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Economic and Environmental Aspects of *Porphyra* spp. Cultivation: Current Practices and Future Prospects

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Abstract *Porphyra* spp. Is one of the farmed seaweeds with the highest global output value and has an important impact on the coastal fishery economy and ecological environment. This study reviews the current industrial status of major porphyra producing countries, analyzes the economic value and industrial chain of porphyra cultivation, and explores the ecological and environmental impacts of cultivation activities. The results show that while the porphyra industry generates economic benefits, it can improve Marine water quality and increase carbon sequestration and carbon sinks. However, it also poses risks such as eutrophication and disease transmission. This study introduces the progress of sustainable aquaculture technologies such as eco-friendly breeding models, digital monitoring, and germplasm improvement, and discusses the promoting effects of government policies, fishermen's cooperation, and social awareness on the development of the industry. Take Fujian Province as an example to analyze the experience of sustainable development of the porphyra industry. Finally, we look forward to the future prospects and challenges of the porphyra industry under the influence of climate change and market fluctuations, and put forward comprehensive management suggestions. The results of this study provide a theoretical reference for promoting the sustainable development of the porphyra industry.

Keywords Porphyra cultivation; Economic value; Environmental impact; Sustainable technology; Policy support

1 Introduction

Porphyra,also known as seaweed, belongs to the phylum Rhododenta in classification. It was originally just a common farmed species along the Asian coast, but now it has become a globally valuable Marine agricultural product. It is cultivated on a large scale in countries such as China, Japan and South Korea. The East Asia region almost accounts for half of the world's supply of porphyra, with an annual output of several million tons (wet weight) and export footprints all over the world (Qiu et al., 2021). In the entire aquaculture system, the proportion of seaweed is not small, and porphyra has always ranked among the top in terms of economic benefits due to its high added value. Its driving effect on the coastal economy is obvious. It not only increases the income of fishermen but also becomes a foreign exchange earning industry for many countries (Show, 2020). On the other hand, the nutritional value of porphyra has also made it popular in the food market for a long time, with high levels of protein, vitamins and minerals. As Asian foods such as sushi and bento boxes go global, the international demand for porphyra is still on the rise. It is precisely for this reason that both the scientific research field and the industrial sector are now beginning to re-examine the economic significance and ecological impact of porphyra cultivation, and related research is also continuously deepening.

Porphyra has a unique life history and exists in two forms: leaf-like and shell sporophyll. The leaf-like body is a purplish red thin sheet, adhering to rocks by the seaside in autumn and winter. The shell sporophyte is a microfilament and parasitizes inside the shell in summer (Sapatinha et al., 2022). In the middle of the 20th century, scientists revealed this hidden generation of porphyra, solving the long-standing problem of artificial seedling cultivation and freeing the breeding industry from its reliance on natural seedling sources. Porphyra species are widely distributed in temperate seas around the world, especially abundant along the coasts of East Asia. In the northern coastal areas of China, the main crop of Laver is the striped laver, while the southern coastal areas are rich in the jar laver. Porphyra farms are also widespread in the coastal waters of Japan and South Korea. These

porphyra generally thrive in water temperatures ranging from 10 ° C~20 ° C. Therefore, climate and seasonal changes directly affect the cultivation cycle and geographical distribution of porphyra (Machado et al., 2020).

This study aims to comprehensively explore the current economic and environmental status and future development directions of porphyra cultivation. Through literature review and case analysis, this paper analyzes the economic output, employment and trade contribution of the porphyra industry, assesses the positive and negative impacts of its aquaculture activities on Marine ecosystems, and sorts out the technical and management measures for achieving sustainable development. At the same time, pay attention to the role of policy support and social factors in the rise and fall of industries.

2 Current Status of the Porphyra Cultivation Industry

2.1 Major porphyra producing countries and global yield distribution

Porphyra cultivation takes the coastal countries of East Asia as the core, forming a huge industrial cluster. Among them, China is currently the world's largest producer of porphyra, with an annual dry porphyra output of over 200 000 tons (equivalent to several million tons of wet weight), accounting for more than half of the global supply. South Korea ranks second in terms of porphyra production, with an annual wet weight of approximately several hundred thousand tons, and also holds a significant market share. Although the output of porphyra in Japan reached its peak in the 1990s, it has remained stable at around 200 000~300 000 tons (wet weight) per year in recent years due to factors such as Marine environment and labor force. Countries like North Korea have also developed porphyra farming, but due to the limitations of technological levels, the scale is relatively limited. Apart from China, Japan and South Korea, some Southeast Asian and European and American countries have also attempted to develop porphyra cultivation. However, the current output is relatively small, and the global market supply mainly still relies on the East Asian region. The production areas of porphyra in China are mainly distributed in coastal provinces such as Fujian, Zhejiang and Jiangsu. There are large-scale porphyra farming areas along the Ariake Sea and Setonaikai Sea in Japan, as well as in the southwestern and southern waters of South Korea (Qiu et al., 2021). Due to the high natural conditions and technical requirements for porphyra cultivation, the East Asia region, with its suitable sea areas and rich experience, will still dominate the global porphyra supply pattern in the foreseeable future.

2.2 Comparison of porphyra industries in china, japan, and south korea

China, Japan and South Korea, as major producers, each have their own characteristics in the development of the porphyra industry. After China mastered the artificial seedling cultivation technology of porphyra in the middle of the 20th century, the scale of its cultivation expanded rapidly. Provinces such as Fujian, Zhejiang and Jiangsu formed a complete industrial chain of seedling cultivation - cultivation - processing. The main breeding entities are family farmers and cooperatives, with high output and a wide variety of products. Besides supplying the domestic market, the products are also exported in large quantities overseas (Show, 2020). The Japanese seaweed industry has a long history. It implements unified management of aquaculture areas and production and sales by fishery cooperatives. The products are of excellent quality and mainly target the domestic market (Machado et al., 2020). In recent years, due to the aging of the fishing labor force and the decline in output, it is necessary to import some high-quality seaweed from South Korea to make up for it. The porphyra industry in South Korea has developed rapidly since the 1960s. By introducing new varieties and expanding the aquaculture sea areas, it has now achieved stable high yields. Most South Korean farmers entrust fresh porphyra to cooperatives or enterprises for centralized processing, creating internationally renowned porphyra brands and exporting a large number of products.

2.3 Product diversification and market trends of porphyra

With the upgrading of consumption and technological innovation, porphyra products are becoming increasingly diverse. In the past, dried seaweed slices were mainly used for sushi and soup bases. Nowadays, various seasoned ready-to-eat seaweed snacks are popular in the market, meeting the leisure consumption demands of the young generation. Porphyra fragments have also been added to foods such as biscuits and noodles to enhance Marine flavor and nutrition (Qiu et al., 2021). Porphyra is rich in active substances such as protein and polysaccharides. It

has also begun to attract attention in the fields of health food and skin care products. Some enterprises have developed porphyra extract health products. In terms of market trends, the global trend of healthy eating has made porphyra, a low-calorie and high-nutrition Marine vegetable, highly favored. The increased acceptance of seaweed products by Western consumers has driven the growth of international demand for porphyra. At present, the annual global trade volume of porphyra products has exceeded one billion US dollars.

3 Economic Value Analysis of Porphyra Cultivation

3.1 Economic output and employment contribution of the porphyra industry

The porphyra industry has made significant contributions to the coastal economy and employment. In recent years, the annual output value of China's porphyra industry has reached 10 billion yuan. In major production provinces such as Fujian and Zhejiang, it has become a pillar industry for fishermen to increase their income, directly driving tens of thousands of jobs. For instance, Xiapu in Fujian Province is renowned for its laver cultivation, and many agricultural and fishery families have been lifted out of poverty and become prosperous by relying on laver. The South Korean porphyra industry is also a major source of income from the fishery. The large-scale export of ready-to-eat seaweed has made it a star export product. Although the scale of the seaweed industry in Japan has shrunk, it still provides stable income for coastal communities due to the high added value of its products (Ji et al., 2021). Porphyra cultivation requires low investment, has a short cycle and quick returns, making it an important way for underdeveloped coastal areas to achieve economic improvement. More job opportunities have also been provided in related industries such as the processing and sales of porphyra. It is estimated that for every 10 tons of dried porphyra produced, one job can be directly created. The porphyra industry drives the secondary and tertiary industries such as processing services through the primary industry, and the indirect employment opportunities are even more considerable (Qiu et al., 2021).

3.2 Processed products and value-added industrial chains

The economic value of porphyra is not only reflected in the cultivation process but also significantly enhanced through a rich processing industrial chain. Fresh porphyra is washed, dried and pressed to make dried porphyra slices for sale as raw materials. Many cooperatives and enterprises have established processing plants to turn porphyra into a variety of products such as ready-to-eat seaweed and seaweed snacks on the spot, significantly increasing the added value. For instance, the seasoned seaweed crisps developed by South Korean enterprises have swept the world, making the brand value of porphyra far exceed that of the raw materials themselves. The scraps produced during the processing of porphyra are also fully utilized and can be used as aquatic feed additives or made into organic fertilizers to achieve resource recycling (Machado et al., 2020). More enterprises extract polysaccharides, phycobile proteins and other components from porphyra for use in health foods and cosmetics, expanding into new value-added fields. The complete porphyra industrial chain has greatly enhanced the overall economic benefits.

3.3 Export trade and international market competitiveness

porphyra has become a global trade commodity, with its main competitors coming from East Asia. With its huge output, China has been exporting a large amount of porphyra products to the world for many years and is an important supplier to the international market. In recent years, with the improvement of product quality in China, the demand for high-end laver within the country has also increased. It is worth noting that Japan has imported a large amount of porphyra from South Korea over the years, but rarely directly imported porphyra from China. This is related to factors such as product standards and trade policies (Ji et al., 2021). South Korea has stood out in the international market with its high-quality seasoned seaweed, and "Korean seaweed" has become a well-known brand, with its export volume ranking among the top in the world. Japanese seaweed is mainly supplied domestically with limited exports, but it enjoys a reputation in the high-end market for its outstanding quality. At present, the international competition in porphyra is shifting from competing in output to competing in quality and brand. Countries enhance their competitiveness by setting strict standards and building brand images. Enterprises and countries that can continuously provide safe, high-quality and distinctive porphyra products will occupy a dominant position in the international market.

4 Ecological and Environmental Impacts of Porphyra Cultivation

4.1 Positive effects of cultivation on marine ecosystems

porphyra farming has multiple positive effects on Marine ecology. On the one hand, porphyra absorbs nutrients such as nitrogen and phosphorus from seawater, which can effectively reduce the degree of eutrophication in nearshore waters and decrease the occurrence of algal blooms and red tides. On the other hand, porphyra fixes carbon dioxide through photosynthesis and has a certain "blue carbon" carbon sequestration effect (Zhao et al., 2015). Secondly, the laver farming facilities provide new habitats for Marine life. Many small fish and shrimp will avoid enemies and forage among the net structures, and the biodiversity in some local sea areas has increased, as if an artificial Marine ranch has been formed. It can be seen that under scientific management, porphyra cultivation not only does not pollute the environment, but also plays a positive role in purifying water quality, sequestering carbon and providing habitats, and is regarded as an environmentally friendly cultivation model.

4.2 Potential environmental risks: eutrophication and disease transmission

Although porphyra cultivation is environmentally friendly, improper management may still cause environmental problems. If the stocking density is too high or chemical fertilizers are applied artificially, there may be an excess of nutrients in the seawater, which may instead breed algae and lead to deterioration of water quality. If there is a large amount of seaweed residue floating and rotting after harvest, it will also increase the organic pollution load. Therefore, the scale of aquaculture must be controlled and the residual algal bodies should be cleared in time to avoid local eutrophication (Reverter et al., 2020). Another hidden danger is the prevalence of diseases. High-density single-variety cultivation is prone to induce diseases such as "red rot" in porphyra, which can spread rapidly through water flow (Figure 1), potentially leading to reduced yields or even total crop failure in large areas of cultivation. In addition, if the introduction of porphyra varieties from other places is not properly managed, it may also cause the risk of genetic hybridization or ecological invasion. In this regard, it is necessary to strengthen disease monitoring, promote disease-resistant varieties, and implement crop rotation or temporary breeding in the breeding areas to reduce the probability of epidemic occurrence (Liu et al., 2024). Under standardized management, the environmental and biosecurity risks in porphyra cultivation are completely controllable.

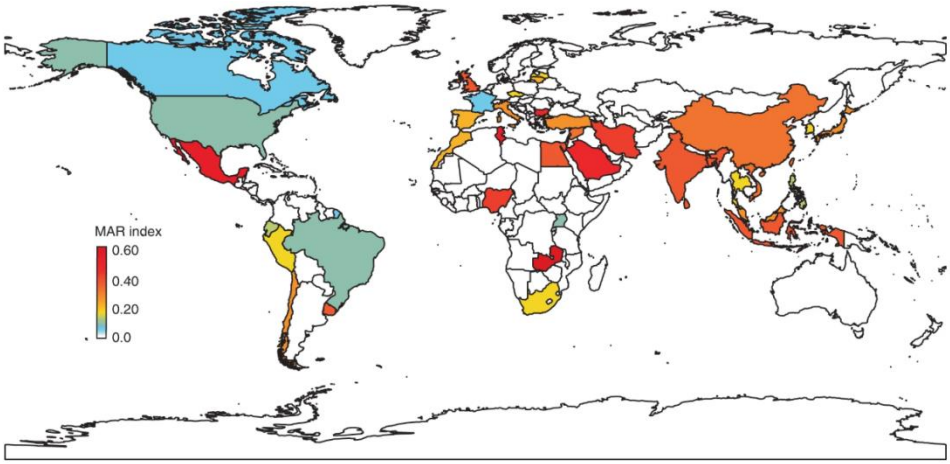

Figure 1 Global multi-antibiotic resistance (MAR) index calculated from aquaculture-derived bacteria (Adopted from Reverter et al., 2020)

4.3 Sustainable aquaculture and ecological restoration functions

Under proper management, porphyra farming can even serve as an assistant for Marine ecological restoration. Through scientific planning and layout as well as model innovation, the breeding activities themselves achieve sustainability while also having a positive impact on the environment. For instance, promoting integrated farming of porphyra with shellfish, fish, etc., enables the waste from farming to be absorbed by porphyra and the shellfish to purify the water quality, achieving the effect of "treating aquaculture with aquaculture". Appropriately expanding the aquaculture area to offshore deep water can relieve the pressure of nearshore sea use (Bricker et al., 2018). The use of degradable aquaculture materials and the implementation of a rotational fallow system also help

protect the Marine environment. Some pilot projects have also utilized the ability of porphyra to rapidly absorb nutrients to treat eutrophic waters, achieving good results (Tedesco et al., 2018). It is evident that porphyra cultivation, in its innovative practice, has achieved dual functions of production and ecological restoration.

5 Development of Sustainable Porphyra Farming Technologies

5.1 Innovations in eco-friendly cultivation models

A variety of eco-friendly model innovations have emerged in the field of porphyra cultivation. Integrated multi-trophic level aquaculture (IMTA) is a major highlight. By co-culturing shellfish and fish near the porphyra field, porphyra can absorb nutrients from the aquaculture waste, and shellfish can filter the water quality, achieving nutrient recycling and improving environmental benefits (Li et al., 2024). Another innovation is deep-water anti-wave aquaculture. By using sturdy floating rafts to set up porphyra net curtains in the offshore deep water area, far from the ecologically sensitive nearshore areas, the deep-sea water quality is better, which is conducive to high porphyra yields and reduces the occupation and impact on the coastal areas. In addition, promote the use of degradable and biomaterials to replace foam plastic floats and reduce aquaculture waste pollution (Zhao et al., 2015). Through these model innovations, the environmental footprint of porphyra cultivation has been further reduced, and the level of sustainable development has been continuously improved.

5.2 Progress in germplasm improvement and stress resistance research

The major producing countries are continuously promoting the selection and breeding of high-quality varieties of porphyra to increase production and enhance stress resistance. China has cultivated six new varieties of porphyra through techniques such as mutagenesis and hybridization (including four of the jar porphyra and two of the striped porphyra), which has extended the porphyra cultivation season in the south and increased the unit yield. Japan and South Korea have also bred porphyra varieties with better quality and stronger disease resistance for industrial improvement (Medina et al., 2022). To support breeding research, China and other countries have established laver germplasm resource banks, preserving a rich variety of strains for selection and utilization. The large-scale promotion of excellent new varieties such as high-temperature resistance and disease resistance has significantly enhanced the stable production capacity and product quality of the porphyra industry, providing support for responding to environmental changes in the future (Tham et al., 2021).

6 Social and Policy Drivers

6.1 Government policy support and industry standardization

The growth of the porphyra industry cannot be separated from the multi-faceted promotion of the government. At first, the government mainly focused on the use and management of sea areas, avoiding disorderly competition and ecological damage by designating aquaculture zones and restricting density. Subsequently, tangible support was provided in terms of finance and technology. porphyra was included in the revitalization plans for Marine economy and modern fishery, and projects such as breeding of superior varieties and upgrading of processing were funded. Farmers could also obtain loan interest subsidies and insurance subsidies. These measures significantly reduced operational risks (Parrao et al., 2021). Meanwhile, the government has gradually improved product quality standards and food safety regulations, enabling the quality and international competitiveness of porphyra to be enhanced simultaneously. Environmental protection supervision has also been emphasized: it is required to clear abandoned nets in a timely manner and monitor water quality regularly to ensure the safety of the aquaculture environment (Liu et al., 2024). With the "protection" of these policies, the porphyra industry can steadily expand in a regulated and orderly manner.

6.2 Fisher cooperatives and local economic development

Compared with the macro guidance of policies, fishermen's cooperatives are more like the "micro engines" for industrial development. Many small-scale farmers can purchase seedlings together, share processing equipment and sell products centrally by joining cooperatives, thereby enhancing their bargaining power and income (Belton et al., 2020). The experiences of Japan and South Korea show that the strict management of cooperative organizations can not only ensure product quality but also stabilize fishermen's income. In recent years, there has

also been a wave of establishing laver cooperatives along China's coast. By implementing unified technical standards, order-based purchasing and brand marketing, the quality and market recognition of laver have both been on the rise. In some places, a model of "company + cooperative + farmers" has even been developed. Enterprises sign contracts to purchase at guaranteed prices, cooperatives coordinate production, and farmers focus on farming and breeding. With the popularization of this model, the porphyra industry has shown a significant scale effect, the local economic vitality has increased, and the income of fishermen has naturally risen accordingly (Yu and Chen, 2025).

6.3 Public awareness and ecological branding

All regions are making vigorous efforts to shape the ecological brand image of porphyra and enhance its social recognition. For instance, after Fujian's "Xiapu porphyra" was granted a geographical indication, it won the trust of consumers with its pollution-free and high-protein quality, and its product price and reputation have significantly increased. It is reported that after the successful registration of the geographical indication trademark "Xiapu porphyra", the output value of local porphyra enterprises has doubled and the brand benefits have become prominent (Machado et al., 2020). The government and enterprises promote the cultural and health values of porphyra through food programs, exhibitions and other means, enabling more people to understand and recognize the porphyra industry. With consumers' preference for green and healthy food, brands such as "Organic Seaweed" have emerged. A good brand image and social support also force enterprises to strictly control quality and promote the healthy development of the industry.

7 Case Study: Sustainable Development Model of the Porphyra Industry in Fujian Province

7.1 Economic contribution and environmental management of porphyra farming in coastal Fujian

Fujian is the top province in China for porphyra cultivation, with its output accounting for a significant share of the national total. The province's porphyra cultivation area exceeds 70 000 hectares (with an output of approximately 80 000 tons in 2019, accounting for nearly one-third of the national total). Porphyra has become a pillar industry for increasing the income of coastal fishermen. All regions in Fujian attach great importance to environmental management: strictly control the density of aquaculture, regularly clean up residual algae and waste, and keep the sea areas clean. The government has strengthened the supervision of sea use and prohibited blind expansion of aquaculture scale in ecologically sensitive areas. Fishermen's environmental awareness has also been continuously enhanced, and they voluntarily participate in ecological protection activities such as mangrove planting and seedling release. By promoting both economic development and environmental protection, the porphyra industry in Fujian has achieved stable production and increased income as well as a virtuous ecological cycle (Figure 2) (Li et al., 2023).

7.2 Collaboration mechanism among government, enterprises, and research institutions

The reason why the porphyra industry in Fujian has been able to continuously innovate is due to a close collaborative relationship formed among the government, enterprises and research institutions. It is not solely the efforts of any one party. The government is responsible for building platforms and providing project funds, while universities and research institutions join hands with leading enterprises to solve front-line problems such as breeding and processing (Wang and Wang, 2025). Researchers often go to the aquaculture sites in person to guide production. This practice of "putting research into business" is not uncommon in Fujian. For instance, the Fujian Provincial Fisheries Research Institute has jointly established a laver engineering technology research and development center with local leading enterprises, achieving breakthroughs in seedling cultivation and processing. One of the results was the successful breeding of new heat-resistant varieties such as the "Shenfu" series (Waheed et al., 2023). Such cooperation has significantly enhanced the technological level of Fujian's porphyra industry and enabled it to maintain a leading position among its peers across the country.

7.3 Successful practices in sustainable cultivation and brand-oriented management

Porphyra from Fujian did not become popular overnight. The local area has long been exploring an aquaculture model that combines ecology and economy, such as co-breeding porphyra and shellfish, or regularly allowing the

sea area to "rest" to restore the environment. Such an arrangement may seem troublesome, but it makes the water quality more stable and the output more guaranteed. On the other hand, the promotion of brand building has also played a significant role. Relying on geographical indications such as "Xiapu Porphyra", the local area has implemented standardized production and strict quality inspection, making the products more recognizable. With the addition of emerging channels such as e-commerce live streaming, the reputation and price of Fujian porphyra have been rising steadily. Adhering to ecological priority and attaching importance to brand building have been proven to be the right paths. In 2009, Xiapu County was awarded the title of "Hometown of porphyra in China", an honor that seems more like an affirmation of years of efforts.

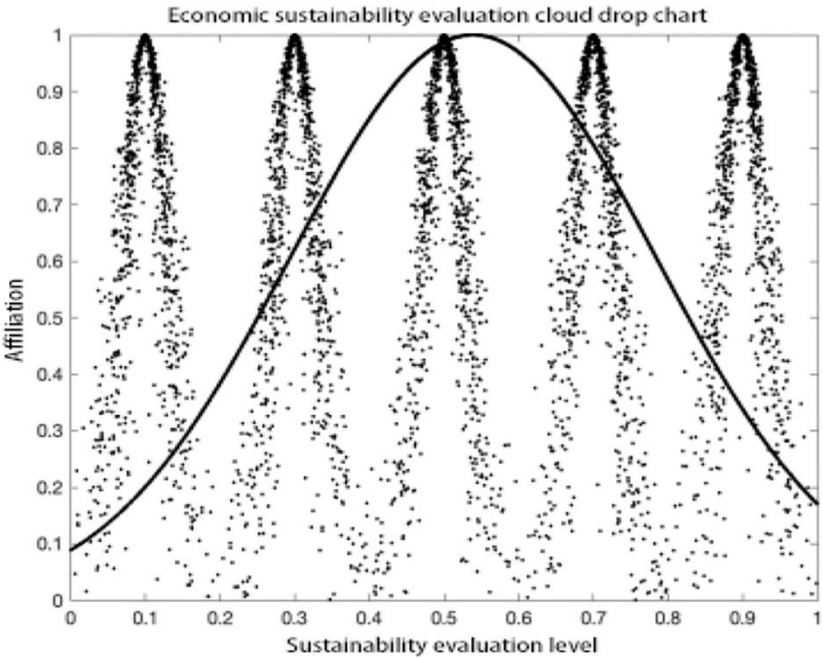

Figure 2 Economic sustainability evaluation cloud drop chart (Adopted from Li et al., 2023)

8 Future Prospects and Challenges

8.1 Potential impacts of global climate change on porphyra cultivation

The issue of global warming is no longer a "future risk" for the porphyra industry, but an immediate problem. In recent years, many aquaculture areas in the south have witnessed a significant decline in production due to warmer winters. The rise in seawater temperature has shortened the growth period of porphyra. What is more troublesome is that extreme weather conditions such as typhoons and heavy rain are becoming increasingly frequent, and it is not uncommon for facilities to be destroyed and suffer heavy losses. Abnormal water temperature and salinity can also easily cause disease outbreaks, while the slow change of ocean acidification is quietly affecting the reproduction and physiological state of porphyra (Chapot et al., 2024). However, farmers raising livestock are not helpless. Fujian, Zhejiang and other places have begun to attempt to cultivate new varieties with high temperature resistance, strengthen the breeding racks and anti-wave facilities, and adjust the seedling release and harvesting time according to climate prediction to minimize risks (Singh et al., 2023). The uncertainty of the climate may not be completely eliminated, but the wisdom to deal with it is accumulating.

8.2 Challenges of market fluctuations and industrial upgrading

The fluctuation in the price of porphyra is sometimes even more worrying than the weather. During the harvest season, supply exceeds demand and prices plummet. Once a disaster year comes, insufficient production causes prices to soar, which in turn stimulates blind expansion and makes the risks even higher. To stabilize the market, insurance and industry self-discipline are particularly important. On the other hand, the problem of labor shortage is becoming increasingly prominent. Young people are reluctant to go into business to grow seaweed, and labor costs are also on the rise. The transformation towards mechanization and intelligence is imperative. For instance,

the development of automatic harvesting and drying equipment can enhance efficiency and reduce reliance. The product structure also needs to be upgraded. It can no longer rely on low-priced raw materials, but should develop towards branding and high added value (Bo et al., 2024). Internationally, Southeast Asian countries are also accelerating their layout in porphyra cultivation, and the competition in the future will not be easy. Whether China can maintain a leading position in technology and management will determine the pattern of its porphyra industry.

8.3 Future directions and integrated management recommendations

For the porphyra industry to truly "thrive in the long term", it needs to take multiple approaches simultaneously, with policies, technologies and markets all working in coordination. Technological innovation remains key, especially the breeding of new varieties and the promotion of intelligent breeding systems, which can increase production while reducing risks. At the policy level, it is possible to consider improving disaster insurance and price control mechanisms to help farmers stabilize their income. In terms of layout, the breeding area should also be rationally planned based on the environmental carrying capacity to avoid ecological problems caused by excessive development. The market competition is fierce. Quality and brand have become new moats. Strict quality control can win the trust of consumers. At the same time, international cooperation and popular science publicity should not be ignored either, as they can expand influence and enhance public support for ecological breeding. Ecological priority, innovation-driven development, and collaborative governance, these three points may sound cliched, but only by persisting can the porphyra industry move forward steadily, increase fishermen's income, boost the coastal economy, and achieve a true win-win situation while protecting the Marine ecology.

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Conflict of Interest Disclosure

The author confirms that the study was conducted without any commercial or financial relationships and could be interpreted as a potential conflict of interest.

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