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Evaluation of Sustainable Farming Models for Nori Cultivation

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Abstract As a vital marine economic seaweed in my country, *Porphyra* (nori) cultivation has expanded significantly, playing a crucial role in ensuring the supply of high-quality seaweed products and driving the development of coastal fishery economies. However, while traditional cultivation models have grown rapidly, they face challenges such as excessive stocking densities, low resource utilization efficiency, mounting environmental pressure, and accumulating ecological risks, all of which constrain the industry's sustainable development. Green cultivation models have garnered widespread attention in recent years as a key pathway for the transformation and upgrading of the *Porphyra* industry. This paper systematically reviews the theoretical foundations and technical characteristics of green *Porphyra* cultivation, focusing on the application status of typical models such as eco-friendly management, Integrated Multi-Trophic Aquaculture (IMTA), and digital intelligent cultivation. On this basis, a comprehensive evaluation indicator system-encompassing ecological, economic, and social benefits-is constructed to assess the effectiveness of green cultivation models in terms of yield and quality improvement, resource utilization optimization, environmental load reduction, and enhanced industrial competitiveness. Furthermore, using typical *Porphyra* production regions as case studies, the paper analyzes changes in ecological and economic benefits following the implementation of green cultivation technologies, summarizing experiences in their promotion and identifying existing issues. The study concludes that green cultivation models can effectively enhance the stability of cultivation systems, promote efficient resource use and ecological improvement, and achieve synergistic gains in both economic and ecological benefits. Future efforts should focus on fostering key technological innovations, refining standardized management systems, and strengthening policy support mechanisms to drive the *Porphyra* industry toward high efficiency, environmental sustainability, and long-term viability.

Keywords *Porphyra*; Green cultivation; Sustainable development; Comprehensive evaluation; Integrated multi-trophic aquaculture (IMTA); Ecological benefits

1 Intruction

Porphyra-commercially known as nori or laver-is among the most economically important cultivated seaweeds in the world, with especially strong production and consumption bases in East Asia. Modern cultivation technologies introduced since the 1960s, including artificial seeding, floating-net systems, and improved processing, enabled rapid increases in annual nori yield and helped transform *Porphyra* into a major mariculture commodity. Its market value is tied not only to production volume but also to its role as a premium edible seaweed: *Porphyra*/*Pyropia* accounts for about 8.6% of global cultivated seaweed output, and *Porphyra* species have been reported to achieve some of the highest fresh-weight values among cultivated seaweeds, reflecting their importance in food markets and aquaculture-based coastal economies (Da Silva et al., 2025).

The industry's economic significance is further reinforced by the nutritional and commercial versatility of nori. *Porphyra*, *Pyropia*, and *NeoPyropia* are widely cultivated and consumed because they combine high food value with nutraceutical potential, containing proteins, minerals, lipids, and bioactive compounds that support expanding consumer demand in both traditional and emerging markets (Da Silva et al., 2025). Historically, this value has been substantial: as early as 1992, global production reached approximately 15 billion sheets, or about 45,000 dry metric tons, with an annual value of US$1.8 billion, illustrating that nori had already developed into a high-value marine crop decades ago. Continued demand growth, together with market expansion beyond Asia, has kept nori strategically important for food supply diversification and value-added marine product development.

Despite its economic promise, traditional nori farming models face growing resource and environmental constraints that challenge long-term sustainability. Production systems are highly sensitive to environmental variability, particularly temperature, irradiance, and the availability of nitrate and dissolved inorganic carbon, all of which directly affect photosynthesis, reserve accumulation, and yield stability (Tac et al., 2025). Resource-use assessments also show that although seaweed farming is less input-intensive than many fed aquaculture systems, most impacts in *Porphyra* production are still linked to fuel use during operation and maintenance, indicating that farm design and logistics remain central sustainability concerns. In practice, traditional expansion is also limited by finite suitable farming areas, labor demands, and management constraints, factors that have contributed to stagnation in some established producing regions even as market demand continues to rise (Da Silva et al., 2025).

These pressures make the development and evaluation of green farming models an urgent research priority. Seaweed aquaculture is increasingly viewed as a nature-based production system that can contribute to food supply, climate mitigation, and eutrophication control, while avoiding some of the land and freshwater constraints that limit terrestrial agriculture (Duarte et al., 2021). For *Porphyra* specifically, cultivation can remove substantial amounts of dissolved inorganic nitrogen and phosphorus from coastal waters, showing that appropriately designed systems can generate both marketable biomass and measurable environmental services. At the same time, not all "green" models will perform equally well across ecological and economic contexts, so evaluation frameworks are needed to compare options such as low-input farming, integrated multi-trophic aquaculture, and site-optimized cultivation in terms of productivity, resilience, resource efficiency, and environmental benefit. Such evaluation is essential if nori cultivation is to move from a traditionally successful industry toward a genuinely sustainable and scalable blue-food system (Zhu et al., 2025).

2 Theoretical Basis of Green *Porphyra* Farming Models

2.1 Concepts of green aquaculture and ecological fisheries

Green *Porphyra* farming can be understood as an aquaculture model that prioritizes low external inputs, efficient nutrient use, and positive ecological functions while maintaining commercial productivity. In the broader seaweed sector, cultivation is increasingly framed as a nature-based production system because it can provide food and industrial raw materials while also contributing to carbon uptake, eutrophication mitigation, and circular bioeconomy development (Duarte et al., 2021). Ecological aquaculture extends this logic by arguing that seaweed farms should be designed to mimic the form and function of natural ecosystems and be managed as knowledge-based production systems embedded in social as well as environmental contexts (Augyte et al., 2021).

Within this framework, ecological fisheries and green aquaculture converge around the principle that farming systems should not merely reduce damage, but should actively recycle materials and generate ecosystem services. Integrated multi-trophic aquaculture is especially relevant because seaweed functions as an extractive component that assimilates dissolved nutrients released by fed species, thereby improving nutrient recycling and potentially increasing both environmental and economic performance (Lead et al., 2021; Zhu et al., 2025). For *Porphyra* cultivation specifically, this principle supports a transition from single-output farming toward ecosystem-based and restorative production models in which biomass harvest is linked to water-quality regulation and coastal ecological management.

2.2 Structure and function of the *Porphyra* farming ecosystem

The *Porphyra* farming ecosystem is structured by interactions among cultured blades, their life-history stages, surrounding water conditions, and associated microbial communities. *Porphyra* cultivation depends on a complex life cycle in which the conchocelis phase is maintained under controlled laboratory conditions before transition to blade production, making hatchery management and environmental regulation central parts of the farming system rather than auxiliary steps (García-Poza et al., 2020). Early nursery production also involves tightly managed developmental stages with controlled temperature, light, aeration, and stocking density, indicating that the farming ecosystem begins in enclosed technical environments and later expands into open-water ecological interactions (Cortez et al., 2026).

Its functional performance is governed primarily by biophysical and biogeochemical processes, especially light capture, temperature response, and nitrogen and carbon assimilation. A mechanistic model of *Porphyra* aquaculture showed that structural biomass accumulation, reserve dynamics, and blade expansion are strongly driven by temperature-adjusted carbon assimilation and nitrogen uptake, while seasonal carrying-capacity thresholds determine sustainable biomass under farming conditions (Tac et al., 2025). At the same time, farmed *Porphyra* hosts abundant and developmentally structured bacterial communities, and many associated strains show auxin-producing potential, suggesting that microbiome function may contribute to algal growth, morphogenesis, and system resilience in sustainable cultivation models (Cortez et al., 2026).

2.3 Requirements for industry transformation under sustainable development goals

Transforming the *Porphyra* industry under the Sustainable Development Goals requires moving beyond output growth toward integrated environmental, social, economic, and governance performance. Seaweed aquaculture is widely recognized as capable of contributing to food security, livelihood creation, nutrient removal, and climate-related goals, but these benefits are not automatic and depend on how production systems are regulated and scaled (Duarte et al., 2021; Spillias et al., 2022). The SDG framework is inherently cross-sectoral, so sustainable industry transformation requires alliances among producers, regulators, researchers, and communities, supported by legislation that coordinates development while protecting environmental quality and social stability (Jolly et al., 2023).

In practical terms, this transformation requires diversification, technological upgrading, adaptive governance, and value-chain development. Current research identifies species diversification, advanced cultivation technologies, digital tools, biosecurity planning, and supportive policy frameworks as necessary for sustainable seaweed sector expansion, especially where production systems remain narrow or technologically uneven. A broader industry roadmap also shows that sustainability assessment must extend beyond the conventional triple bottom line to include governance and cultural dimensions, while future growth should leverage synergies with sectors such as IMTA and offshore infrastructure to achieve economic viability without losing ecological integrity (Jueterbock et al., 2025).

3 Main Types and Technical Characteristics of Green *Porphyra* Farming Models

3.1 Ecological farming management models

Ecological farming management models for *Porphyra* emphasize low-impact production, environmental matching, and cultivation practices that align farm operation with coastal ecological processes. At the farm scale, *Porphyra* growth is strongly controlled by temperature, irradiance, and nutrient availability, and mechanistic modeling shows that carbon assimilation, nitrogen uptake, and seasonal carrying capacity are central variables for sustainable biomass management (Tac et al., 2025). This means ecological management is not simply "low input," but a strategy of regulating stocking density, harvest timing, and farm intensity to remain within environmental thresholds that support stable growth (Tac et al., 2025).

Field evidence also shows that *Porphyra* farms can provide direct ecological services when managed appropriately. Large-scale cultivation of *P. yezoensis* significantly reduced dissolved inorganic nitrogen and phosphate in open coastal waters, with reductions of 50%-94% for ammonium and 42%-67% for phosphate relative to controls, indicating strong bioremediation potential (He et al., 2008). In addition, cultivation periods were associated with elevated dissolved organic carbon and enhanced production of refractory dissolved organic matter, suggesting that ecological *Porphyra* farming can also contribute to coastal carbon sequestration functions (Wang et al., 2025).

3.2 Integrated multi-trophic aquaculture models

IMTA models incorporate *Porphyra* or other seaweeds as extractive species that recover dissolved nutrients released by fed aquaculture, converting waste into harvestable biomass. The core principle is trophic complementarity: seaweeds capture inorganic nutrients, suspension feeders use fine particulates, and deposit feeders process larger organic wastes, allowing nutrient recirculation within one farming system. Reviews of IMTA performance show that this approach can substantially retain nutrients supplied to aquaculture, with theoretical retention efficiencies of 79%-94% for nitrogen, phosphorus, and carbon, although realistic values are lower in practice because of spatial and biological constraints (Nederlof et al., 2021).

For *Porphyra*, IMTA is attractive because the genus functions as an efficient inorganic nutrient extractor while retaining commercial value as a food crop. Modeling studies indicate that macroalgal bioremediation performance depends strongly on species choice, flow regime, optical conditions, and harvest frequency, and that management can increase nutrient removal capacity by up to 25-fold. Broader reviews also note that although IMTA improves ecological balance and co-cultured species performance, long-term adoption still depends on practical issues such as seaweed selection, cultivation-area allocation, infrastructure cost, and economic evaluation rather than environmental benefit alone (Zhu et al., 2025).

3.3 Digital and intelligent green farming models

Digital and intelligent green farming models apply sensors, remote sensing, and predictive analytics to improve environmental control, crop monitoring, and harvest decisions in seaweed aquaculture. In precision aquaculture, interconnected sensors are used to monitor farm conditions and support data-driven management, and this model is increasingly framed as part of an Internet of Things architecture for sustainable aquaculture intensification. For seaweed specifically, low-power underwater devices can now log temperature, light, depth, and motion directly on cultivation structures, giving farmers continuous environmental information relevant to biomass development and farm stress (Da Silva et al., 2021).

The technical characteristic that distinguishes intelligent *Porphyra* farming is the shift from periodic manual inspection to continuous prediction and automated decision support. Drone-based multispectral monitoring has already shown that seaweed biomass and product traits can be estimated at the level of individual cultivation lines, opening a pathway toward plot-scale precision management (Nurdin et al., 2023). Likewise, IoT-based monitoring combined with physics-constrained machine learning improved biomass forecasting accuracy and can identify growth plateaus or suboptimal conditions early enough to support better harvest timing and operational adjustment (Kunapinun et al., 2024).

4 Construction of an Evaluation Indicator System for Green *Porphyra* Farming Models

4.1 Indicators for ecological and environmental benefits

Ecological and environmental indicators should measure whether *Porphyra* farming improves coastal ecosystem quality while remaining within ecological carrying capacity. In seaweed aquaculture, carrying capacity is a core concept under the Ecosystem Approach to Aquaculture because it defines the upper production limit that does not compromise ecosystem functioning, and indicator systems therefore need to track water quality, benthic effects, cultured-organism health, food-web interactions, and resource use. For green *Porphyra* models, these dimensions can be operationalized through indicators such as dissolved inorganic nitrogen and phosphorus removal, dissolved oxygen change, water transparency, sediment condition, and stocking density relative to site capacity.

Nutrient removal and carbon-related services are especially important because they capture the distinctive ecological value of seaweed farming. Large-scale seaweed aquaculture in China removed about 75,563 t of nitrogen and 9,592 t of phosphate, while also sequestering 539,555 t of carbon and absorbing 1,980,167 t of CO2, showing that nutrient extraction and carbon regulation are quantifiable environmental outputs. For *Porphyra* specifically, cultivation significantly lowered coastal nutrient concentrations and also enhanced refractory dissolved organic matter production, supporting the inclusion of nitrogen and phosphorus uptake, carbon sequestration potential, and water-column organic carbon dynamics as key indicators (Wang et al., 2025).

4.2 Indicators for economic benefits

Economic indicators should assess whether green *Porphyra* farming models can convert environmental performance into stable commercial returns. At the production level, yield, biomass quality, product standardization, and output reliability are essential because seaweed productivity and quality vary strongly with site conditions, cultivation method, and stock characteristics (Rimmer et al., 2021). Controlled land-based cultivation also shows that high-quality and standardized biomass can be produced efficiently when systems allow traceability and optimal expression of genetic potential, so evaluation should include premium-quality rate, processing suitability, and price realization as well as simple biomass output.

Profitability indicators should also capture cost structure, market resilience, and the ability to benefit from diversified value chains. Seaweed farming can become profitable when biomass sales are counted, but profitability is constrained by labor costs, annual biomass variation, immature supply chains, and limited access to space, so net profit margin, benefit-cost ratio, labor productivity, and market-channel diversity are all relevant metrics (Hasselström et al., 2020). Because continued growth depends on rising demand, output diversification, and in some settings compensation for environmental services, a complete indicator system should also include value-added product share, demand stability, and access to policy support or ecosystem-service payments.

4.3 Indicators for social benefits and industrial sustainability

Social-benefit indicators should measure how green *Porphyra* farming contributes to livelihoods, community resilience, and broader sustainable-development goals. Expert and policy-oriented assessments show that seaweed farming can support food security, decent work, economic growth, sustainable production, and multiple other SDGs, but these benefits depend on effective regulation and mitigation of negative trade-offs (Spillias et al., 2022). For this reason, social evaluation should include employment creation, household income support, participation of smallholders, contribution to local food systems, and alignment with public sustainability goals (Hossain et al., 2021).

Industrial sustainability indicators should then evaluate whether the *Porphyra* sector can remain competitive and adaptive over time. Long-term sustainability depends on improved and more consistent farm productivity, better product quality, technical support services, and diversification of value chains to reduce vulnerability to price fluctuations (Rimmer et al., 2021). Industry transformation also requires supportive governance, strategic planning, and robust value-chain coordination, so indicators such as technical extension coverage, innovation adoption, supply-chain maturity, marketing capacity, and policy support should be incorporated alongside ecological and economic measures (Yong et al., 2024).

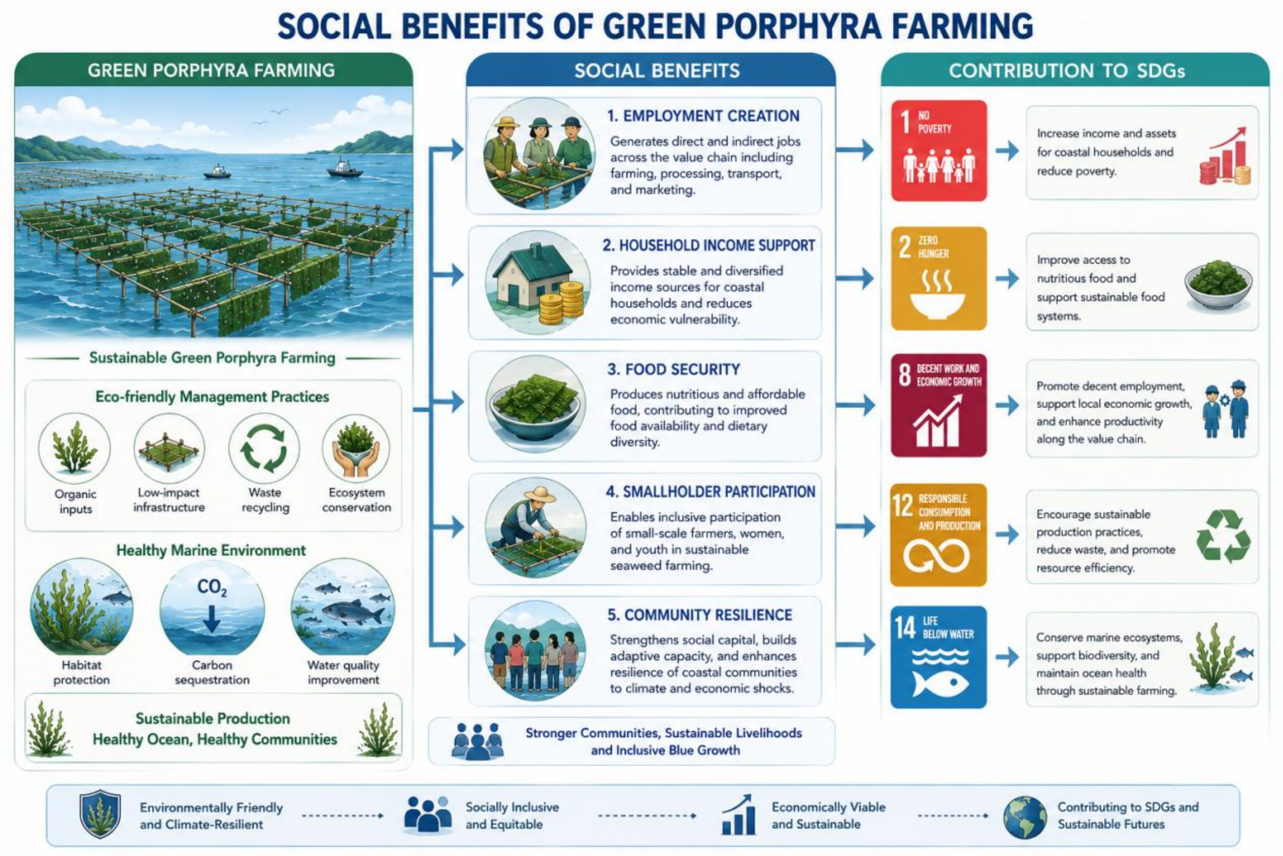

Figure 1 Conceptual pathways linking green *Porphyra* farming to social sustainability outcomes and sustainable development goals (SDGs)

5 Evaluation of the Application Effects of Green *Porphyra* Farming Models

5.1 Impact on farming yield and product quality

Green *Porphyra* farming models tend to improve yield stability by aligning cultivation intensity and harvest timing with environmental conditions that control growth. Field-based and mechanistic evidence shows that *Porphyra* biomass accumulation is strongly shaped by temperature, nutrient availability, irradiance, and stage-specific growth dynamics, so management that responds to these variables is better positioned to sustain production across the culture cycle (Lin et al., 2025). This effect is practical rather than theoretical, because seasonal thresholds for sustainable biomass and growth have already been identified in cultivation models, allowing managers to reduce overstocking and better match harvest schedules to peak biomass formation (Lin et al., 2025).

Product quality also appears to benefit when green models reduce environmental stress and improve farm management precision. In the Maine case, organically certified nori was successfully produced and marketed, showing that environmentally oriented production can support differentiated, higher-value product pathways. At the same time, unstable site conditions, disease, farming inexperience, and drought-related nitrogen depletion caused inconsistent production, indicating that green production only supports quality advantages when site selection and environmental management are robust.

5.2 Impact on resource utilization efficiency and environmental load

Green *Porphyra* farming models improve resource utilization efficiency mainly through nutrient recovery and ecosystem-based purification. Large-scale *P. yezoensis* cultivation in Jiangsu significantly reduced ambient inorganic nutrient concentrations, with ammonium, nitrite, nitrate, and phosphate all lower in the cultivation season than in non-cultivation periods, confirming that the crop efficiently converts dissolved nutrients into harvestable biomass (He et al., 2008). Harvested biomass also removed substantial amounts of nitrogen and phosphorus from the water, directly linking production output to nutrient extraction rather than to feed or fertilizer input (He et al., 2008).

These environmental gains extend beyond nutrient removal to broader reductions in coastal environmental load. At the national scale, seaweed aquaculture in China removed 75,563 t of nitrogen and 9,592 t of phosphate from coastal waters in 2015, while also sequestering carbon and reducing the need for chemical fertilizers and pesticides compared with land-based vegetable production. *Porphyra* cultivation also appears to support carbon-focused resource efficiency, because cultivation zones showed higher dissolved organic carbon and a 169% higher estuarine addition of microbially sourced humic-like C3 during the farming period, consistent with enhanced transformation of organic matter into more refractory carbon pools (Wang et al., 2025).

5.3 Impact on farming profitability and industrial competitiveness

Green *Porphyra* farming models can strengthen profitability when environmental services are translated into lower input intensity, improved market positioning, or greater resilience. Resource-use analysis in southeastern China found that *Porphyra* production had a mean exergy demand of 0.98 GJ eq. per live-weight ton, much lower than major animal mariculture products, suggesting an inherent efficiency advantage that can support competitive production if farm operations and fuel use are well managed. However, 83%-99% of seaweed-production impacts were linked to fuel used in operation and maintenance, so green competitiveness depends heavily on farm design, logistics, and spatial planning rather than on biology alone.

Industrial competitiveness also improves when green *Porphyra* farming is embedded in broader blue-economy value creation. China's seaweed cultivation has been framed as a sustainable mariculture model with ecological and economic benefits, including major contributions to carbon sequestration and blue-carbon development, which can expand the industry's strategic value beyond food production alone (Wang et al., 2025). Even so, evidence remains mixed on how easily environmental benefits convert into farm-level profits, because regional water quality, species selection, and management intensity still require spatial adjustment, and poorly matched farming layouts can reduce both ecological and economic performance.

6 Case Study: Application of a Sustainable Nori Farming Model

6.1 Overview of the case study area and farming model design

The case study area can be framed as a nutrient-influenced coastal zone suitable for *Porphyra*/*Pyropia* cultivation, with model design guided by the dual goals of biomass production and environmental service delivery. Seaweed aquaculture is already recognized as a large and growing component of global mariculture, and it is increasingly valued for climate mitigation, eutrophication control, and broader circular-bioeconomy functions (Duarte et al., 2021). For nori specifically, site suitability depends strongly on temperature, irradiance, and nutrient availability, because these drivers regulate photosynthesis, reserve accumulation, and final yield under field conditions.

Accordingly, the farming model was designed as a seasonal, ecosystem-based production system that combines offshore or nearshore cultivation with controlled nursery support and adaptive capacity limits. Early-stage *Porphyra* production is commonly stabilized in indoor nurseries where stocking density, temperature, light, and aeration are controlled before scale-up (Cortez et al., 2026). At the farm scale, sustainable layout also requires matching cultivation density to environmental carrying capacity and using scenario-based planning tools that can forecast biomass performance under changing field conditions (Tac et al., 2025).

6.2 Implementation of sustainable farming techniques and management measures

Implementation centered on three linked measures: controlled seedling production, nutrient-efficient cultivation, and integrated environmental management. Nori cultivation is inherently challenging because of its heteromorphic life cycle, so reliable hatchery control over the conchocelis, spore, and young blade stages is essential for stable commercial output (Cortez et al., 2026). Where full conchocelis control is difficult, simplified propagation pathways such as neutral-spore-based culture can reduce technical barriers and support low-cost local expansion of *Pyropia* farming.

Field management emphasized water-quality regulation, spacing, and timing in order to maximize nutrient uptake while limiting stress and crop quality loss. Large-scale *Porphyra* cultivation in open coastal waters has been shown to reduce dissolved inorganic nitrogen and phosphorus substantially, with reported reductions of 50%-94% for ammonium and 42%-67% for phosphate relative to controls (He et al., 2008). Because farming outcomes are highly site-specific, operational practices such as net depth, seeding timing, and periodic exposure or other anti-fouling measures must be adjusted to local current, light, temperature, and water-quality regimes rather than transferred unchanged across sites.

6.3 Analysis of application results and summary of experience

The application results indicate that a sustainable nori farming model can generate both production and ecological gains when cultivation intensity is aligned with local environmental conditions. *Porphyra* farming can function as an extractive component in integrated multi-trophic aquaculture, recycling excess nutrients and improving the environmental performance of aquaculture sites while adding total biomass value. More broadly, seaweed cultivation in China has been estimated to remove large nutrient loads and sequester substantial carbon, although the magnitude of benefits depends on spatial management and local water quality.

The main lessons from the case study are that sustainable nori farming depends on adaptive site selection, biological risk management, and realistic economic planning rather than on yield maximization alone. Long-term resilience requires attention to disease, pests, governance, and climate-related stressors, because short-term success can be undermined if environmental and operational risks are underestimated (Zhu et al., 2025). It also requires protecting genetic resources and avoiding overly narrow cultivation bases, since reduced diversity and unmanaged farm-wild interactions can weaken resilience over time (Brakel et al., 2021).

7 Challenges in Promoting Green *Porphyra* Farming Models

7.1 Insufficient technology integration and standardization

A central constraint on promoting green *Porphyra* farming models is that many enabling technologies remain fragmented rather than integrated into standardized production systems. Reviews of seaweed aquaculture show that sustainable expansion depends on combining site selection, cultivation engineering, environmental monitoring, breeding, and biosecurity into coherent farm-management frameworks, yet current development is still characterized by uneven technical adoption and unresolved operational bottlenecks (Khan et al., 2024). This fragmentation is especially important for *Porphyra*, because cultivation performance depends on jointly managing environmental variability, seasonal growth dynamics, and infrastructure design rather than optimizing any single component in isolation (Sen et al., 2025).

Standardization is also limited by the diversity of cultivation environments and control methods used across farms. For *NeoPyropia*/*Pyropia* culture, fixed-pole, floating, and semi-floating raft methods are all used, while epiphyte control can rely on desiccation or pH treatment, indicating that operational practices remain heterogeneous and not yet fully harmonized into common green-production standards (García-Poza et al., 2020). More broadly, seaweed farming studies stress that economically and ecologically sustainable production requires state-of-the-art but practical methods, along with country-specific standards and monitoring protocols, which suggests that green *Porphyra* farming still lacks sufficiently unified technical norms for large-scale replication (Khan et al., 2024).

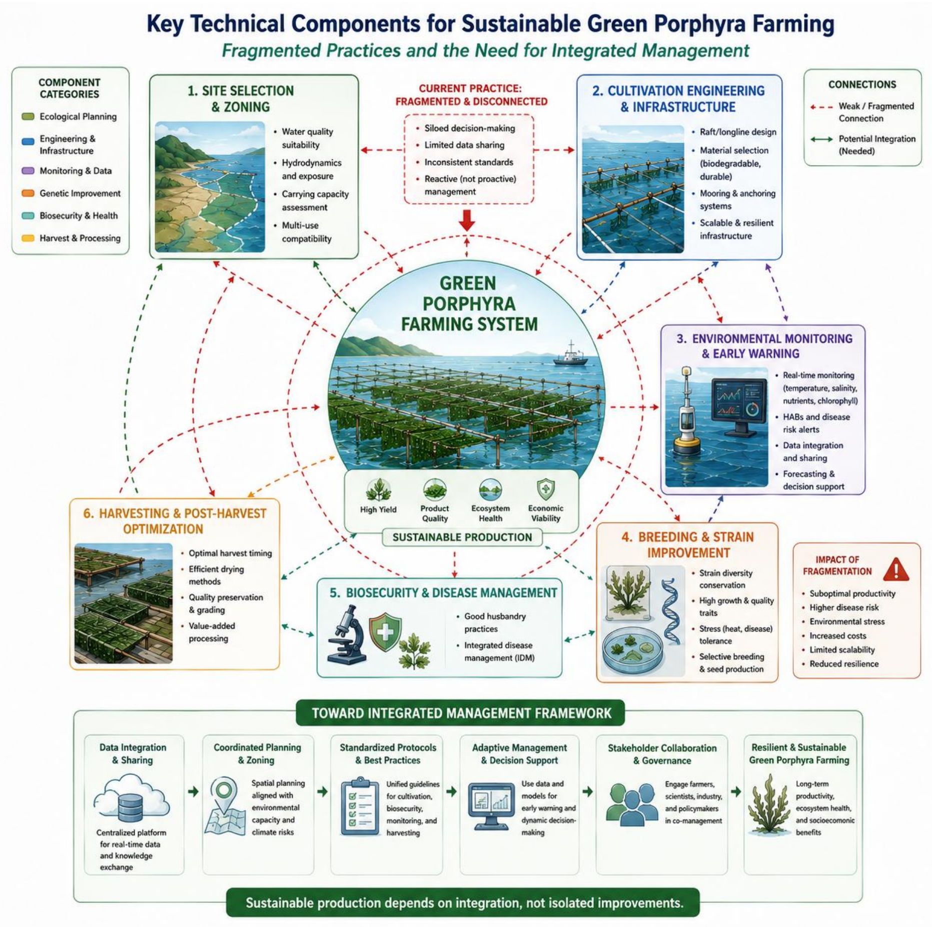

Figure 2 Conceptual framework illustrating the fragmented technological components involved in green *Porphyra* farming systems

7.2 Disparities in awareness and management capabilities among farming entities

A second challenge is the uneven awareness, technical knowledge, and management capacity among different farming entities. Evidence from broader seaweed aquaculture shows that farmers need access to educational programs, technical support, and affordable planting materials and equipment to manage threats and production risks effectively, implying that green transitions are constrained where training and extension systems are weak (Khan et al., 2024). This matters because the sustainable development of aquaculture increasingly depends on integrating technical, environmental, and governance knowledge, yet progress is uneven across producer groups and regions (Mair et al., 2023).

Capability gaps also appear in the ability to respond to biotic and abiotic stressors. Seaweed yield is highly sensitive to temperature, salinity, light, nutrient availability, pests, and disease, so farms with weaker monitoring and management capacity are less able to maintain stable output under changing conditions (Khan et al., 2024). Reviews further emphasize that careful site selection, development of disease-resistant strains, and improved mitigation strategies are essential for overcoming these pressures, which means disparities in management competence directly translate into disparities in green-farming performance (Khan et al., 2024).

7.3 Need for improvement in market mechanisms and policy support systems

Green *Porphyra* farming also faces a structural challenge in that market mechanisms often do not fully reward ecological performance. Seaweed aquaculture delivers ecosystem services such as climate mitigation, eutrophication control, and circular-bioeconomy benefits, but these benefits do not automatically translate into farm-level returns unless value chains, product markets, and institutional incentives are aligned (Duarte et al., 2021). Even when seaweed farming is environmentally cost-effective, long-term industry growth still requires rising demand, output diversification, and some form of compensation or policy recognition for nutrient-removal services (Khan et al., 2024).

Policy support systems also remain incomplete relative to the scale of transformation required. Efficiency analyses of China's seaweed sector indicate that green development has improved, but significant regional disparities persist and future progress depends on technology innovation, structural optimization, carbon-sink trading policy, and specialized talent development (Le and Wei, 2023). At the global level, sustainable aquaculture roadmaps similarly stress stronger governance, regulatory frameworks, research investment, and planning integration, indicating that green *Porphyra* farming will advance fastest where market design and public policy evolve together rather than separately (Mair et al., 2023).

8 Conclusions and Future Outlook

Overall, green *Porphyra* farming models have shown clear application value because they combine biomass production with measurable ecological services. Open-sea cultivation of *P. yezoensis* significantly reduced dissolved inorganic nitrogen and phosphorus, demonstrating that nori farming can function as an effective bioremediation system in eutrophic coastal waters. At the broader seaweed-aquaculture level, seaweed farming is recognized as a nature-based pathway for climate mitigation, eutrophication control, and circular bioeconomy development, which reinforces the strategic value of green *Porphyra* models beyond simple yield enhancement.

The effectiveness of these models is also reflected in their contribution to carbon-related ecosystem functions, although the strength of evidence differs by mechanism. Recent field evidence shows that *Porphyra* cultivation increased dissolved organic carbon and promoted refractory dissolved organic matter formation, indicating a positive role in coastal carbon sequestration processes. At the same time, national-scale analysis in China found that seaweed cultivation has already generated substantial CO_2-emission reduction and blue-carbon benefits, supporting the view that green nori farming should be evaluated as part of a larger low-carbon mariculture transition rather than as an isolated farm technology.

Future progress in green *Porphyra* farming will depend first on strengthening breeding and production-control technologies. Across seaweed aquaculture, breeding and genetic improvement are identified as priorities for developing strains that are more productive, stress resistant, and better suited to climate change, while recent reviews also point to tissue culture, selective breeding, and gene-editing approaches as promising tools to improve yield, stress tolerance, and biochemical traits. For *Porphyra* specifically, this direction is important because strain performance under warming, nutrient fluctuation, and disease pressure will increasingly determine the real effectiveness of green farming systems.

A second technology direction is the integration of intelligent monitoring, automation, and advanced environmental management. Reviews of seaweed farming emphasize automated cultivation and harvesting systems as a route to higher efficiency and lower cost, while Industry 4.0 analyses show that digitalization is becoming a core pathway for improving seaweed aquaculture techniques and management precision. In parallel, nanosensors and related monitoring tools are being proposed for water-quality surveillance, disease detection, and biofouling control, suggesting that future green *Porphyra* models will increasingly rely on real-time sensing and early-warning capacity rather than periodic manual observation alone.

The high-quality development of the *Porphyra* industry will require moving from farm-level greening to whole-industry coordination across governance, markets, and value chains. Global aquaculture assessments emphasize that sustainable growth depends on stronger governance, regulatory frameworks, social responsibility, and greater investment in research and development, while China's green-aquaculture framework likewise defines green development as the joint achievement of environmental friendliness, technical efficiency, product safety, income growth, and consumer satisfaction. This means that the future of the nori industry should not be judged only by production expansion, but by whether ecological, economic, and product-quality goals are advanced together.

A second pathway is to build a more diversified and resilient blue-economy structure around *Porphyra* biomass. Recent reviews indicate that *Porphyra* has expanding potential in food, pharmaceuticals, nutraceuticals, and biofuel applications, while broader seaweed outlooks argue that scaling seaweed aquaculture is essential for food security and sustainability under future resource constraints. In this sense, the long-term outlook for green *Porphyra* farming is strongest when the industry links high-standard cultivation with value-added processing, ecosystem-service recognition, and low-carbon development pathways.

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