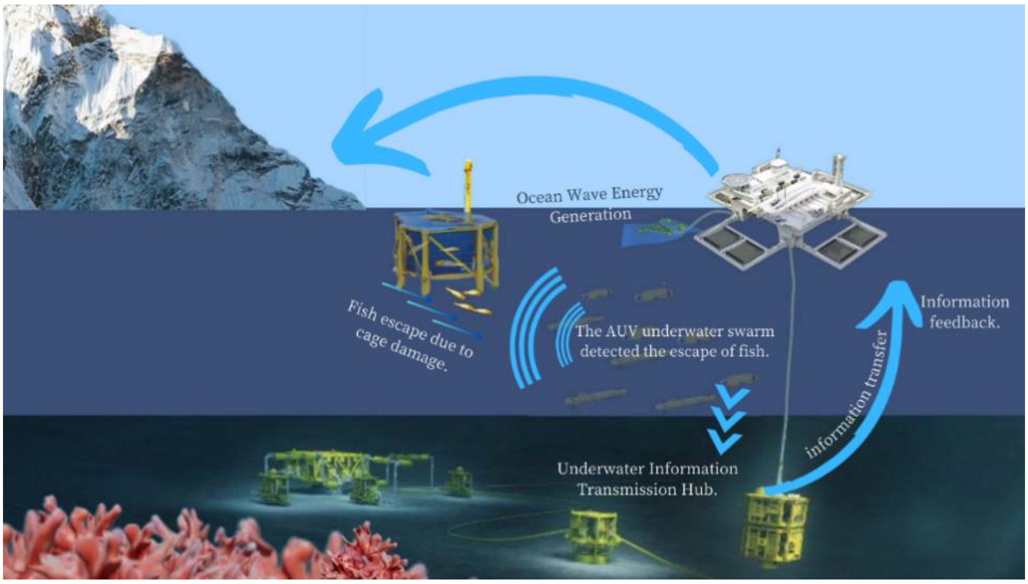

Figure.10. Utilize an underwater swarm of unmanned vessels for monitoring and management

This system represents an innovative solution for ocean monitoring and renewable energy, integrating ocean wave energy conversion technology with advanced underwater monitoring equipment. The core of the system is a device capable of capturing wave energy and converting it into electrical power, which not only provides clean energy for ocean monitoring but also reduces dependence on traditional energy sources. Underwater, a fleet of Autonomous Underwater Vehicles (AUVs) is deployed, capable of autonomous navigation and task execution, such as monitoring the marine environment and detecting anomalies [45]. In practical applications, the AUV fleet can detect fish escape events caused by damaged cages and transmit this critical information to the Underwater Information Transmission Center [46] Serving as a data hub, the Underwater Information Transmission Center collects data from the AUV fleet and sends it to the surface monitoring station through information transmission links. This design ensures real-time and accurate information, enabling rapid responses from relevant entities, such as timely repairs of damaged fish farms, thereby minimizing losses from fish escapes. Overall, this system not only demonstrates sustainable management of ocean resources but also underscores the vital role of technology in ocean conservation and energy utilization. Through this integrated solution, we can more effectively monitor and protect the marine environment while harnessing the natural power of the ocean to provide clean energy for humanity.

The introduction of Unmanned Surface Vehicle (USV) technology signifies a shift towards intelligent and automated monitoring and management in the field of marine ranching. USVs are equipped with autonomous route planning and dynamic monitoring capabilities, reducing the reliance on manual operations and significantly enhancing monitoring efficiency. Combined with intelligent warning systems, USVs can analyze collected data to predict environmental changes or biological growth issues and issue timely alerts to assist managers in taking appropriate measures [47]. In emergency situations, USVs can be rapidly deployed for on-site reconnaissance and data collection, providing real-time information for emergency decision-making. Notably, USVs employ advanced collaborative control technology and acoustic monitoring equipment, supported by the deep autonomous learning functionality proposed by Yan, C. H. [48], such as the Split Beam Scientific Echosounder (Simrad EK80), to conduct targeted monitoring of fishery resources in marine ranches. By analyzing data such as the distribution of Target Strength (TS) of fishery resources, changes in the Normalized Acoustic Scattering Coefficient (NASC), and ocean current conditions, the diurnal variation patterns of fishery resources in marine ranches are revealed. This provides data support for the dynamic management of fishery resources in marine ranches, aiding in the timely detection of fish escape phenomena and promoting the effective management and sustainable utilization of marine resources.

3.2 The environmental benefits of traditional marine ranching.

Ocean ranching, as an effective model for the development of marine resources, has profound positive impacts on the environmental protection of marine ecosystems and the promotion of biodiversity. These systems, by constructing key habitats such as artificial reefs, seaweed beds, and seagrass meadows, not only significantly enhance the ocean's carbon sequestration capacity [49], but also effectively improve the ocean's long-term carbon fixation efficiency in capturing and depositing organic carbon in seagrass beds and oyster reefs, thereby providing a rational approach to the utilization and resolution of marine blue carbon issues [39]. Furthermore, ocean ranching provides a solid foundation for increasing marine biodiversity and enhancing biomass through ecological restoration measures [49]. At the same time, management strategies such as stock enhancement further enrich marine biological communities and optimize the structure of ecological chains. The implementation of ocean ranching effectively reduces human interference and pollution in the marine area, improves water quality, suppresses eutrophication, and maintains ecological balance [50].

These measures are crucial for protecting the integrity and stability of marine ecosystems, and also provide a healthier and more diverse living environment for marine life. While pursuing economic benefits, marine ranching also emphasizes the role of ecological benefits. Through scientific management and sustainable resource utilization, it achieves a coordinated unity of ecological protection and economic development [51]. Moreover, the successful implementation of marine ranching relies on interdisciplinary research and technological innovation, which can promote the integration and development of various disciplines such as marine science, ecology, and fisheries. In addition, the environmental benefits of marine ranching are also reflected in its continuous monitoring and assessment of the marine environment. Regular monitoring of the marine ecosystem can identify and address potential environmental issues in a timely manner, ensuring that the impact of the construction and operation of marine ranches on the environment is minimized. This science-based data collection and analysis provide a solid foundation for adaptive management and decision-making in marine ranching.

Compared to traditional nearshore marine ranches, deepwater ultra-large marine ranches have achieved significant technological and managerial innovations in environmental sustainability. In terms of ecological and environmental protection technologies, deepwater ultra-large marine ranches utilize intelligent aquaculture technologies and eco-friendly high-tech, such as the underwater environmental monitoring systems and distributed energy management systems equipped in "Cultivating Sea No.1", to achieve real-time monitoring and protection of the marine environment, as well as efficient use of clean energy, promoting green and low-carbon operations. Regarding disease control and health management of the products, deepwater ultra-large marine ranches leverage 5G technology to implement remote consultations with fish disease experts, increasing the survival rate of aquaculture and reducing the occurrence of diseases. Moreover, precise feeding systems are employed to minimize feed waste [52], thereby reducing pollution to the marine environment.

Deepwater ultra-large marine ranches have achieved significant technological and managerial innovations in terms of environmental sustainability compared to traditional nearshore marine ranches. In the aspect of ecological and environmental protection technology, deepwater ultra-large marine ranches utilize intelligent aquaculture technologies and eco-friendly high-tech, such as the underwater environmental monitoring systems and distributed energy management systems equipped in "Cultivating Sea No.1" [52], to achieve real-time monitoring and protection of the marine environment, as well as efficient use of clean energy, promoting green and low-carbon operations.

In terms of disease control and health management, deepwater ultra-large marine ranches can leverage 5G technology to implement remote consultations with fish disease experts [53], reducing the incidence of diseases. In terms of resource conservation and sustainable use, deepwater ultra-large marine ranches place greater emphasis on the protection of key deep-sea ecological species, achieving self-replenishment of biological resources, and actively adopt automated monitoring and intelligent harvesting technologies to ensure the ecological safety of the marine ranch and the sustainable use of resources. At the same time, taking advantage of the distant sea area, deepwater ultra-large marine ranches can minimize their environmental impact. In contrast, nearshore marine ranches, due to excessive farming density, often lead to water quality issues such as excessive heavy metal content [54] and water acidification [55], causing ecological imbalances. Deepwater ultra-large marine ranches make full use of the high-quality water quality in the distant sea, and through more rational layout and modern technological means, effectively reduce the negative impact of farming activities on the nearshore environment. Specifically, the deep-sea area has strong self-cleaning capabilities for the aquatic environment, and the deeper water layer and vast sea area can quickly dilute and decompose the waste produced by farming, avoiding local nutrient excess. At the same time, the geographical location far from land pollution sources further reduces the risk of external pollutant input. In terms of monitoring, deepwater ultra-large marine ranches have achieved precise management of the farming environment and effective control of waste through the application of advanced technologies such as remote sensing monitoring, automatic feeding, and waste treatment, thereby ensuring the long-term stability and health of water quality. In addition, this ranch model can alleviate the farming pressure in the nearshore area, reduce the direct impact of farming pollution on the coastal ecosystem, and help protect the fragile coastal water environment and maintain marine biodiversity. Deepwater ultra-large marine ranches also have more opportunities to develop new integration models. With the advantages of water depth and area, as an important new industry model and future development direction for intensive and efficient use of the sea, deepwater ultra-large marine ranches have more opportunities to explore integration with new energy sources, such as the combination of offshore wind power and marine ranches [56].

The integration of offshore wind farm structures with marine ranching offers a new perspective on the intensive use of marine resources. Studies have shown that wind turbine foundations not only exist as physical structures in the marine environment but also have the potential to transform into artificial reefs, attracting fish aggregations and thus having a positive impact on marine ranching. This study aims to assess the impact of offshore wind farm structures on the biodiversity of adjacent marine ranches and explore their potential as artificial reefs [57]. By comparing the fish population structure and numbers before and after the construction of wind farms, combined with underwater video monitoring and sonar technology, we can quantify the impact of wind farm structures on marine biological communities. In addition, this study will also evaluate the potential impact of noise and electromagnetic fields during the operation of wind farms on the behavior of marine organisms, as well as how these factors may affect the entire ecosystem through the food chain. These findings are of great significance for optimizing the spatial layout of offshore wind farms and marine ranches, designing environmentally friendly wind farm structures, and formulating integrated management strategies.

In the study of fish community structure and its influencing factors in the waters of the offshore wind farm at the Yangtze Estuary, multivariate statistical and redundancy analysis (RDA) methods were used to analyze the composition of fish communities and their relationship with environmental factors in these waters. The study found that the abundance, biomass, richness index (D), evenness index (J'), and diversity index (H') of fish in the wind farm waters showed no significant differences ($P > 0.05$) compared to adjacent waters, indicating that the impact of the wind farm is limited [58]. This suggests that the impact of offshore wind farm structures on marine biological communities may not be as significant as expected, and their potential impact on biodiversity requires further long-term monitoring and research.

The integrated utilization model of deepwater ultra-large marine ranches is primarily reflected in several aspects: wind-fishery complementary symbiosis, multifunctional offshore wind power platforms [59], energy complementary systems, environmental monitoring and protection, waste heat utilization, integrated planning and spatial layout, offshore wind power hydrogen production [60], ecological design and construction, data sharing platforms, and the wave protection function of wind power facilities. This comprehensive utilization model not only enhances the efficiency of ocean resource use but also promotes the diversified development of the marine economy, providing innovative solutions for achieving marine ecological protection and optimizing the energy structure [61].

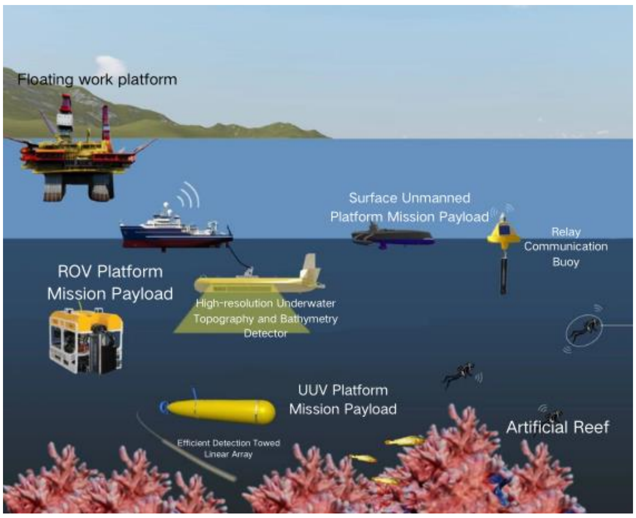

Figure.11. Ultra-large-scale Deepwater Marine Ranching Information Intelligent System Schematic Diagram.

Figure.10.illustrates a sophisticated, integrated marine monitoring and research network, where each component is meticulously coordinated and interconnected to facilitate comprehensive oceanographic data acquisition and environmental stewardship. The floating work platform serves as the central nexus, offering a stable foundation for maritime operations and potentially acting as a launch and recovery site for various equipment. Remotely operated vehicles (ROVs) and unmanned underwater vehicles (UUVs) [62], under the control of skilled operators, are equipped with specialized mission payloads to conduct underwater exploration, sampling, and surveillance. These vehicles are instrumental in gathering critical data that contributes to our understanding of the marine environment. Additionally, high-resolution underwater topography and bathymetry detectors play a pivotal role in charting the seafloor, providing essential geographical information that underpins marine research. Surface unmanned platforms, equipped with mission payloads, are utilized for surface monitoring and may also serve as carriers for relay communication buoys. These buoys are crucial for ensuring seamless data transmission among diverse devices, acting as vital links in the communication chain. The relay communication buoys significantly enhance the signal coverage and reliability of data transmission across the network.

Furthermore, the efficient detection towed linear array, towed by UUVs or vessels, is employed to probe for underwater organisms or objects, thereby expanding the depth and breadth of our monitoring capabilities. This technology allows for a more nuanced understanding of the subsurface marine environment. Artificial reefs, an integral part of the ecosystem, provide habitat for marine life and potentially synergize with the floating platform and other devices to form part of a marine ranching system. This integration promotes the sustainable use of marine resources and enhances biodiversity. Collectively, this system, through the harmonious operation of its constituent elements, achieves a holistic approach to marine environmental monitoring and management. It provides a scientific foundation and technical support for the conservation of marine ecosystems and the development of marine resources, thereby contributing to the broader goals of ocean sustainability and scientific inquiry.

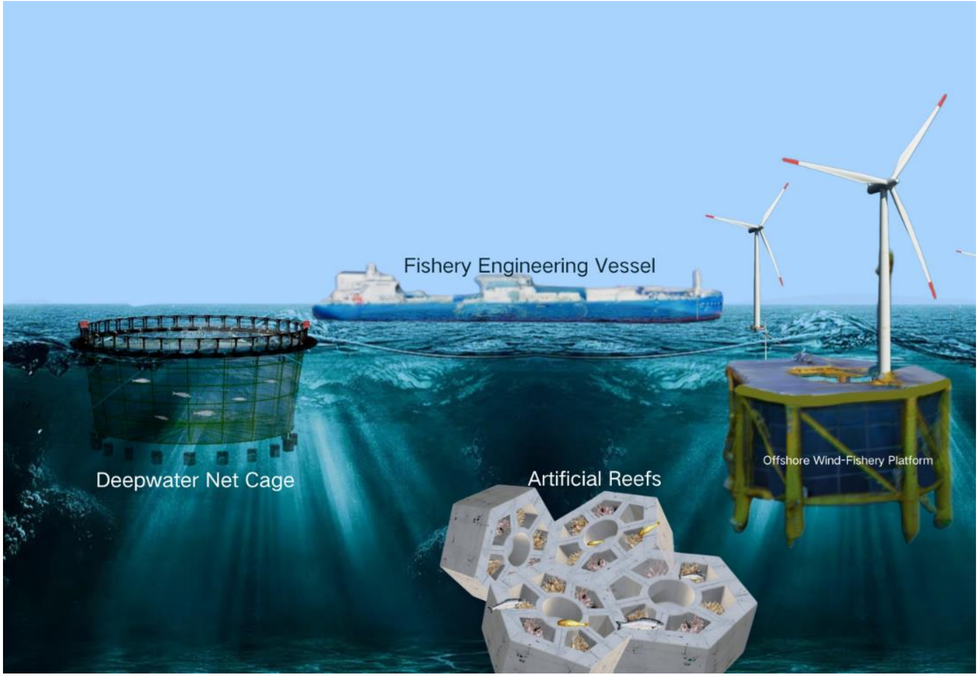

Figure.12. Offshore Floating Wind–Solar–Aquaculture System（WSA）

Figure.11.presents an innovative model for the integrated use of marine resources, where the fishery engineering vessel is utilized to support the management and development of marine fisheries. Deepwater net cages serve as aquaculture facilities in the deep sea, contributing to increased fishery yields while reducing reliance on wild fishery resources. Artificial reefs are designed as habitats on the ocean floor, intended to attract and protect marine life, promoting the recovery of coral reef ecosystems and enhancing biodiversity. The offshore wind-fishery platform integrates wind power generation with aquaculture [63]; the wind turbines generate electricity, and the space beneath the platform is used for cultivating marine organisms, achieving dual purposes of energy and food production. This model reflects the sustainable use of marine resources and the diversification of the marine economy. By combining renewable energy generation with marine aquaculture, it aims to improve the efficiency of ocean space utilization and simultaneously protect and promote the health of marine ecosystems, offering an innovative solution for marine ecological conservation and the optimization of the energy structure.

4. Technical Comparison

4.1 Monitoring Technologies of Marine Ranches.

Marine ranching, as an efficient model for the development of marine resources, has profound positive impacts on the environmental protection of marine ecosystems and the promotion of biodiversity. These systems, by constructing key habitats such as artificial reefs, seaweed beds, and seagrass meadows, not only significantly enhance the ocean's carbon sequestration capacity, but also effectively improve the ocean's long-term carbon fixation efficiency in capturing and depositing organic carbon in seagrass beds and oyster reefs, thereby enhancing the ocean's ability to sequester atmospheric carbon dioxide. The monitoring systems of marine ranches, as a comprehensive technical system that integrates modern sensing, information processing, automatic control, and intelligent decision-making, are gradually becoming a key tool for the sustainable use of fishery resources. The system, through the deep integration of various monitoring modules, not only achieves comprehensive, real-time, and accurate monitoring of the marine farming environment but also provides strong data support and technical assurance for the management, protection, and optimization of fishery resources.

Currently, the water environment monitoring sensor network in marine ranch monitoring systems serves as the cornerstone of the system, using arrays of high-precision, high-stability sensors to achieve continuous and automatic monitoring of key environmental parameters such as seawater temperature, salinity, dissolved oxygen, and pH value. The real-time collection and transmission of these data provide a scientific basis for assessing the suitability of the breeding environment, predicting biological growth trends, and warning of potential environmental risks [64].

Secondly, the introduction of underwater imaging and biological recognition systems has brought revolutionary changes to the biological monitoring of marine ranches. The system utilizes methods such as 3D coverage involving dynamic underwater wireless sensor networks [65], combined with advanced biological recognition algorithms, to achieve accurate identification and analysis of the species, quantity, growth status, and behavioral patterns of cultured organisms. Additionally, the combination of meteorological monitoring stations and satellite remote sensing technology further broadens the perspective of marine ranch monitoring. Meteorological monitoring stations provide timely and accurate early warning information for the stability of the breeding environment by monitoring meteorological elements such as wind speed, wind direction, and atmospheric pressure in real-time. Satellite remote sensing technology, with its large-scale and high-resolution advantages, achieves macro monitoring of environmental elements such as sea surface temperature, currents, and chlorophyll concentration, providing a scientific basis for regional planning and macro management of marine ranches.

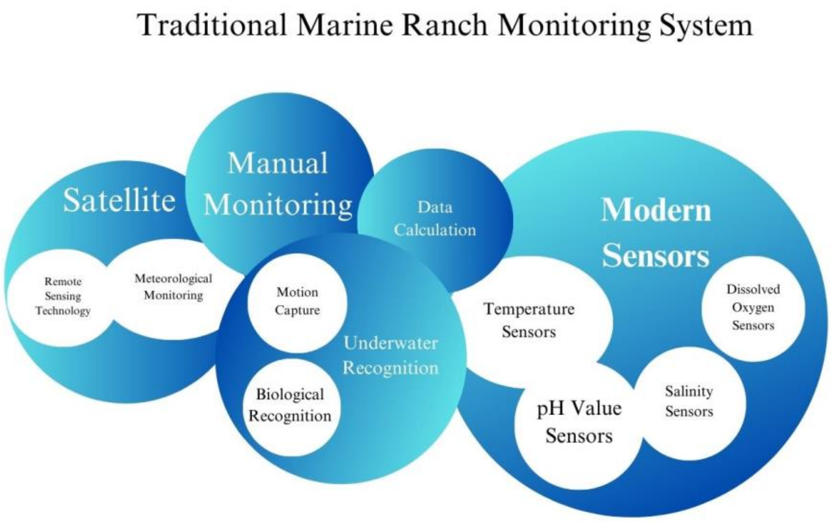

Figure.13. Traditional Marine Ranch Monitoring Systems

Finally, marine ranch monitoring systems primarily consist of various sensors, including dissolved oxygen sensors, temperature sensors, salinity sensors, pH sensors, turbidity sensors, ammonium sensors, nitrate sensors, chlorophyll sensors, current velocity and direction sensors, and water level and tidal sensors, among others. The data collected by these sensors often requires manual monitoring and calculation, which not only increases the operating costs of marine ranches but also makes the data processing procedure cumbersome and time-consuming.

4.2 Deep-water ultra-large marine ranch monitoring technology.

Deepwater ultra-large marine ranches, due to their vast scale and complex ecosystem, demand more refined monitoring and management. To meet this challenge, these types of ranches have adopted innovative technology integration solutions that closely combine the Internet of Things (IoT) with artificial intelligence (AI) and big data, creating a highly integrated monitoring network. This network, through a widely deployed array of sensors and multi-parameter monitoring systems, supported by unmanned patrol devices such as drones, unmanned boats, and underwater robots, and integrated with advanced underwater sonar monitoring technology [66], conducts multi-faceted monitoring of the deep-sea net cage group, achieving comprehensive, real-time data collection and monitoring of water quality parameters, fish behavior patterns, and overall environmental conditions, ensuring high precision of measurements and timeliness of data. At the same time, based on the collection of these key parameters, algorithms such as SSD and YOLO [67] have been further integrated, deeply integrating principles of fisheries ecology with deep learning technology, to conduct more systematic and detailed monitoring of deep-sea net cages. The system is capable of accurately analyzing the sub-health status of the marine ranch, subtle changes in the ecological environment, and the health status of the cultured organisms, achieving daily statistical analysis, trend prediction, and immediate early warning functions, significantly enhancing the scientific and foresight nature of ranch management [68].

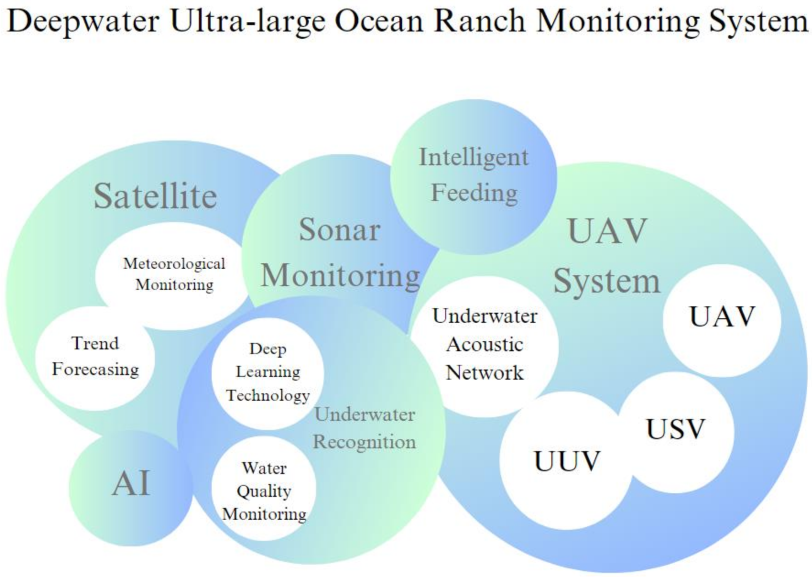

Figure.14. Deepwater Ultra-large Ocean Ranch Monitoring System

4.3 The biotechnology of marine ranching

Marine ranching biotechnology is currently undergoing a process of intelligent transformation, deeply integrating the development trends of informatization and smartization. By intensifying the tackling of key technologies, the new generation of information technology has been widely applied in the construction management, equipment facilities, and aquaculture of marine ranches, significantly enhancing their modern development quality. The integrated development model has promoted the transformation of marine ranches from a single industry to a deep integration of primary, secondary, and tertiary industries, facilitating the development of the entire industry chain and the formation of a multi-format complex. In terms of biological resource assessment, innovative technologies based on electronic and acoustic principles, such as fish finders and acoustic monitoring [69], accurately obtain information on biological populations and fishery resource conditions, providing a scientific basis for resource management and protection. Biological propagation technology, through means such as stocking, bottom sowing, and transplantation, effectively increases the number of biological resources in marine ranches, promoting the recovery and balance of the ecosystem. In addition, target species domestication control technology, combining physical and biological methods, achieves precise control of the behavior of target organisms, improving breeding efficiency and resource utilization rates. Research on the hydrodynamics of artificial fish reefs and biological materials not only ensures the scientific design of reef structures and the effectiveness of engineering implementation but also further guarantees the propagation potential and stability of biological resources in the reef area. The development of marine ranch monitoring and early warning information technology, including in situ online monitoring, three-dimensional monitoring, hydrodynamic-ecological coupling analysis, and disaster early warning, has significantly improved the informatization and intelligent level of marine ranches, providing strong support for dealing with environmental changes and disaster risks. Utilizing the accumulation of biological carbon and the transformation of natural fish reefs to create more suitable habitats for deep-water organisms. This integrated use model not only improves the efficiency of ocean resource utilization but also promotes the diversified development of the marine economy, providing innovative solutions for the realization of marine ecological protection and the optimization of the energy structure [70]. This not only promotes the efficient use of marine resources but also paves a new way for the development of green, low-carbon, and sustainable marine economy.

4.4 Marine Ranch Information Technology

Marine ranching, as an innovative model for the sustainable development of modern fisheries, is increasingly becoming a focus of research and practice due to the integration and application of information technology. The introduction of intelligent equipment, such as multi-parameter monitoring systems and smart feeding devices, has not only greatly improved the level of intelligent production in aquaculture but also optimized aquaculture efficiency and enhanced the quality of seafood products through real-time monitoring and precise regulation [71]. These devices can monitor the marine environment and the growth conditions of organisms in real-time, providing data support for ranching management and achieving precise control over the breeding environment. The construction of a marine environmental monitoring network provides marine ranches with the ability to monitor key environmental parameters such as temperature, salinity, and dissolved oxygen over the long term and in real-time. This provides a scientific basis for the early warning and prevention of ecological disasters. The establishment of this network has significantly enhanced the ecological risk management capabilities of marine ranches and improved their response speed and handling efficiency to changes in the marine ecosystem. Adequate policy and financial support provide a solid foundation for technological innovation and equipment development in marine ranches [72]. Scientific research institutions' in-depth exploration in the basic research and information equipment development of marine ranching provides theoretical support and practical guidance for technological progress and model innovation in this field. The planning and construction of marine ranches not only focus on maximizing economic benefits but also emphasize the harmonious unity of ecological and social benefits, reflecting the dual pursuit of protecting marine ecosystems and the sustainable use of fishery resources.

Overall, the current state of information technology in marine ranching demonstrates multi-dimensional characteristics such as intelligent management [73], environmental monitoring, equipment development, policy support, scientific research innovation, and a balanced emphasis on ecological and economic benefits. With the continuous advancement of technology and the ongoing optimization of the policy environment, it is expected that marine ranches will achieve a higher level of intelligence and precise management driven by information technology in the future. This will not only pave new ways for the efficient management and sustainable use of marine resources but also have a profound impact on the green transformation and high-quality development of global marine fisheries.

4.5 Cutting-edge Information Technology Applications in Ultra-large-scale Deepwater Marine Ranching

In the field of deep-water, ultra-large marine ranching, the integrated application of intelligent technology is leading the development of marine aquaculture towards more efficient and sustainable directions. Intelligent breeding platforms, represented by "Genghai No. 1," have achieved real-time monitoring and precise data analysis of the complex and variable environment in deep-water areas through the deep integration of 5G technology, significantly enhancing breeding efficiency and the ability to respond to sudden environmental changes [74]. Among them, the multi-parameter monitoring system, as one of the core components of the intelligent breeding platform, comprehensively covers the real-time monitoring of key environmental parameters such as water temperature, salinity, dissolved oxygen, and light intensity, providing data support for scientific decision-making by breeding managers. This system ensures that breeding organisms can grow in the optimal ecological environment, thereby increasing both yield and quality.

The introduction of intelligent early warning systems is particularly crucial for mitigating the potential risks of natural disasters and disease outbreaks in deep water areas. Far-sea aquaculture, which is characterized by superior water quality, faster currents, and a larger marine ecological capacity, provides a more natural environment for fish to grow in, reducing the need for medication. However, compared to coastal aquaculture, far-sea aquaculture is more susceptible to uncontrollable factors in the natural environment. In China's southeast coastal regions, where typhoons are frequent, marine farming enterprises and farmers face the constant threat of typhoons, making meteorological observation extremely important. Building on its original foundation, this system integrates meteorological forecasting models and water quality analysis algorithms to identify and issue advance warnings about potential environmental risks, providing valuable time for farms to respond promptly and effectively reducing disaster losses. Furthermore, it can be applied in aquaculture management practices, where intelligent feeding equipment is used to further enhance farming efficiency and cost control. By accurately calculating the nutritional needs and feeding amounts of aquatic organisms, it maximizes feed utilization while minimizing errors and costs associated with human intervention. Especially in deep water areas, intelligent feeding equipment demonstrates its irreplaceable advantages.

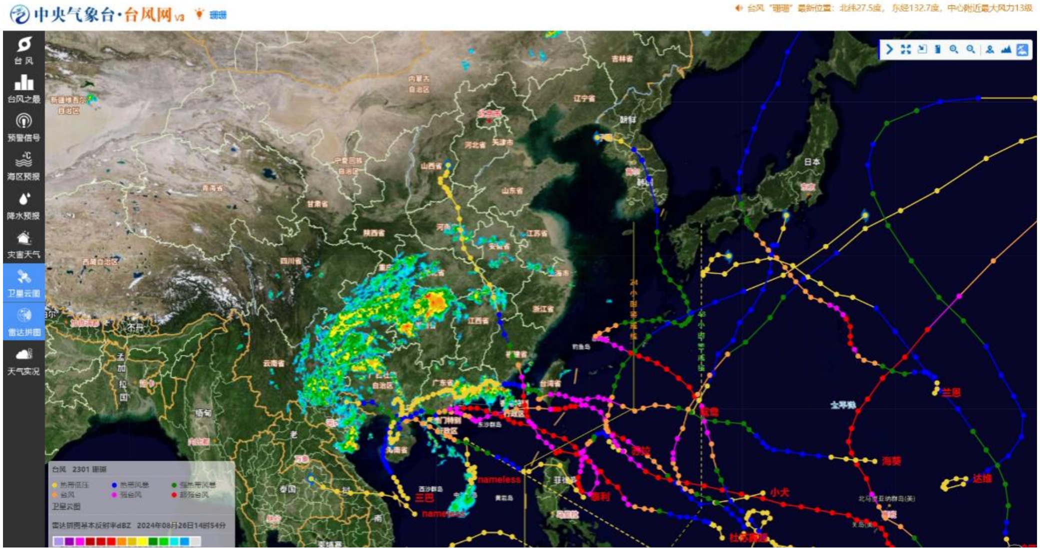

Figure.15. The typhoons that affected China in 2023.

In addition, the extensive application of unmanned cruise equipment integrated with information technology has greatly expanded the monitoring and operational scope of marine ranching. These devices can perform long-duration, high-precision monitoring tasks under harsh sea conditions, fully meeting the needs of deepwater and super-large marine ranching. The emergence of deep-sea aquaculture vessels such as "Guoxin 1" has provided a novel solution for aquaculture in deepwater areas. These aquaculture vessels boast strong wind and wave resistance capabilities, allowing them to flexibly adjust their aquaculture locations in response to environmental changes, thereby creating a more stable growth environment for aquatic organisms [38]. Meanwhile, their mobility also facilitates flexible adjustments to aquaculture activities and optimal allocation of resources.

The integration of information technology-based wind-fishery hybrid technology and enhanced gravity-style cage technology provides a green, efficient, and safe aquaculture model for super-large marine ranches in deep waters. The "Guo Neng Share" demonstration project, by integrating offshore wind power and deep-sea aquaculture technology, has shown the feasibility and efficiency of the wind-fishery integration model. This platform combines a 4-megawatt wind turbine unit with 10,000 cubic meters of aquaculture space, achieving the simultaneous development of energy production and marine biological resource exploitation [75]. At the same time, the digital platform for renewable energy enables remote monitoring and intelligent management of both wind power and aquaculture processes, enhancing the overall efficiency and sustainability of the system. This model provides innovative technological solutions for the green development of the marine economy and the efficient utilization of marine resources.

Additionally, by integrating advanced information technologies such as the Internet of Things (IoT), big data analysis, and artificial intelligence, real-time monitoring of the aquaculture environment, intelligent management, and risk warning systems are achieved, ensuring the health and safety of aquatic organisms. Furthermore, the use of blockchain technology enhances the transparency of the supply chain, while the application of virtual reality (VR) and augmented reality (AR) technologies in marine ranching offers new perspectives for education and research. This comprehensive application of technology not only optimizes aquaculture efficiency but also contributes to the sustainable development of marine ranches and the protection of marine ecosystems.

In the process of industrial transformation and upgrading of marine ranching, Artificial Intelligence (AI) technology is increasingly becoming a key support for the construction and management of marine ranches. The application fields of AI technology are extensive, including environmental monitoring, biodiversity assessment, and intelligent aquaculture management, providing a solid technical foundation for the sustainable development of marine ranches. Specifically, deep learning technology has shown significant advantages in the classification and target detection of underwater biological images [76], which not only greatly enhances the accuracy of marine biological identification but also opens up new horizons for marine ecological monitoring. At the same time, the deep integration of modern information technology and engineering equipment, such as the 'AquaGent' artificial intelligence assistant researched by Ayesha Jasmin's team [77], enables marine ranches to achieve the process optimization，mechanization，and intelligentization of aquaculture production, thereby improving breeding efficiency and product quality. Moreover, AI technology in predicting and managing natural disaster risks, as discovered by Gelian Song and his team [78], especially in aspects like typhoons, also shows great potential, helping to mitigate the impact of extreme weather on the biological communities of marine ranches. Overall, the comprehensive application of AI technology not only enhances the adaptability of marine ranches to environmental changes but also provides innovative solutions for the rational development and protection of marine resources, which is of great significance for promoting the transformation of marine fisheries towards green and low-carbon development. In the future, research and practice should further focus on the integrated application of AI technology with other advanced technologies, as well as the application effects of these technologies in diverse marine environments, in order to achieve comprehensive modernization and intelligentization of marine ranch management.

5. Conclusion

5.1 Comparison results

In terms of economic viability, traditional marine ranches in nearshore areas demonstrate a lower initial investment threshold and cost structure due to the relative simplicity of infrastructure construction and maintenance. This means less initial investment and faster payback. However, due to the limitations of resource carrying capacity and increasing environmental pressures, the future economic prospects of traditional marine ranches are not as promising as those of deepwater ultra-large marine ranches. For deepwater large-scale marine ranches, this model involves higher upfront investments, reflected in the cutting-edge technologies and facilities necessary for the deep-sea environment. Nevertheless, its exceptional capacity in resource carrying and risk resistance, along with its market revenue potential, provides a reasonable economic justification for the high investment.

In the comparison of environmental protection, traditional marine ranches have a positive impact on promoting biodiversity and the sustainability of fishery resources through ecological engineering such as artificial reef deployment and seaweed bed construction. However, the risks of ecological balance disruption and biological invasion cannot be ignored, including the potential to break natural ecological balance, cause pollutant sedimentation, reduce biodiversity, increase environmental pressure, trigger water quality deterioration, and cause physical disturbance to seabed habitats, among others. On the other hand, deepwater ultra-large marine ranches have achieved significant technological and management innovations in the application of environmental protection technology and resource utilization efficiency. For example, deepwater ultra-large marine ranches effectively promote marine biodiversity and achieve sustainable resource management through advanced ecological engineering and environmental protection technologies. Their advantages include optimizing water quality protection, reducing environmental pollution, utilizing clean energy, disease control and health management, and precise feeding, thereby reducing the impact on nearshore environments and promoting the green, low-carbon development of the marine economy.

In the field of technology, traditional marine ranching technology is based on manual monitoring and conventional management, which, while meeting basic needs, has limited efficiency and accuracy and cannot match modern standards of efficient and precise management. In contrast, deepwater ultra-large marine ranching technology has made a leap forward by integrating cutting-edge technologies such as the Internet of Things, AI, and big data analysis to build a highly automated intelligent monitoring system. This system enables real-time monitoring of multiple environmental parameters and scientific decision support, significantly improving farming efficiency and decision-making accuracy. 5G technology aids in remote fish disease diagnosis, optimizing biological health management with its high-speed, low-latency characteristics, and increasing survival rates. Blockchain technology ensures data transparency and credibility, enhancing the standardization of management and the quality assurance of market circulation, collectively promoting the transformation of marine ranching towards intelligence and efficiency. Overall, the technological advantages of deepwater ultra-large marine ranches are not only reflected in the efficient management of marine environments and biological resources but also in the deep integration and innovative application of modern information technology. This provides strong technical support for the sustainable development of the marine aquaculture industry [79].

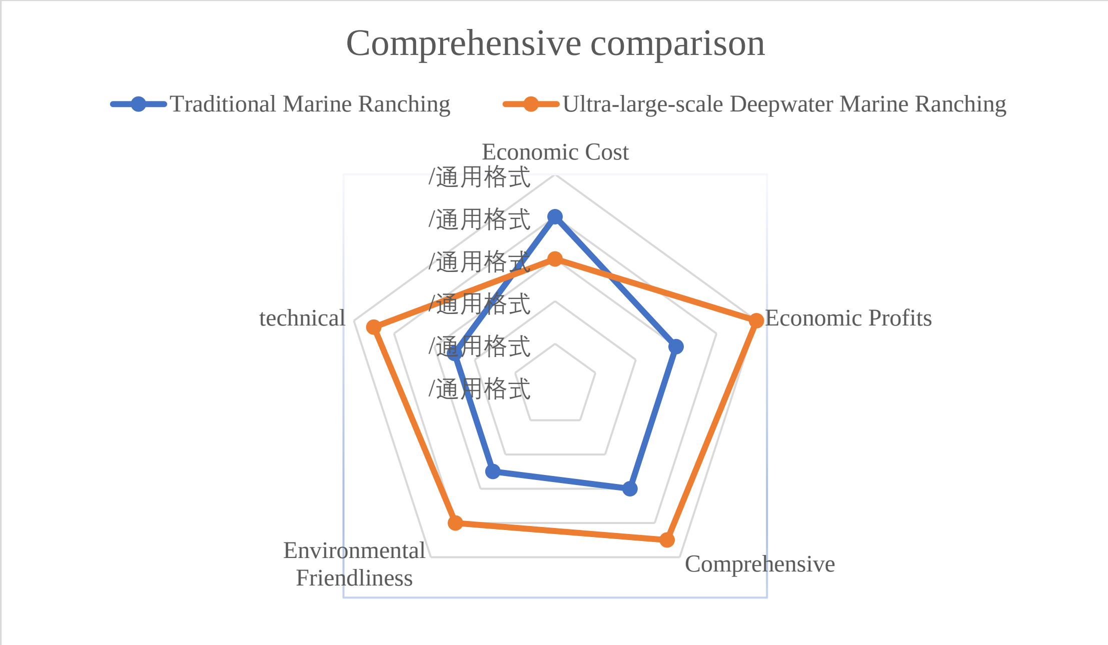

Figure.16. The comparison between traditional marine ranches and deep-water ultra-large marine ranches

The radar chart from Figure 15 compares traditional and ultra-large-scale deepwater marine ranching across key metrics. Traditional ranching scores higher on economic cost, indicating greater financial investment needs. Ultra-large-scale deepwater ranching excels in economic profits, suggesting higher earning potential due to scale and efficiency. Technically, ultra-large-scale deepwater ranching is superior, implying a need for advanced technology and expertise. Both methods score low on environmental friendliness, showing room for improvement in sustainability and ecosystem impact reduction .In overall performance, ultra-large-scale deepwater ranching has a marginal edge, possibly due to a more balanced performance across dimensions. Its strong economic profit margin suggests it could become a preferred choice for marine resource management with technological and environmental advancements.

5.2 Development Suggestions and Future Prospects

The future development of marine ranching lies in the exploration of multi-dimensional innovation. Facility integration and spatial optimization are key to enhancing the operational efficiency of marine ranching. By adopting modular design and multifunctional integration technology in the future, marine ranches will be able to achieve multiple functions such as aquaculture, monitoring, and energy production within a limited space. They will also be able to better construct a multifunctional platform in deep-water areas that integrates aquaculture and scientific research. This design strategy not only optimizes space utilization but also significantly reduces construction and operational costs. At the same time, the design of integrated facilities takes into account flexibility and scalability to adapt to the continuous evolution of the market and the continuous progress of technology.

Ecological safety and environmental protection are the cornerstones of the sustainable development of marine ranching. Future marine ranches will place greater emphasis on eco-friendly design, effectively utilizing biological waste and other by-products. Waste can be transformed into valuable resources such as biochar and oyster shell powder, promoting resource recycling and enhancing the diversity of the marine ecosystem. This approach will reduce carbon sinks and mitigate the impact on the nearshore environment, thus promoting the green, low-carbon development of the marine economy.

Looking ahead, due to the development of aquaculture in recent years, the density in nearshore areas has increased, leading to eutrophication and greater pollution. The inevitable trend is for marine farming to shift from inshore shallow waters to offshore deep waters. Companies aiming to improve farming efficiency and increase production will move towards the deep sea as the future direction. By moving towards the deep sea, the high-quality water quality can be fully utilized. Marine ranching, as a new engine to promote the transformation and upgrading of the global ocean economy, is gradually moving from theory to practice. This shift is based on a deep understanding of the sustainable use and protection of marine resources, as well as the dual drive of technological innovation and industrial upgrading. Under the guidance of technological innovation, marine ranching will achieve intelligent and precise management, using advanced technologies such as the Internet of Things, big data, and artificial intelligence to monitor water quality, marine ecology, and the growth of aquatic products in real-time, achieving precise control of the breeding environment and early warning of diseases. The application of automation and robotics will greatly improve the efficiency and safety of breeding operations, supporting large-scale and intensive development. In terms of ecological protection, marine ranching, through scientific planning and reasonable layout, constructs ecological structures such as artificial reefs and seaweed beds, enhances the diversity of marine life, and becomes an important force in the restoration and protection of the marine ecosystem. At the same time, the sustainable development model of marine ranching will guide society to pay more attention to the protection of the marine ecological environment, promoting harmonious coexistence between humans and the ocean.

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