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

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Abstract This study focuses on the cultivation of *Porphyra* spp., and although its cultivation helps carbon sequestration, reduces nutrient pollution and provides prospects for circular economy applications, large-scale cultivation also brings risks such as habitat destruction and biodiversity loss. The article explores the economic and environmental significance of laver cultivation and its key role in modern aquaculture, summarizes the opportunities and challenges of laver cultivation, and shows the successful experience and difficulties of laver cultivation through several case studies. Finally, it emphasizes the importance of policy formulation, international cooperation and market access to promote the sustainable development of laver industry.

Keywords: *Porphyra* cultivation; Carbon sequestration; Nutrient pollution; Biodiversity loss; Sustainable development

1 Introduction

Laver is a *Bangiaceae* and is one of the most economically and ecologically valuable species in current marine aquaculture. Its rich nutritional content, especially carotenoids represented by lutein and zeaxanthin, makes it highly favored in the field of health foods and considered to have various health promoting effects (Pi ñ a and Contreras Porcia, 2021). With the continuous rise of environmental pressure, the cultivation technology of laver has also undergone significant evolution, including not only basic breeding methods, but also extended to breeding strategies, strain preservation, and regulation of farm ecosystems (Blouin et al., 2011). This high degree of adaptability enables it to grow stably in water bodies with large temperature differences and frequent salinity fluctuations, demonstrating its broad prospects in the field of sustainable aquaculture.

As an important marine resource, laver has developed into an industry with significant economic impact globally. It is estimated that its annual output value has reached approximately US$1.3 billion (Qiu et al., 2021). This impact is not only reflected in international trade, but is further embedded in the industrial structure of many coastal countries and regions. Taking East Asia as an example, laver is not only an important ingredient in residents' daily diet, but is also widely used in the research and development of traditional food processing and modern functional nutritional products. With the advancement of biotechnology, the application fields of laver are constantly expanding, covering functional foods, skin care products and even medicinal products, further promoting the integration and innovation of upstream and downstream industrial chains.

However, the continuous expansion of laver farming has also caused a series of ecological and environmental problems. Intensive farming may break the original ecological balance, affect local species diversity, and aggravate the risk of water pollution (Lin and Zhou, 2024). While increasing production, how to effectively reduce the interference of aquaculture on the ecosystem has become the core issue of the sustainable development of the industry. It is worth noting that in recent years, the research on the regulation mechanism of abiotic environmental factors on laver metabolism has made positive progress. For example, the impact of light intensity, salinity changes and temperature regulation on the synthesis of important active substances such as lutein is providing theoretical basis and technical support for the construction of a green and efficient production model.

This study aims to systematically sort out the current development status and future development trends of the laver industry. From multiple dimensions such as economic value, ecological role, breeding technology to sustainability strategies, it analyzes how laver, as a marine crop that combines economic potential and environmental adaptability, plays an increasingly important role in global marine resource development.

2 Cultivation Practices of *Porphyra* spp.: Current Trends

2.1 Traditional farming methods and their evolution

In East Asia, laver farming has a history of hundreds of years, and traditional farming methods originate from long-term fishery practice and ecological cognition. Early farming mainly relies on natural conditions and manual operations. Fishermen usually set up bamboo poles or hanging nets in the intertidal zone to tie the collected wild laver to it, and use the natural changes of the tide to promote its growth. Although this method is simple, it fully reflects traditional knowledge's deep understanding of marine ecological laws. With the continuous development of breeding technology, traditional methods have gradually been replaced by more controllable and efficient systematized methods. Studies have shown that the use of oyster shells as shell spore attachment substrates helps laver to obtain a stable growth environment in the early development stages, thereby improving the consistency of reproductive success rate and breeding (Knoop et al., 2019; Pattiasina et al., 2023). The promotion of modern online aquaculture technology not only improves the spatial utilization efficiency of laver planting, but also significantly improves yield and quality, making this long-standing industry show new vitality in the modern agricultural system.

2.2 Innovative aquaculture techniques for *Porphyra* spp.

The latest innovation in aquaculture technology has significantly promoted the cultivation of laver. A significant advancement is the use of satellite remote sensing to monitor and manage large-scale farming areas. In order to improve the overall accuracy of extracting laver farming areas using medium resolution HY-1C images, research has used suspended sediment concentration (SSC) as an independent variable and combined it with high-resolution Sentinel-2 satellite images to construct a new model in Haizhou Bay, China using linear regression method. The new model was compared and analyzed with traditional random forest classification algorithms and pixel binary models in seawater environments with different SSC contents. The results showed that the new model performed the best in extracting laver farming areas, with the lowest overall relative error and root mean square error in both area extraction and validation sample points among all models. In the absence of SSC variables, experiments were conducted using the same processing flow as the new model, and the results showed that SSC played a key role in the new model, particularly suitable for nearshore seawater environments such as HY-1C with high suspended sediment content in kelp images (Cheng et al., 2022). Another innovative technology involves controlling the release of spores in a laboratory environment, which has shown promising results in improving the germination and growth rate of laver. The integration of bioremediation practices, in which laver is used to remove dissolved nutrients and control harmful algal blooms, has demonstrated environmental and economic benefits (Wu et al., 2015).

2.3 Comparison of offshore and onshore cultivation systems

The cultivation methods of laver mainly include offshore cultivation and onshore cultivation, both of which have their own advantages and face different challenges. Marine aquaculture is usually set up in nearshore or offshore areas, relying on natural water flow and abundant nutrients, which is beneficial for the rapid growth and healthy development of laver colonies. China has widely applied this model, not only achieving large-scale production, but also showing positive results in bioremediation, reduction of water nutrients, and control of harmful algae (Venkatraman and Mehta, 2018). However, due to the significant fluctuations in the marine environment, aquaculture systems need to have good wind and wave resistance capabilities and robust infrastructure to cope with the impacts of extreme weather or ocean conditions (Clementel et al., 2020). In contrast, land-based aquaculture operates through closed systems such as ponds or reactors, which can accurately regulate key environmental factors such as temperature, light, and nutrients, providing more stable and optimized growth conditions for laver. In a laboratory controlled environment, researchers have successfully achieved a large release of spores and significantly improved their germination rate (Knoop et al., 2019; Pattiasina et al., 2023). However, land-based systems have relatively high resource consumption and are usually accompanied by significant initial infrastructure investment, which to some extent limits the speed of their widespread adoption and application.

3 Economic Aspects of *Porphyra* spp. Cultivation

3.1 Market demand and global trade of *Porphyra* spp. products

Laver, a very valuable marine crop with a global market value of approximately US $1.3 billion per year. The demand for Nori products is driven by its high nutritional value, including large amounts of proteins, carbohydrates and micronutrients, which lead to their wide consumption and commercialization, especially in Southeast Asia (Venkatraman and Mehta, 2018). Increasing interest in Nori cultivation in other regions (such as the Northeast Atlantic Ocean) highlights the growing global trade and market potential of these growing products (Knoop et al., 2019).

3.2 Cost analysis: Inputs, labor, and technology in cultivation

The cultivation of laver involves several cost components, including inputs, labor and technology. Inputs such as substrates (such as oyster shells) and polyethylene nylon mesh are crucial for the growth of shell spores, and in the laboratory, the nacres of pearl shells are used instead of the natural matrix. The cyspores germinate after attachment to the nacre and develop into conchocelis. The sacspores are then formed outwardly into conchosporangia and releases conchospores. Shell spores are the source of neoalgae and can be grown on polyethylene nylon web. Shell spores growing on nylon nets develop into new algae and are transferred to the natural environment to continue to grow, and the labor costs of bacteria are very high (Pattiasina et al., 2023), especially during the maintenance and harvesting stages. Technological advances, such as new web seeding techniques and controlled abiotic factors to promote lutein synthesis, can increase yield and reduce costs (Piña and Contreras-Porcia, 2021). However, the variability of culture conditions required for different species and life stages increases complexity and potential costs.

3.3 Contribution to local economies and livelihoods of coastal communities

Laver cultivation has made significant contributions to the local economy and the livelihoods of coastal communities. In areas such as Ambon Island, the cultivation of laver is favored by local communities and has the potential to meet a wider market demand, thereby providing a sustainable source of income (Kunwar et al., 2020). A large-scale aquaculture project was conducted from 2012 to 2013 in the radiation sandbar area of Jiangsu Province to study the bioremediation efficiency of China's largest scale *Porphyra yezoensis* aquaculture in removing dissolved nutrients and controlling harmful algae. Research has shown that the average nutrient concentration in laver farming areas is significantly lower than that in non farming areas, especially during the farming season ($p<0.05$). The nitrogen and phosphorus contents in laver tissue are 5.99%~0.80% and 0.16%~0.19% of dry weight, respectively. The dry weight production of laver in that year reached 58950.87 tons. Based on this, it is estimated that laver removed a total of 3 688.15 tons of nitrogen and 105.61 tons of phosphorus through harvesting. During the laver farming season, the richness index of red tide species decreased from 0.32 to 0.05. These results indicate that large-scale *Porphyra yezoensis* aquaculture can effectively alleviate eutrophication problems and control the occurrence of harmful algal blooms in open waters (Wu et al., 2015). The economic impact extends to the creation of employment opportunities and the development of related industries, such as processing and distribution.

3.4 Challenges in maintaining profitability in small-scale farming

Small-scale laver growers face many challenges in achieving sustainable profitability. One of the notable problems is the instability of cultivation conditions, with factors such as water temperature, light and nutritional status fluctuating frequently, resulting in large differences in yields and thus driving up production costs (Knoop et al., 2019). Diseases caused by *Olpidiopsis* pose a serious threat to the health of laver and, once outbreak, may cause significant yield loss and economic damage (Badis et al., 2020). To cope with these problems, small farmers urgently need to continue to invest in technology and training to improve the level of planting management, but this has also increased their originally limited financial burden. With the continued demand for laver in the domestic and foreign markets and the possibility of increasing value through processing and conversion, small-scale growers are still expected to maintain and even improve their profitability in the market.

4 Environmental Benefits and Impacts of *Porphyra* spp. Cultivation

4.1 Role in carbon sequestration and mitigating ocean acidification

Laver cultivation exhibits important ecological functions in carbon sequestration and marine acidification mitigation, especially when integrated into integrated multi-nutrient aquaculture (IMTA) systems, its role is more significant. Research in recent years has shown that the IMTA system can not only improve aquatic production efficiency, but also have ecological regulation service functions such as carbon absorption and nutrient restoration, which is of positive significance to the sustainable management of coastal ecosystems (Papageorgiou et al., 2023). In the potential IMTA model in the eastern Mediterranean, different biological combinations were used to evaluate nutrient removal effects and their impact on the environmental footprint of water and sediments, and the results showed that collaborative farming significantly reduced the nutrient enrichment pressure brought by fish farming and formed a positive regulatory effect on the carbon cycle. Chinese scholars also found in field surveys of multiple coastal laver aquaculture areas that laver and other economic lavers can buffer local seawater acidification by increasing the pH of water in the aquaculture area. Among them, the pH increase caused by kelp (*Saccharina japonica*), followed by geese (*Gracalariopsis lemaneiformis*) and Fujian laver (*Porphyra haitanensis*), indicating that there are certain differences in different laver species in relieving the pressure of the carbonic acid system (Xiao et al., 2021). In an integrated aquaculture system with the goal of carbon sequestration, laver not only locks in organic carbon through biomass accumulation, but also creates a high primary productivity environment that helps to enhance the overall system's carbon sink capacity.

4.2 Reduction of nutrient pollution in marine ecosystems

Laver farming, especially large-scale *Porphyra yezoensis* cultivation, has shown significant ecological restoration potential in marine nutrient control and harmful algae bloom inhibition. Taking the radiated sandbank sea area in Jiangsu Province as an example, studies from 2012 to 2013 showed that the concentration of dissolved nutrients in the water of the laver farming area was significantly lower than that in the non-cultivated area, and the difference was particularly significant during the breeding season ($p<0.05$), reflecting its excellent purification ability in the actual production environment (Wu et al., 2015). A total of 3688.15 tons of nitrogen and 105.61 tons of phosphorus were removed from the water by about 58,950 tons of dry weight laver, and accumulated in algae at tissue content of 5.99%~0.80% and 0.16%~0.19% respectively.

Laver farming also has a significant inhibitory effect on harmful algae species in the sea. The richness index of the red tide indicator *Skeletonema costatum* dropped from 0.32 to 0.05 during the breeding period, indicating that laver may effectively limit the expansion of harmful algae through competitive absorption of nutrients. Nori planting also has a positive effect on controlling the green tide caused by *Ulva prolifera*. Related research has constructed a coupling system combining hydrodynamics and biological growth models, successfully recreating the spatiotemporal distribution characteristics of the Yellow Sea green tide in 2012 (Sun et al., 2020). Among the divided northern, central and southern breeding areas, the northern and central regions contribute more to weakening the intensity of green tides, while the central regions are the key to affecting the accumulation of algae on the beach. In addition, adjusting the recycling time of laver facilities has also been proposed as a potential management strategy to control the scale of green tides, especially when it is more operational when facing changes in environmental factors such as temperature and nutrients.

4.3 Potential ecological risks: habitat disruption and biodiversity loss

Although laver cultivation has certain positive effects on environmental protection, such as absorbing nutrients and improving water quality, its ecological impact cannot be ignored. Large scale aquaculture often accompanies the transformation or even replacement of native habitats, which may lead to the exclusion of local animal and plant populations and changes in ecological structure. Some studies suggest that high-density cultivation of laver in specific regions is closely related to the intensification of green tide, especially the large-scale reproduction of *Ulva spp*. The outbreak of such algae not only changes the benthic environment, but may also cause local ecosystem dysfunction, and in severe cases, even trigger ecological collapse (Sun et al., 2020). Therefore, while developing the laver industry, it is necessary to strengthen the construction of ecological assessment and risk warning mechanisms. By scientifically planning the breeding density, selecting breeding areas reasonably, and establishing a dynamic monitoring system, we can protect the diversity and stability of marine ecology while increasing production.

4.4 Environmental policies and regulations affecting *Porphyra* spp. cultivation

Environmental policies and regulations play a crucial regulatory role in promoting the healthy development of the laver industry. These policies not only focus on the economic output of industries, but also emphasize the protection and coordination of marine ecosystems. Specifically, regulations may limit the scale of aquaculture, regulate the use of technical means, and develop corresponding measures to prevent habitat destruction and loss of species diversity. In recent years, China has introduced multiple management systems that clearly define the regional layout, technical standards, and environmental protection responsibilities for laver cultivation, aiming to promote industrial growth while minimizing the impact on the ecological environment (Tang et al., 2014). At the same time, the international community is increasingly emphasizing the promotion of sustainable aquaculture models. The systematic aquaculture concept represented by Integrated Multi trophic Level Aquaculture (IMTA) is widely advocated. This model achieves resource recycling and enhances ecosystem stability by co cultivating laver with species such as shellfish and fish (Papageorgiou et al., 2023).

5 Integration with Other Sustainable Practices

5.1 *Porphyra* spp. in integrated multi-trophic aquaculture (IMTA) systems

5.1.1 Ecological role of *Porphyra* spp. in IMTA systems

In the integrated multi-nutrient aquaculture (IMTA) system, laver not only has economic value, but also plays a key role in maintaining the ecological balance of water bodies. As a typical "extractive species", it can effectively absorb inorganic nutrients such as excess nitrogen and phosphorus discharged during fish and shrimp farming, thereby reducing the risk of eutrophication in water and improving overall water quality (Chopin et al., 2012; Biswas et al., 2020). The latest research shows that in the IMTA model introduced with different extraction species, the concentration of inorganic nitrogen and phosphorus in the water body is significantly reduced compared with traditional mixed-raised systems, especially in the treatment group containing aquatic vegetables and filter-feeding shellfish (such as water spinach and oysters), the content of dissolved organic carbon and suspended particulate matter also decreased significantly, showing a strong environmental purification effect. The mechanism of action of laver in the system is similar to that of aquatic plants. By absorbing excess nutrients in the water, the nutrients can be reused and provided a more suitable ecological environment for fish and shrimps. This complementarity not only optimizes the vertical utilization efficiency of the breeding space, but also promotes the coordinated growth of various breeding organisms in the system, thereby improving the output per unit area and economic benefits. It can be seen that in building an efficient and sustainable aquaculture model, the rational introduction of extracted species such as laver will not only help with efficient resource utilization, but also provide an important path for achieving environmentally friendly breeding goals.

5.1.2 Contribution of *Porphyra* spp. to water quality improvement

Integrating *Porphyra* spp. into the IMTA system significantly improves water quality by reducing nutrient load. Research shows that laver can remove large amounts of dissolved inorganic nutrients, including ammonia, nitrates and phosphates, from aquaculture wastewater. Another red macroalgae, *Agardhiella subulata*, shows high efficiency in nutrient removal, which emphasizes the potential setting of laver that has similar performance in IMTA (Li et al., 2019; Lohroff et al., 2021; Resende et al., 2021).

5.1.3 Complementary effects of *Porphyra* spp. with other cultured species in IMTA

In the integrated multi-nutritional aquaculture (IMTA) system, laver can provide additional economic benefits to the system through its own biomass output, and to a certain extent improve water quality and system stability. Co-raising practices with fish and shellfish show that laver not only helps absorb excess nutrient salts released during the breeding process, but also enhances the health level and resource utilization efficiency of the overall breeding environment. Recent joint breeding experiments on the economical echinoderm of Mediterranean, sea cucumber (*Holothuria tubelosa*) and sea urchin (*Paracentrotus lividus*), have further verified the effectiveness of this ecological synergy mechanism. In the land-based circulating water system, the two are co-cultivated and co-cultivated, and they show good growth and organic waste conversion capabilities through multiple feed ratio tests (including plant-based feeds with different fish meal contents). Among them, feed (D-20) with a fish meal content of 20% is the most significant in improving the growth rate of both. Research shows that the organic residue in the entire system is controlled within 24%, sea urchins can intake 87% of the feed and absorb 64% of the organic matter, while sea cucumbers further utilize 54% of the sea urchin feces residues. This hierarchical energy and matter transfer model effectively reduces the accumulation of organic waste and improves final output efficiency.

It can be inferred that as another low-trophic extractive species, laver may also have similar ecological and economic synergy potential in the IMTA system. It can not only further reduce the nutrient content in the water body, but also improve the resource utilization of other species in the system through a synergistic mechanism, thereby enhancing the environmental friendliness and sustainable development capabilities of the overall breeding model (Sanz-Lázaro et al., 2020; Grosso et al., 2021).

5.2 Synergies with fish and shellfish farming

Laver can be synergistically combined with fish and shellfish farming to create a more sustainable and productive aquaculture system. Farming laver together with fish such as sea bass and snapper, or shellfish such as oysters, can bring mutual benefits. laver absorbs excess nutrients from fish waste, promoting cleaner water for shellfish and promoting their growth and health. This synergistic effect not only improves the environmental sustainability of aquaculture systems, but also enhances economic feasibility by producing a variety of marketable products (Li et al., 2019; Biswas et al., 2020). Case studies compared the concentration changes of nutrients (NO_3^-, NO_2^-, and NH_4^+) in water at different time points. In the early stages of the experiment (d0 and d1), the concentration of nitrate (NO_3^-) was higher, indicating that the water was rich in nutrients. Over time, especially during the period of d2 to d4, a significant decrease in nitrate concentration can be observed, which may be related to the growth of laver and its absorption of nitrate nitrogen. Similarly, the concentration of ammonium ions (NH_4^+) also showed a decreasing trend, further supporting the role of laver as an efficient nutrient absorption carrier. The changes in nitrite (NO_2^-) are relatively small, but there are significant fluctuations at certain time points (such as d5 and d6), which may be related to the conversion dynamics during the nitrogen cycle. The letter annotations (such as a, b, A, B) at different time points in the experiment reflect significant differences, indicating that the absorption capacity of different forms of nitrogen by laver cultivation varies at different times. This absorption dynamics may be influenced by environmental conditions such as temperature, light intensity, or water flow conditions (Figure 1) (Resende et al., 2021).

5.3 Circular economy approaches in *Porphyra* spp. by-product utilization

The by-products produced during laver cultivation have the potential to be fully developed and utilized, which will help promote the development of the circular economy. These residual biomass can be converted into a variety of high value-added products such as organic fertilizers, animal feed, and even renewable bioenergy. In this way, not only the reuse of resources is achieved, but the economic benefits of the entire aquaculture system are also improved. In integrated multi-nutritional aquaculture (IMTA) systems, the introduction of halogen plants and other extracted crops has been shown to have obvious advantages in nutrient circulation and the synthesis of high-value compounds. Similarly, *Porphyra* spp. also demonstrates the potential to play a role as a key link in this system, indicating that its role in promoting a circular economy cannot be ignored (Custódio et al., 2017).

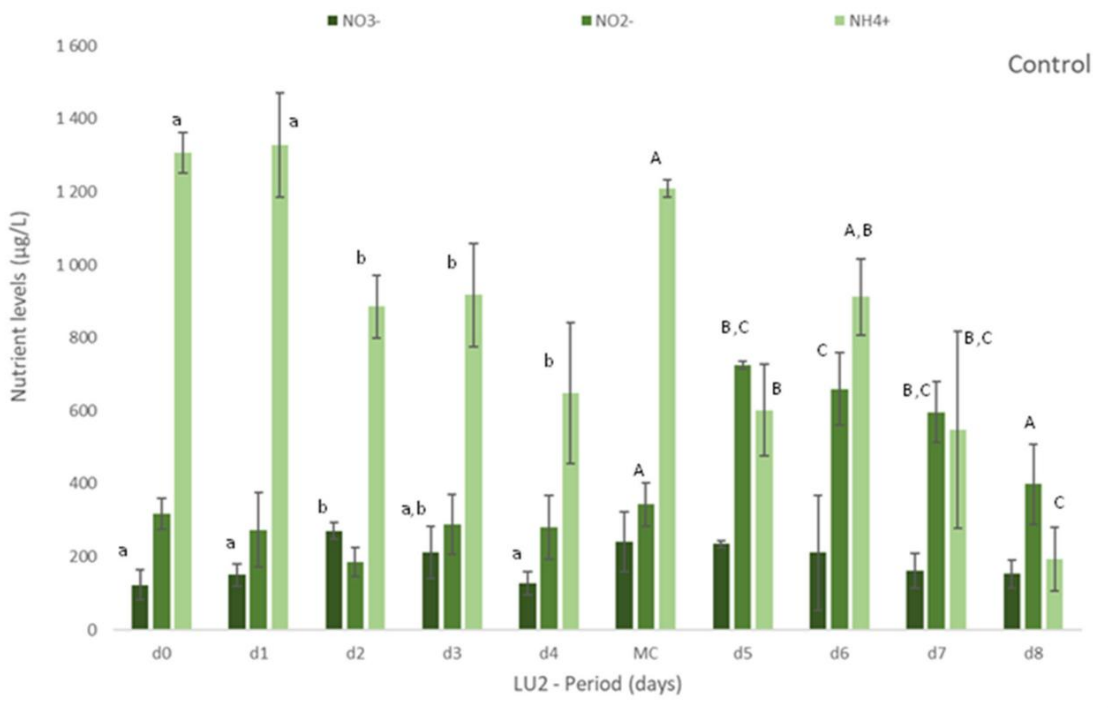

Figure 1 Nutrient levels measured in fresh fish effluent collected continuously for four days prior to experiment LU2 before medium replacement (d1, d2, d3, d4) or at the end of the experiment (d5, d6, d7, and d8), as well as in the culture media of control and Ulva species ponds (Adopted from Resende et al., 2021)

6 Case Studies of *Porphyra* spp. Cultivation

6.1 Successful implementation of *Porphyra* spp. farming in China

China has achieved significant success in the large-scale breeding of leafy laver, especially in the radial sandbank waters of Jiangsu Province. This culture has shown high biorepair efficiency, effectively removing dissolved nutrients and controlling the large reproduction of harmful algae. During the breeding season from 2012 to 2013, the nutrient concentration in the breeding area was significantly lower than that in the non-cultivated area, and the tissue nitrogen and phosphorus content of laver was greatly reduced. The yield of lepin reached 58,950.87 tons of dry weight (DW), and 3,688.15 tons of tissue nitrogen and 105.61 tons of tissue phosphorus were removed by harvesting. In addition, the richness index of the red tide species *Skeleton emacostatum* has a significant decline during the breeding season, indicating that large-scale *P. yezoensis* breeding has the potential to alleviate eutrophication and control harmful algae reproduction in the high seas (Cheng et al., 2022).

6.2 Challenges in *Porphyra* spp. farming in South Korea

In recent years, the Korean laver industry, especially cultivars mainly composed of Pyropia, has increasingly faced serious challenges caused by pathogenic microorganisms. Among them, the oomycosis fungus *Olpidiopsis* has been confirmed to be one of the important pathogens that cause red algae diseases and has caused significant losses to breeding laver in multiple sea areas (Kim et al., 2014; Badis et al., 2020). In the past, the genus was believed to have limited distribution of pathogens, but the latest research shows that its species diversity and global distribution range are far beyond expectations, and genetic markers that are highly similar to *Olpidiopsis* can be detected in algae without obvious symptoms. What is more worthy of attention is that laboratory cross-infection tests have confirmed that *O. Porphyrae* from Scotland can successfully infect the main Korean variety *Pyropia yezoensis*, while the isolated strain in South Korea can also infect the wild Bangia in Scotland. This finding suggests that laver pathogens have cross-regional transmission and host adaptability, may enter new ecosystems through international seedling circulation and pose a threat to local species. Against the backdrop of rapid global laver aquaculture expansion, lag in biosafety regulation is amplifying this risk. The lack of effective monitoring and quarantine measures will make the silent spread of pathogens such as *Olpidiopsis* a potential dual ecological and economic crisis.

6.3 Introduction of *Porphyra* spp. cultivation in non-traditional regions (e.g., Europe)

The introduction of laver cultivation in non-traditional regions such as Europe has shown promising prospects, but also faces some challenges. Experimental studies in places such as the British Isles have shown that factors such as substrate type, temperature, photoperiod, and light intensity significantly affect the growth and development of laver. During the gametophyte stage, appropriate light and temperature can promote the formation and growth of gametes, while prolonging the photoperiod further enhances growth efficiency. During the formation stage of zygotic spores, fine-tuning of environmental conditions, such as adjusting the photoperiod, can significantly improve the survival rate of zygotic spores, especially in temperate regions with variable climates. The development of dinoflagellates during the sporophyte stage usually relies on specific substrates, such as oyster shells, which provide a stable growth environment for the sporophyte. In the experiment, it was found that long sunshine and suitable temperature (18 °C) can significantly enhance the development of *Chlamydomonas reinhardtii*. As the temperature drops to 9 °C, the release of spores is triggered, but their germination rate is generally low, indicating that existing planting techniques need further improvement (Figure 2). These findings reflect *P dioica* adapts to seasonal environmental conditions in temperate regions and emphasizes the importance of optimizing these conditions for successful cultivation (Knoop et al., 2019)

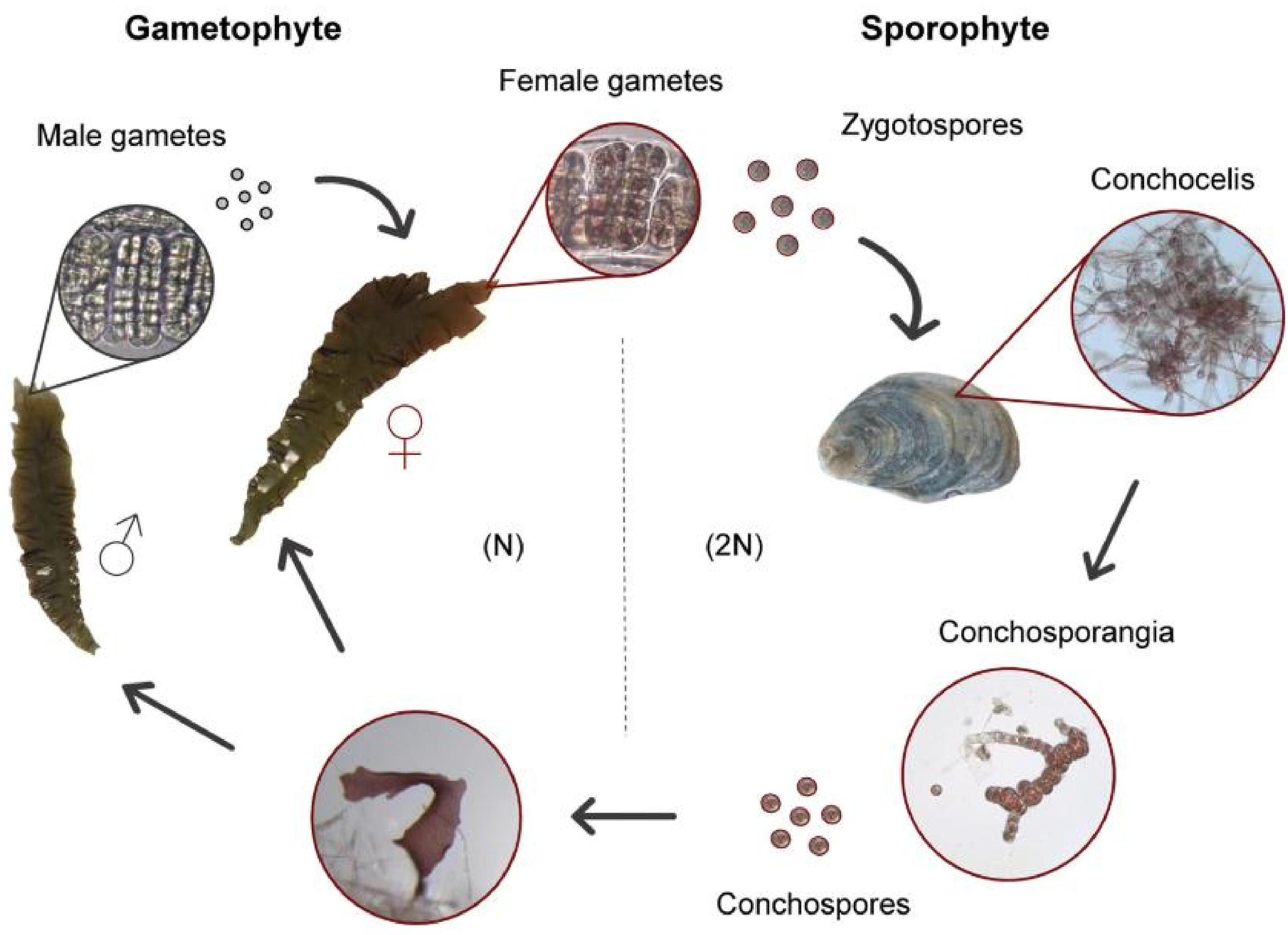

Figure 2 The sexual life cycle of laver alternates between macroscopic bacterial bodies (gametophytes) and microscopic shell spotted filamentous bodies (sporophytes) (Adopted from Knoop et al., 2019)

7 Policy and Market Recommendations for Sustainable Growth

7.1 Encouraging sustainable farming practices through subsidies and incentives

In order to promote seawater aquaculture industries such as laver toward resource conservation and environmentally friendly directions, policy design should pay more attention to systematic guidance and resource efficiency improvement. Studies have shown that in the production of laver and other laver products, although the overall resource consumption is lower than that of animal aquatic products, the fuel use required during operation and maintenance still accounts for a relatively high proportion, which has become an important factor affecting its environmental footprint. Therefore, policy formulation should start with optimizing breeding models and investment management, and guide growers to adopt low-energy consumption and low-emission breeding technologies by building targeted incentive mechanisms. Promoting efficient online broadcasting methods and encouraging the selection and breeding of laver varieties with strong resistance tone can help improve ecological adaptability and output stability. At the same time, from a macro perspective, policies should support the rational planning of marine space and the optimization of farm layout to reduce the ecological pressure brought by high-density planting. By coordinating the use of inputs and infrastructure construction, achieving resource allocation optimization from "point" to "surface" can not only significantly improve output efficiency per unit area, but also help reduce the burden on the nearshore environment (Marín et al., 2019).

7.2 Development of international standards for environmental monitoring

Establishing a unified and scientific environmental monitoring standard system is an important foundation for ensuring the sustainable development of laver aquaculture industry. Especially in the context of the coexistence of global aquaculture expansion and ecological risks, it is urgent to formulate a comprehensive monitoring framework covering dynamic changes in water nutrient concentration, habitat health status and surrounding ecological response. By clarifying key indicators, sampling methods and frequency, it can not only achieve cross-regional data comparability at the technical level, but also enhance the management's ability to predict and respond to potential ecological impacts. Studies have pointed out that under specific environmental conditions, large-scale cultivation of laver varieties such as *Porphyra yezoensis* may reduce the concentration of nutrients such as nitrogen and phosphorus in water and play a certain role in ecological restoration (Kunwar et al., 2020). However, premature harvesting or improper management may also have a counter-effect on local ecosystems, as revealed by the phenomenon that some medicinal plants have degraded habitats and endangered populations due to disorderly collection. It can be seen that systematic and long-term ecological monitoring is crucial to identify the positive and negative ecological effects brought about by laver farming. Therefore, promoting cross-border collaboration to establish a standardized environmental monitoring mechanism will not only help to timely grasp the ecological impact of aquaculture activities, but also provide a data basis for policy formulation and breeding planning, thereby achieving a win-win situation in industrial development and ecological protection.

7.3 Strengthening global trade partnerships and market accessibility

While promoting the laver industry toward sustainable development, expanding international trade channels and improving market access capabilities have become one of the key strategies. Similar to the problems of market closure and insufficient sustainability facing Indonesia in promoting the export of Porang (konjac) tuber, the laver industry also needs to systematically respond to the coordination challenges between trade barriers and sustainable development (Riptanti et al., 2022). Research shows that single-dimensional development often finds difficult to support the long-term export competitiveness of agricultural products, and it is necessary to strengthen the support system in multiple aspects of the environment, economy, society, system and technology at the same time. Promoting laver exports should start from a multi-dimensional perspective: on the one hand, by building a stable international cooperation mechanism and strengthening linkage with overseas processing enterprises, industry associations and regulatory agencies, it can promote the unity of production standards, product certification and technical specifications, and enhance the recognition of laver products in the international market; on the other hand, it is necessary to pay attention to the improvement of infrastructure and institutional guarantees, such as improving the cold chain logistics system, optimizing customs clearance procedures and streamlining the export approval process to lower the threshold for entering the international market.

7.4 Promoting awareness of the environmental and nutritional benefits of *Porphyra* spp.

Enhancing public awareness of the multiple benefits of laver can help drive market demand and create a more favorable social atmosphere for sustainable cultivation. As a marine crop that combines ecological functions and nutritional value, laver plays an important role in purifying water bodies and regulating ecosystems. It can absorb excess nutrients in water, inhibit the expansion of harmful algae, and improve the overall health level of aquaculture environments (Pattiasina et al., 2022). Moreover, laver itself is rich in protein, minerals, and various trace elements required by the human body, making it a high-quality component in many healthy dietary structures. Public education and brand promotion centered around its green, healthy, and environmentally friendly attributes can not only guide consumer preferences, but also enhance consumers' recognition and support for sustainable production. By building a consumer group with ecological awareness and nutritional knowledge, all parties in the industry chain will be more likely to form a virtuous cycle, promoting the development of laver farming towards a more environmentally friendly and resilient direction.

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The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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