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).