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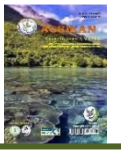

Comparing Seaweed Cultivation Methods (Longline, Raft, Offshore, and Land-Based Systems): *A Systematic Review of Productivity, Cost Efficiency, and Environmental Risks*

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Abstract

Seaweed aquaculture is expanding rapidly as a source of food, hydrocolloids, biomaterials, and ecosystem services, yet its sustainability depends strongly on the cultivation technologies employed. This systematic literature review synthesizes and compares evidence on four major seaweed cultivation methods longline, raft, offshore, and land-based systems using three decision-relevant dimensions: productivity, cost efficiency, and environmental risk. Following PRISMA-guided procedures, studies were systematically identified, screened, and synthesized from major scientific databases. The review reveals that no single cultivation method consistently outperforms others across all dimensions. Land-based and integrated systems demonstrate high and stable productivity and strong nutrient-mitigation potential but incur higher capital and operational costs, often driven by energy and infrastructure requirements. Nearshore longline and raft systems offer lower entry barriers and favorable economic performance under supportive policy and labor conditions, yet face substantial variability in productivity due to seasonality, biofouling, disease, and spatial conflicts. Offshore systems enable spatial expansion and exposure-driven growth potential, but current evidence emphasizes engineering survivability over robust yield and cost benchmarks, while environmental benefits particularly related to carbon sequestration are highly context- and season-dependent. Across methods, the review identifies persistent challenges arising from inconsistent productivity metrics, heterogeneous techno-economic boundaries, and fragmented environmental-risk assessments, which limit cross-study comparability. To address this gap, the review proposes an integrated, decision-oriented synthesis that maps trade-offs among yield, cost, and risk and highlights context-specific "best-fit" applications rather than universal rankings. The findings provide actionable insights for researchers, industry stakeholders, and policymakers seeking to align seaweed aquaculture development with economic viability and environmental sustainability.

I. INTRODUCTION

Global seaweed aquaculture is diversifying and scaling to supply sustainable biomass for multiple value chains and coastal livelihoods. Seaweeds are framed as contributors to resilient food systems by providing alternative nutrition amid rising demand for plant-based diets, while supporting economies through aquaculture employment and trade (Budhathoki et al., 2024; Theuerkauf et al., 2021). Cultivation also feeds industrial markets, including hydrocolloids for food and textiles (Forbes et al., 2022). However, expansion generates optimism about ecosystem services (e.g., habitat-related functions) alongside concerns about marine space use and ecosystem health (Corrigan et al., 2022; Msuya et al., 2022). Environmental strain and market dynamics can undermine long-term viability (Corrigan et al., 2023; Munguti et al., 2025), reinforcing calls for policies that balance ecological integrity with socio-economic objectives (Setiawan et al., 2025; Spillias et al., 2023).

Scaling also exposes persistent constraints in performance, cost, and risk. Production instability is linked to seasonality and site conditions; growth varies across species and responds to temperature and light, producing fluctuating yields (Behera et al., 2022). Climate variability can increase disease events and crop losses (Gazali et al., 2023), while biofouling reduces growth and quality and increases labor and maintenance burdens (Cao & Guo, 2023; Druvari et al., 2023; Hopkins et al., 2021). Feasibility remains uncertain because costs reflect high upfront investment, price volatility, and uneven access to finance in emerging or smallholder systems (Delannoy et al., 2025), with additional disease and biofouling management further eroding profitability (Zhang et al., 2021).

Environmental risks and spatial conflicts intensify as footprints expand. Farms may alter habitats and ecosystem functioning when density or placement exceeds environmental capacity (Ashkenazi et al., 2022; Gephart et al., 2021), influence nutrient dynamics in nutrient-rich settings with eutrophication-related risks (Zollmann et al., 2021), and generate marine debris from infrastructure that harms organisms and raises maintenance needs (Liu et al., 2025). Competition with fisheries, conservation, tourism, and other industries can create tensions and governance challenges (Steinhagen et al., 2025; Toth et al., 2025), implying sustainability assessments must consider site context, farm design, and cumulative impacts.

These challenges persist partly because cultivation pathways differ in engineering needs, operational intensity, and exposure. Nearshore longline/raft systems emphasize lower capital and accessibility; offshore systems expand into higher-energy areas but require stronger infrastructure and monitoring; and land-based systems increase control and biosecurity while shifting burdens to energy, water, and effluent management. Yet evidence is fragmented due to inconsistent productivity metrics, heterogeneous techno-economic boundaries (CAPEX/OPEX, labor, depreciation, logistics), and varied environmental assessment approaches. Accordingly, this systematic literature review (SLR) compares evidence on (i) productivity and stability, (ii) cost efficiency and techno-economics, and (iii) environmental risks across longline, raft, offshore, and land-based systems, integrating TEA and life-cycle perspectives to clarify feasibility and hotspots (Johnson et al., 2024; Wu et al., 2023) and to identify configurations that improve nutrient-management outcomes while avoiding unintended burdens (Narvarte et al., 2025). Comparative synthesis can support stakeholders in selecting practices that reduce ecological risks while maintaining economic performance and yields (Schmid et al., 2023).

Research questions: (1).RQ1: How do productivity levels and production stability differ across longline, raft, offshore, and land-based cultivation systems?; (2). RQ2: How do cost structures and cost-efficiency outcomes compare across these methods, and which cost drivers are most consistently reported? (3). RQ3: Which environmental risks are most salient for each method, and how do indicators and assessment approaches differ across the literature? (4). RQ4: What yield–cost–risk trade-offs are most robust, and which contextual conditions (e.g., exposure, scale, species, logistics, governance) explain variability in outcomes?

This review covers macroalgae cultivation at plot, pilot, and farm scales, including empirical, monitoring, techno-economic, LCA/LCC, and modelling studies reporting productivity, cost, and/or environmental-risk indicators. Microalgae and processing-only studies are excluded unless boundaries affect system comparability.

The paper is organized as follows. Section 2 details methods; Section 3 summarizes typologies, boundary issues, and risk frameworks; Section 4 synthesizes productivity, cost, environmental risks, and trade-offs; Section 5 discusses implications and gaps; Section 6 concludes.

II. METHODS

This systematic literature review (SLR) followed best practices for evidence synthesis in aquaculture and environmental economic research, prioritizing transparency, reproducibility, and cross-study comparability.

2.1. Search strategy

The protocol followed the PRISMA framework for rigorous reporting of rationale, searches, screening, and synthesis Page et al., (2021), strengthening reproducibility and credibility through standardized documentation (Rector et al., 2021). Where applicable, PRISMA-P principles informed protocol definition before full screening and extraction.

Searches were conducted in Scopus and Web of Science to capture broad peer-reviewed coverage across aquaculture, marine science, environmental assessment, and techno-economic analysis. Google Scholar was used as a supplementary source to retrieve early-access and grey-edge peer-reviewed literature.

Search strings were iteratively refined to balance sensitivity and specificity, using Boolean operators (AND/OR/NOT) to combine keyword clusters on cultivation systems, performance, and sustainability dimensions (Carpio et al., 2024). Core terms captured seaweed cultivation (e.g., *seaweed* OR *macroalgae* AND *cultivation* OR *farming*), method descriptors (*longline*, *raft*, *offshore*, *land-based*), and outcomes (*productivity*, *yield*, *growth rate*, *techno-economic*, *cost*, *environmental risk*, *impact*, *LCA*, *EIA*). Searches were limited to 2010–2026, English-language publications, and relevant document types (peer-reviewed journal articles and selected conference proceedings).

2.2. Inclusion and exclusion criteria

Studies were included if they examined at least one target method (longline, raft, offshore, land-based) and reported quantitative or semi-quantitative evidence on productivity, cost efficiency, and/or environmental risk/impact, with minimum contextual reporting (site/water-body type, species, system design, duration). Empirical and modelling evidence were eligible, including field trials, monitoring, TEA, LCA, and risk/environmental models relevant to cultivation performance (Theuerkauf et al., 2021; Wu et al., 2023). Priority was given to peer-reviewed work with transparent reporting (Basenach et al., 2023; Pollock et al., 2021). Studies were excluded if they focused only on microalgae, post-harvest processing without explicit cultivation linkage, did not specify farming systems, or were conceptual without empirical data (Theuerkauf et al., 2021). Duplicates and out of window records were removed.

2.3. Screening, quality appraisal, and data extraction

Selection proceeded through duplicate removal, title/abstract screening, and full-text assessment, summarized using a PRISMA flow diagram (Figure 1). Quality appraisal used PRISMA-aligned criteria and the MMAT for mixed evidence bases (Basenach et al., 2023; Zibako et al., 2021), focusing on metric clarity (wet vs dry basis; normalization), TEA boundary transparency (CAPEX/OPEX, labor, depreciation, logistics), environmental indicator definition, and uncertainty/replication.

Data extraction employed a structured template capturing method, species, site context, productivity metrics, cost components and outputs, environmental indicators, key findings, and limitations. Standardized extraction supports comparability and synthesis reliability (Pollock, 2025) and enables transparent integration of diverse evidence for decision-relevant analysis (Maynard, 2025; Veroniki et al., 2025).

III. THEORETICAL BACKGROUND

To support the comparative synthesis in Section 4, this section outlines core concepts for interpreting differences among seaweed cultivation methods. Cultivation performance is treated as the outcome of coupled engineering design and ecological drivers, evaluated through techno-economic boundaries (CAPEX/OPEX) and complemented by environmental-risk assessment frameworks. The section therefore links (i) engineering–ecological mechanisms shaping productivity, (ii) TEA logic and boundary choices affecting cost comparability, and (iii) approaches for assessing environmental risks and impacts.

Conceptual framework linking engineering design and ecological drivers to productivity outcomes, techno-economic boundaries (CAPEX/OPEX), and environmental-risk assessment approaches across seaweed cultivation systems

Figure 2 synthesizes the conceptual foundations underpinning this review by illustrating how productivity, economic performance, and environmental risk in seaweed aquaculture emerge from tightly coupled engineering and ecological processes. The framework emphasizes that cultivation methods nearshore longline and raft systems, offshore exposed systems, and land-based tank, pond, or recirculating systems do not operate in isolation but are mediated by shared biophysical drivers, including hydrodynamics, light availability, nutrient supply, temperature, stocking density, biofouling pressure, and biosecurity.

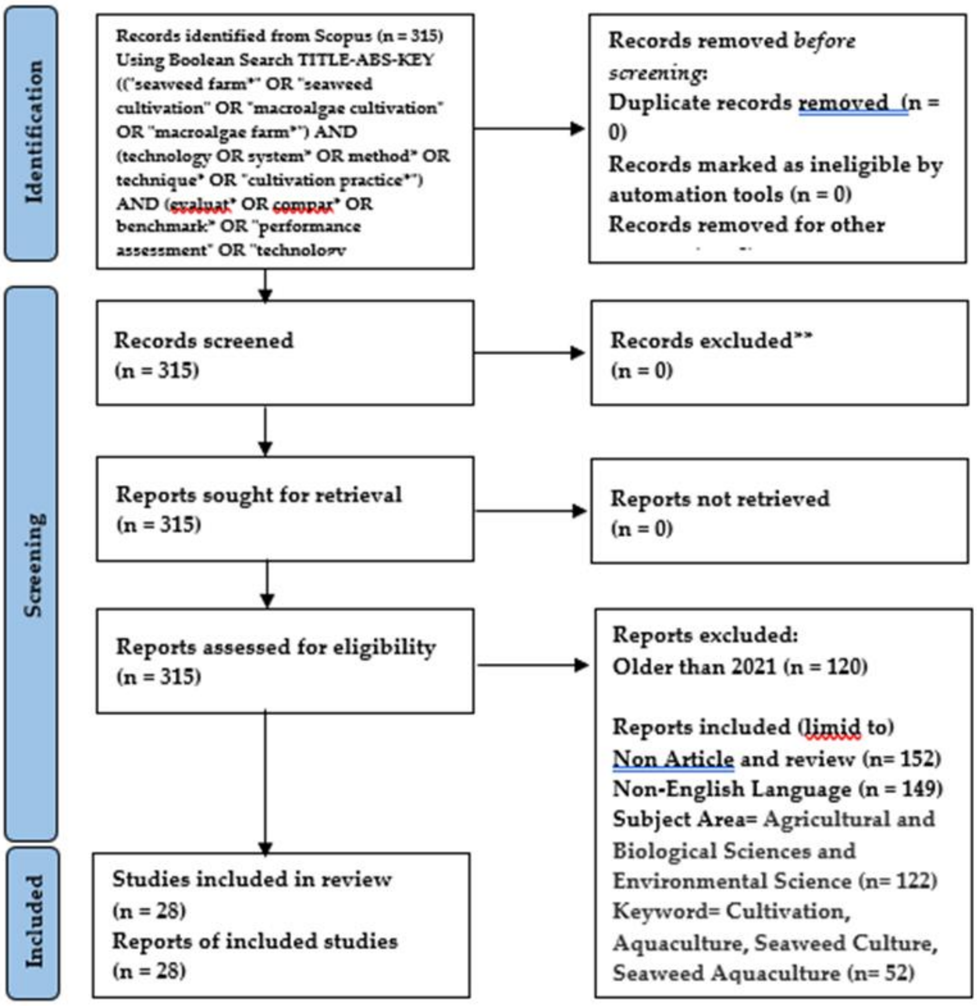

Figure 1. The PRISMA flow diagram detailing the screening and selection process of literature.

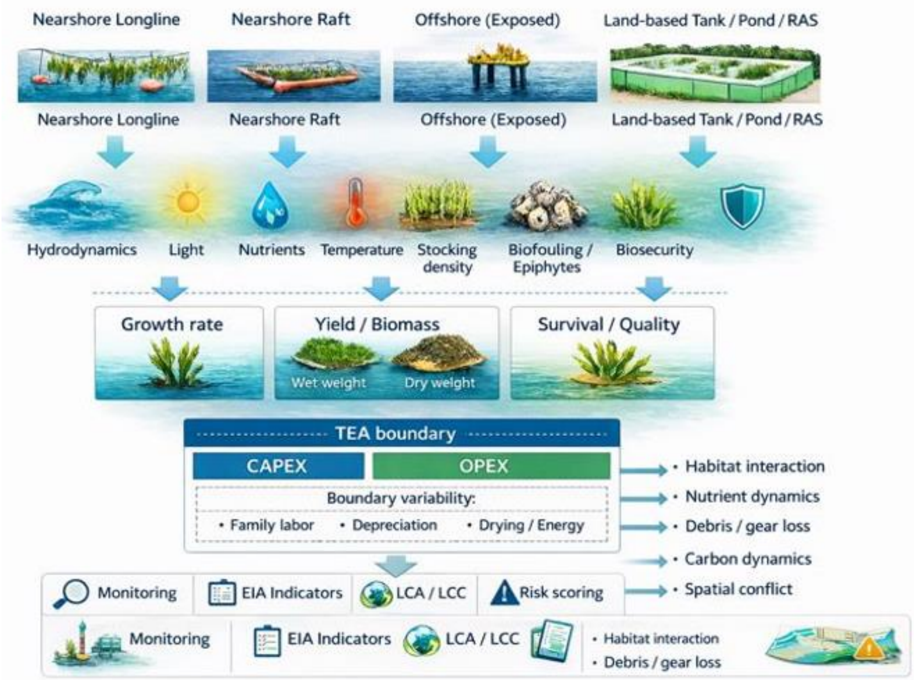

Figure 2. Engineering–Ecology–Economics–Risk: A Conceptual Framework for Seaweed Cultivation Systems.

These drivers are translated into commonly reported productivity expressions such as growth rate, biomass yield, and survival or quality, while explicitly highlighting persistent metric inconsistencies (e.g., wet versus dry weight) that complicate cross-system comparisons. The figure further situates these production outcomes within a techno-economic boundary that separates capital expenditures (CAPEX) from operational expenditures (OPEX), while indicating how boundary choices such as labor accounting, depreciation, logistics, and energy use can lead to divergent techno-economic conclusions. Finally, the framework integrates multiple environmental-risk assessment pathways, including monitoring-based approaches, EIA-style indicators, life cycle assessment or costing, and risk-scoring methods, which converge on key risk categories such as habitat interaction, nutrient dynamics, gear loss and debris, carbon dynamics, and spatial conflict. By linking system design, performance metrics, economic boundaries, and risk frameworks, Figure 2 provides a unifying lens for interpreting the theoretical background presented in this section and prepares the reader for the comparative synthesis of empirical evidence in Section 4.

3.1. Engineering ecological basis of cultivation methods

Seaweed cultivation is commonly grouped into nearshore systems (longline and raft), offshore exposed systems, and land-based systems (tanks, ponds, and recirculating aquaculture systems—RAS). Each configuration shapes production potential, operational constraints, and environmental interactions. Nearshore systems benefit from sheltered conditions, logistical accessibility, and proximity to nutrient inputs, but are sensitive to waves, sediment resuspension, and variable hydrodynamics that affect attachment stability, light, and nutrient fluxes (Araújo et al., 2021). Offshore systems can access higher-energy environments with enhanced water exchange and reduced competition for coastal space, yet exposure increases structural requirements and mechanical-failure risk, influencing crop survival and stability (Pessarrodona et al., 2022). Land-based systems provide the highest controllability (water quality, nutrients, and biosecurity) but require substantial infrastructure and energy to sustain suitable conditions (Turner et al., 2022).

Across systems, productivity emerges from design–ecology interactions: light availability can constrain yields via self-shading in dense or vertically structured farms (Ochoa-Sánchez et al., 2023); nutrient supply (especially N and P) often limits growth, with nearshore waters nutrient-rich but variable due to runoff and seasonal mixing (Gagnon et al., 2023); and temperature sensitivity reflects narrow thermal windows in many cultivated species (Siddik et al., 2024). Biofouling and disease can reduce growth and quality while increasing labor, linking system design and biosecurity to stable output (Theuerkauf et al., 2021). Thus, no method is universally optimal; outcomes depend on alignment between engineering choices and local ecological conditions.

3.2. Techno-economic logic and boundary issues in seaweed farming

Techno-economic analysis (TEA) distinguishes CAPEX (infrastructure, moorings, vessels, land-based facilities) from OPEX (labor, maintenance, harvesting, energy, logistics) (Wu et al., 2023). Nearshore systems often have lower CAPEX due to simpler deployment, whereas offshore systems require higher CAPEX for robust engineering and specialized equipment (Lian et al., 2024), potentially offset by higher long-term yields and reduced spatial competition (Araújo et al., 2021). Comparisons are constrained by inconsistent TEA boundaries: labor valuation, depreciation, and inclusion of drying/energy can differ substantially, obscuring true cost efficiency and scalability (X. Zhu et al., 2025). Recurring cost drivers include labor intensity, input prices (seedstock/materials), and harvesting efficiency (Theuerkauf et al., 2021), while scale effects can improve performance through shared infrastructure and labor productivity (Vickram et al., 2025). Method/species choices, including IMTA, also influence nutrient use, productivity, resilience, and profitability (Pari et al., 2025; X. Zhu et al., 2025), reinforcing that investment decisions are context-dependent and shaped by market and environmental risks (Buccaro et al., 2023; Wu et al., 2023).

3.3. Environmental-risk frameworks for aquaculture systems

Environmental-risk assessment links system design to ecological outcomes using hazard–exposure–vulnerability and likelihood–severity models that increasingly consider cumulative impacts. Monitoring-based approaches support adaptive management and early detection of adverse effects (Klongklaew et al., 2025), while EIA-style assessments evaluate impacts prior to siting, emphasizing habitat alteration, biodiversity, and water-quality change (Klongklaew et al., 2025). Life Cycle Assessment (LCA) complements site monitoring by quantifying impacts across cultivation, harvesting, and processing, enabling method comparison on consistent functional units and identifying energy/material hotspots (Guo et al., 2025; Moutik et al., 2023), consistent with broader sustainability applications in aquaculture (Espadas-Aldana et al., 2021; Nicolás & Geldres-Weiss, 2023). Risk-scoring approaches further translate multiple pressures into indices for prioritizing management and compliance (Klongklaew et al., 2025).

Risk profiles vary by method and location: nearshore farms can modify benthic habitats and organic enrichment at higher densities (Nicolás & Geldres-Weiss, 2023); large-scale operations can alter nutrient cycling when cumulative production exceeds local assimilative capacity (Klongklaew et al., 2025); and carbon outcomes depend on management, with potential net emissions from gear loss, biomass degradation, or inefficient downstream handling (Cano & Kim, 2022). Offshore expansion raises monitoring feasibility and debris risks, while land-based systems shift pressures to energy, water use, and effluent handling. Spatial conflicts with fisheries, conservation, and tourism further condition sustainability, especially in high-value or sensitive areas (Dogra et al., 2024).

Taken together, these perspectives show environmental performance cannot be separated from cultivation-system design and context; integrating engineering–ecological understanding, TEA logic, and environmental-risk frameworks provides the foundation for the comparative synthesis in this review.

IV. REVIEW of FINDINGS

4.1. Productivity performance and production stability across cultivation methods

Productivity across seaweed cultivation methods varies in growth, yield, and stability because outcomes depend on system design, species traits, and environmental context, and are reported with non-equivalent metrics and time scales.

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Figure 3 . Where Productivity Comes From: A Visual Typology of Productivity Pathways Illustrative typology of productivity pathways across longline, raft, offshore, and land-based seaweed systems, emphasizing metric heterogeneity and the drivers of production stability.

Figure 3 provides a visual synthesis of the qualitative productivity patterns reviewed in this section by mapping how cultivation design and operating context shape production outcomes across longline, raft, offshore, and land-based seaweed systems. The figure illustrates that productivity does not arise from a single factor but from the interaction of multiple drivers—such as hydrodynamics, nutrient delivery, light availability, stocking density, biofouling pressure, and biosecurity—whose relative importance varies by method. Nearshore longline and raft systems benefit from accessibility and moderate capital requirements, yet their productivity is constrained by seasonality, fouling, and labor intensity. Offshore systems are characterized by exposure-driven water exchange and spatial expansion potential, but productivity assessments are often secondary to engineering survivability and access constraints. In contrast, land-based systems display the highest degree of controllability and production stability, supported by biosecurity and input regulation, while remaining dependent on external energy, water, and nutrient inputs. A central feature of the figure is the metric compatibility strip, which highlights persistent inconsistencies in productivity reporting, including wet versus dry weight, normalization by length versus area, cycle-based versus seasonal yields, and the distinction between propagule output and harvestable biomass. By visualizing these pathways and constraints, Figure 3 reinforces the argument that productivity evidence is abundant yet unevenly comparable, and it provides a conceptual bridge between the empirical findings summarized in Table 1 and the broader discussion of yield stability and trade-offs developed later in the manuscript.

Land-based systems commonly show high, controllable growth under nutrient-enriched, biosecure conditions. Nursery Kappaphycus alvarezii achieved 4.19–5.78% day^{-1}, while sea-based cultivation showed broader strain- and

duration-dependent variability (0.85–4.47% day⁻¹ at day 30; 3.18–5.26% day⁻¹ at day 60) (Gacura et al., 2026). Controlled Gracilaria edulis reached peak growth of 9.9 ± 0.9% day⁻¹ and yields of 202.5 ± 12.6 mg DW L⁻¹, demonstrating gains under optimized nutrient regimes (Suriya Narayanan & Ruben Sudhakar, 2025). Some land-based/integrated systems emphasize services beyond biomass: shrimp IMTA with Gracilaria caudata and G. birdiae reported carbon storage (8–12.4 g C m⁻² dry biomass) but no growth/yield metrics (Borburema et al., 2026), and tank Chondracanthus chamissoi reported propagule output (31,993 secondary attachment discs from a 3 m³ tank over 90 days) rather than biomass yield (Oyarzo et al., 2021).

Nearshore systems are more heterogeneous due to exposure, density, and operations. In Peru, Gracilariopsis lemaneiformis on polypropylene ropes produced 4.23 ± 0.13% day⁻¹, and low inoculum density (25 g per unit) reached 5.47 ± 0.33% day⁻¹; bottom cultivation slightly outperformed suspended systems by reducing epiphytism, though wet biomass was inconsistently reported (Castañeda-Franco et al., 2026). In Indonesia, Kappaphycus alvarezii showed a growth–yield trade-off: highest specific growth at 50 g per tie but highest final yield at 75 g per tie (Mulyani & Cahyono, 2025), consistent with sensitivities to crowding, seasonality, and biofouling (Theuerkauf et al., 2021).

Open-sea/exposed systems add growth–retention trade-offs. Across seven Gracilaria dura cycles, monoline had higher daily growth (3.11 ± 0.85 to 5.26 ± 1.41% day⁻¹) than tube-nets (2.01 ± 0.69 to 2.61 ± 0.74% day⁻¹), yet tube-nets yielded more (22.23–33.21 kg FW m⁻¹ cycle⁻¹) than monoline (6.64–20.43 kg FW m⁻¹ cycle⁻¹) (Kavale et al., 2021). Offshore Saccharina latissima trials reported survivability under waves (Hs > 2 m; max 5.9 m) but no yields (Moscicki et al., 2024). Commercial examples show scale potential (e.g., 60,000 tons FW from 400 ha) with limited normalization (Li et al., 2024); a low-cost exposed nearshore system achieved 12.7 kg m⁻¹ over ~8 months with similar constraints (St.Gelais et al., 2022).

Overall, comparisons remain sensitive to wet vs dry basis, per meter vs per area normalization, and biomass vs propagule outputs, reinforcing the need for harmonized metrics and contextual reporting (Araújo et al., 2021; Pessarrodona et al., 2022; Turner et al., 2022).

Table 1. Productivity and Production Performance

No.	Study (Author–Year)	Species / focus	Cultivation method category	Site / operational context	Productivity metrics reported	Key productivity-related findings	Notes / limitations (from abstract)
1	Gacura et al., (2026)	Kappaphycus alvarezii (novel haplotypes) vs commercial strain	Land-based nursery vs sea-based farming (in situ)	Comparative cultivation under hatchery/nursery (land) and sea-based conditions; strain screening	Land: 4.19–5.78% day⁻¹; Sea: 0.85–4.47% day⁻¹ (D30) and 3.18–5.26% day⁻¹ (D60)	Land-based growth similar across strains; sea-based growth highly strain- and time-dependent; susceptibility to ice-ice varies by strain (TR-S8 least susceptible among novel strains).	Abstract reports growth ranges but lacks site metadata (depth, seasonality) and standardization (e.g., initial biomass, replication details).
2	Castañeda-Franco et al., (2026)	Gracilariopsis lemaneiformis	Tree-line system; substrate + inoculum density + mode (suspended vs bottom)	Field trials, southern coast of Peru; three experiments manipulating ropes/bags, density, and cultivation mode	Polypropylene ropes: DGR 4.23±0.13% day⁻¹ (higher than mesh bags); 25 g/CU: DGR 5.47±0.33% day⁻¹;	Rope substrate and lower inoculum density increased growth; bottom cultivation slightly higher	WB values not detailed in abstract; effect sizes for suspended vs bottom are described qualitatively.

					productivity also compared via final wet biomass (WB)	productivity than suspended (lower epiphytism; improved stability).	
3	Kavale et al., (2021)	Gracilaria dura (red agarophyte)	Monoline vs tube-net (open-sea)	Seven crop cycles; hydrodynamic CFD used to interpret nutrient flow differences	DGR: 3.11±0.85 to 5.26±1.41% day^{-1} (monoline) vs 2.01±0.69 to 2.61±0.74% day^{-1} (tube-net); Yield: 6.64±1.56–20.43±12.12 kg FW m^{-1} cycle^{-1} (monoline) vs 22.23±7.08–33.21±7.65 kg FW m^{-1} cycle^{-1} (tube-net)	Monoline achieved higher daily growth rates (better nutrient availability per CFD), but tube-net reported higher line-based yields across cycles.	Abstract does not clarify why yield is higher in tube-net despite lower DGR (e.g., stocking density, retention, harvest protocol).
4	St.Gelais et al., (2022)	Saccharina latissima (kelp)	Low-cost nearshore kelp system (user-focused design; mobile anchors/subsurface floats)	Nearshore exposed sites (southern Maine, USA); 3-year testing; designed for community-scale deployment/removal	Harvest: 12.7 kg m^{-1} over an ~8-month fall–winter growth period; deploy/remove <4 h with 3-person crew	Demonstrated feasible harvest from lightweight, mobile gear suited to exposed nearshore conditions; designed to reduce capital barriers.	Yield reported as aggregate harvest per meter; lacks comparators against conventional longline systems in abstract.
5	Moscicki et al., (2024)	Saccharina latissima (kelp)	Experimental offshore cultivation structure (engineered mooring + helical anchors; fiberglass rod substrate)	Exposed offshore site (Gulf of Maine, USA); planted Nov 2021–Jan 2022; harvested May 2022; decommissioned Jun 2022	Productivity sampling stated (kelp sampled 3×; one growth season) but no yield/SGR values in abstract	System survived multiple storms (significant wave height >2 m; max wave 5.9 m) with minor damage; operational issues (access, tension control); holdfast attachment to fiberglass rod was relatively poor.	Productivity outcomes cannot be quantified from abstract; focuses on engineering survivability rather than yield benchmarks.
6	Mulyani & Cahyono, (2025)	Kappaphycus alvarezii	Nearshore cultivation (planting density as method-level design factor)	South Sulawesi, Indonesia; 45-day cycle; densities 25/50/75 g per tie	Highest final biomass yield at 75 g/tie; highest SGR at 50 g/tie; carbon content tracked (no numeric yield/SGR values in abstract)	Medium density optimized growth efficiency and stability; high density increased final yield but showed stress signals; low density	Abstract provides qualitative direction without numeric SGR/yield values, limiting comparability

						underperformed in productivity.	across methods.
7	Suriya Narayanan & Ruben Sudhakar, (2025)	Gracilaria edulis (seedlings) + poultry-manure-derived media (PMES)	Land-based cultivation in enriched media (PMES, 1–5% v/v)	Seedling production + biomass growth in formulated manure extract; focus on low-cost nutrient source	Peak DGR 9.9±0.9% day^{-1} and biomass yield 202.5±12.6 mg DW L^{-1} at 2% PMES	PMES enabled robust seedling growth without stimulants; demonstrates potential for cost-effective land-based biomass production and seedstock scaling.	Lab/controlled setting; transferability to open-water production and farm economics not assessed in abstract.
8	Oyarzo et al., (2021)	Chondracanthus chamissoi (edible red seaweed)	Outdoor tank cultivation using secondary attachment discs (SADs) on artificial substrates	Comparative substrates (fiberglass plates, ceramic plates, PVC pipes); strategy to maintain permanent thalli stock	New erect axes >6 mm after 12 weeks; estimated 31,993 SADs produced in a 3 m^3 tank after 90 days (fiberglass plates)	Fiberglass and ceramic substrates performed best; approach supports scalable propagule production and trait-selected stock maintenance.	Productivity expressed as SAD units rather than biomass yield; market-scale yield implications not given.
9	Borburema et al., (2026)	Gracilaria caudata & G. birdiae in IMTA with shrimp (Penaeus vannamei)	Land-based/outdoor IMTA using recirculating aquaculture systems (RAS) under ambient vs warmed conditions	Outdoor IMTA experiment with two RAS; evaluated nutrient/carbon mitigation and seaweed performance under warming	Seaweed cultivation reduced nutrients (e.g., NO_3^- by 7–39% ambient; 8–31% warmed) and stored 8–12.4 g C m^{-2} in dry biomass	Biofiltration remained effective under warming; G. caudata performed better under elevated temperature; indicates co-benefits for production + environmental services.	Biomass yield/SGR not reported in abstract; carbon storage metric may not translate directly to harvestable yield.
10	Massocato et al., (2022)	Ulva pseudorotundata & Ulva rigida	Outdoor cultivation in fishpond effluents (50% vs 100% effluent)	Pilot-scale effluent mitigation; assessed nutrient uptake, photosynthetic performance, and biomass production	Removed >65% NH_4^+ in 3 h; up to 94.8% NH_4^+ removed by end; >85% NO_3^- removed after 5 days at 50% effluent; growth rates higher at 100% effluent (no numeric growth rates in abstract)	Higher effluent concentration increased growth and protein content; supports productivity improvements when nutrients are abundant.	Growth quantified only comparatively (higher/lower) in abstract; exact productivity metrics absent.
11	Carvalho et al., (2024)	Ulva lactuca integrated with shrimp (P. vannamei) +	Integrated multi-species cultivation in biofloc systems (chemoautotroph	45-day experiment with water recirculation across tanks;	Macroalgae removed nitrate 57% and phosphate 47%; higher specific	Chemoautotrophic treatment favored higher seaweed growth; heterotrophic	No explicit SGR/biomass yield numbers in abstract;

		tilapia (O. niloticus)	ic vs heterotrophic fertilization)	compared fertilizer regimes	growth rate under chemoautotrophic regime; protein up to 18% DM under heterotrophic regime (no SGR values in abstract)	improved protein content and phosphate removal; indicates trade-offs between biomass vs quality.	productivity comparisons are qualitative.
12	Li et al., (2024)	Kelp (species not specified in abstract; commercial Chinese kelp farming)	Large-scale marine cultivation (commercial kelp farm; gear type not specified in abstract)	Shandong, China; 400-hectare commercial farm	Annual harvest: 60,000 tons fresh-weight kelp (functional unit in LCA: 1 ton FW kelp)	Provides scale benchmark for industrial kelp production and highlights operations (recycling after use) as key improvement lever.	Focus is environmental LCA; lacks per-area productivity (e.g., t/ha/year) and cultivation method details in abstract.

4.2. Cost efficiency and dominant cost drivers by cultivation method

Evidence on cost efficiency across seaweed cultivation methods depends strongly on techno-economic boundaries, subsidy regimes, labor accounting, and platform design; thus, outcomes are shaped less by biological productivity alone than by interactions among capital intensity, operational complexity, scale, and local economic context.

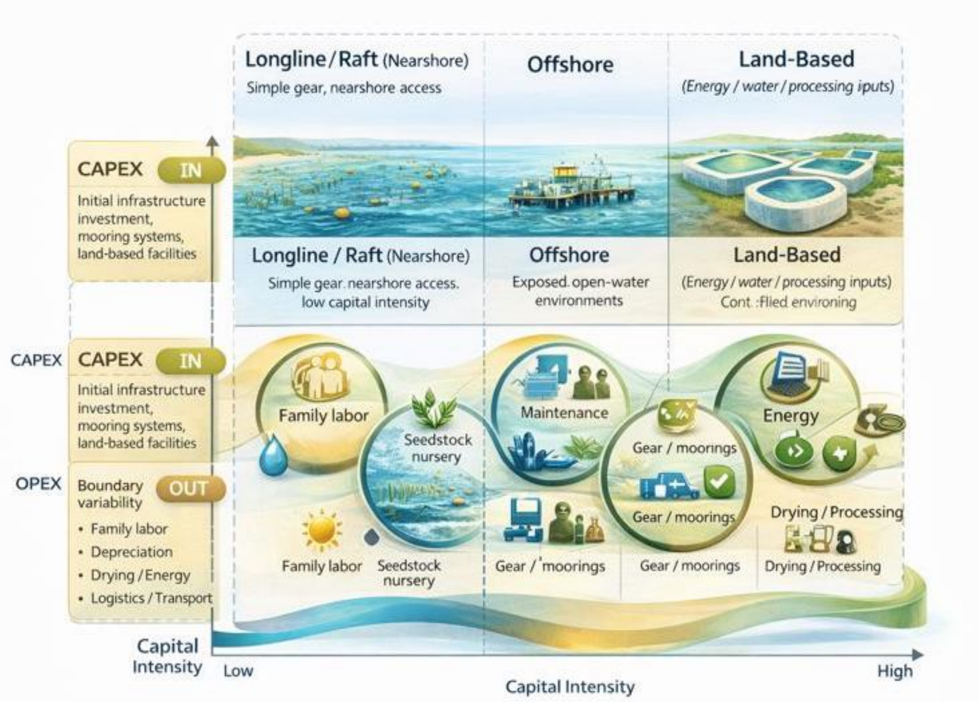

Figure 4. Cost Anatomy by Method: CAPEX–OPEX Boundary and Cost-Driver Map *Conceptual cost-driver map comparing CAPEX and OPEX intensity across seaweed cultivation methods and illustrating how boundary choices (labor, depreciation, logistics, drying/energy) shape reported cost efficiency.*

Figure 4 synthesizes the techno-economic logic discussed in Section 4.2 by visualizing cost efficiency as an emergent property of cultivation-system design and analytical boundaries rather than a fixed attribute of any single method. By positioning longline/raft, offshore, and land-based systems within a capital–operational intensity matrix, the figure clarifies why nearshore systems are often reported as low-CAPEX options, while offshore systems trend toward higher capital requirements and land-based systems toward higher operational intensity driven by energy, water, and processing needs. The surrounding "cost-driver halos" translate the abstract notion of OPEX into tangible components labor, gear and moorings, maintenance, logistics, energy, and post-harvest processing making explicit which drivers dominate across methods. Critically, the dashed boundary overlay highlights common sources of inconsistency in techno-economic analyses, such as whether family labor, depreciation periods, transport, or drying and processing are included. This visualization directly supports the interpretation of Table 2 by showing how identical systems can appear economically viable or unviable depending on boundary choices and policy context, including subsidies and labor costing. The uncertainty ribbon further reinforces that reported cost outcomes vary in robustness across methods, underscoring the need for transparent, standardized TEA boundaries when comparing seaweed cultivation technologies.

Nearshore systems (raft and longline) generally have lower capital barriers but high sensitivity to labor treatment and policy support. Comparative analyses from India show subsidy structure is decisive: national projections found only scenarios with a 40% investment subsidy and explicit manpower costs produced positive NPVs, with raft outperforming tube-nets. Reported IRRs reached 35.29% (raft) and 28.57% (tube-net) with payback periods of 0.7 and 0.8 years (Ramalingam et al., 2025). Species- and organization-specific results further show strong method–species–labor interactions: Kappaphycus alvarezii achieved rapid payback under family-centric models (0.76 years at 0% subsidy to 0.53 years at 60% subsidy) with IRRs of 31–90%, while agarophyte systems yielded negative NPVs across scenarios (Ramalingam et al., 2024).

Engineering design can substantially reduce unit costs by improving space use and biomass retention. A comparative TEA for Saccharina latissima and Gracilaria tikvahiae showed platform configuration can halve dry-weight cultivation costs: single-layer longlines cost ~USD 4.44 kg^{-1} dw, whereas dual-layer strip systems reduced costs to USD 2.19 kg^{-1} dw (Wu et al., 2023). The same study identified drying and post-harvest processing as dominant cost (and environmental) hotspots, indicating cost efficiency cannot be assessed solely at the cultivation stage.

Community-oriented nearshore designs illustrate alternative logics prioritizing accessibility. A low-cost exposed-site kelp system reported modest positive returns (8%) by reducing gear complexity and supporting seasonal livelihoods (St.Gelais et al., 2022). European life-cycle costing over a 20-year horizon found economic viability driven primarily by biomass market development, while carbon offsets contributed only 5% of income, suggesting ecosystem-service monetization alone is insufficient (Collins et al., 2022).

Integrated and land-based systems add cost-efficiency dynamics via system complexity and co-production. Pond polyculture of Gracilaria verrucosa with tiger prawn achieved feasible R/C ratios of 2.11, 1.83, and 1.37 as shrimp density increased (Rustam & Wamnebo, 2021). Conversely, global scenario modeling under extreme conditions estimated costs of USD 400 per ton, highlighting sensitivity to assumptions on labor, capital, and logistics (Hinge et al., 2025).

Overall, cost efficiency is an emergent property shaped by subsidies, labor organization, platform engineering, scale, and TEA boundary definitions. Nearshore systems may appear attractive under supportive policy/labor conditions, while advanced/offshore platform designs can reduce costs via yield concentration and space efficiency, but inconsistent CAPEX/OPEX and post-harvest treatment still limits comparability, reinforcing calls for standardized TEA boundaries (Theuerkauf et al., 2021; Wu et al., 2023).

Table 2. Cost Efficiency and Techno-Economic Performance

No.	Ref.	Method & scale (as stated)	Cost boundary / scenarios (as stated)	Key cost drivers highlighted	Cost-efficiency outputs reported	Sensitivity / uncertainty handled?	Context dependence / notes (from abstract)
1	Ramalingam et al., (2024)	Comparative case study: Kappaphycus alvarezii vs agarophytes farming (India); includes individual vs family-centric operation models	Evaluated subsidy scenarios: 0%, 40%, 60% (economic parameters under different subsidies); "realistic costing" noted (details not fully visible in abstract)	Subsidy level; operational model (family-centric vs individual); cost realism (labor/operations implied)	Payback (K. alvarezii, family-centric): 0.76 y (0%); 0.61 y (40%); 0.53 y (60%). Breakeven: Gracilaria dura 7.3–10.1 dry tons; K. alvarezii 15.1–22 dry tons. NPV/IRR (K. alvarezii): 3123–8863 USD; 31–90% (depending on subsidy). Profit (K. alvarezii): 328–902 USD (individual) and 4905–10,646 USD (family-centric). Agarophytes reported negative NPV across scenarios.	Not clearly stated in abstract	Highlights that economic viability is method/species + organization dependent; family-centric models outperform individual operations under the evaluated assumptions.
2	Ramalingam et al., (2025)	Pan-India commercial cultivation economic proposition; compares raft vs tube-net methods (state-by-state projections)	4 scenarios: 40% subsidy on investment costs, with inclusion/exclusion of manpower costs	Manpower cost treatment; investment subsidy; method choice (raft vs tube-net); regional heterogeneity	Only scenario with 40% subsidy + inclusion of manpower costs yielded positive NPV (as stated). IRR: 35.29% (raft) vs 28.57% (tube-net). Payback: 0.7 y (raft) vs 0.8 y (tube-net). NPV examples: Tamil Nadu highest—USD 38.71M (raft) and USD 27.75M (tube-net); Gujarat & Andhra Pradesh next—USD 25.26M & 18.95M (raft), USD 18.50M & 13.88M (tube-net); lowest NPVs in some union territories (e.g., ~USD 1.44M raft; ~USD 0.93M tube-net).	Not clearly stated in abstract (scenario-based projections reported)	Concludes raft shows superior economic metrics across locations; suggests NPV/IRR/payback/breakeven can be used as performance benchmarks for implementation.
3	Wu et al., (2023)	Multiple cultivation platforms for Saccharina latissima and	Techno-economic analysis (TEA) paired with LCA; scenarios include end-uses (e.g., dried sea vegetables; anaerobic	Drying identified as dominant contributor to both economic & environmental costs	Cultivation cost (dry-weight basis) reported: highest with single-layer longline ($\$4.44\ \mathrm{kg}^{-1}$ dw for *S. latissima* as stated); dual-layer strip reduced to $\$2.19\ \mathrm{kg}^{-1}$ dw (as stated). Dual-layer and strip systems	Not clearly stated in abstract	Provides direct method-level cost comparison and indicates that platform

		Gracilaria tikvahiae: single-layer longline, dual-layer longline, single-layer strip, dual-layer strip	digestion for CHP)	(processing stage)	reduced costs vs common single-layer longline.		design (layering/ strip) can halve cultivation costs (dw basis), while post-harvest drying remains a major cost lever.
4	St.Gelais et al., (2022)	Low-cost kelp aquaculture system engineered for community-scale farming at nearshore exposed sites; designed for seasonal (fall–winter) operation	Economic assessment referenced (details not fully visible in abstract); emphasis on capital accessibility and seasonal livelihood support	Low-capital gear and portability (system fits into fish tote boxes; loadable onto pickup truck); reduced barriers to entry	Economic assessment suggests farmers could realize ~8% return (as stated) and support seasonal income compared with off-season jobs	Not stated	Focus is "design-for-adoption" (user-focused). Provides evidence that engineering choices can reduce capital barriers, but does not report cost/kg in abstract.
5	Collins et al., (2022)	Brown algae cultivation system in Ireland (method details not fully visible in abstract)	Combines economic and environmental analysis; uses life cycle costing (LCC); evaluates feasibility over 20-year lifespan; includes revenue potential from voluntary carbon offset market (VCOM)	Market development and seaweed biomass revenue; carbon credit revenue is minor; long-term system performance	LCC indicates farm is economically feasible over 20 years (as stated). Carbon offset revenue from carbon assimilation contributes only ~5% of revenue (as stated).	Not stated	Suggests biomass market price and scale (and broader market development) are key to economic sustainability; carbon credits alone unlikely to drive viability.
6	Rustam & Wamnebo, (2021)	Pond polyculture: Gracilaria	Business profitability analysis	Stocking density; polyculture configuration;	Reported R/C ratios for seaweed cultivation: 2.11, 1.83, 1.37 (for 8/11/13 ind m^{-2},	Not stated	Demonstrates that integrated cultivatio

		verrucosa with tiger prawn (Penaeus monodon) at densities 8/11/13 ind m^{-2}; seaweed area stated as 50% planted	(feasibility study)	pond operation economics	respectively; as stated). Reported annual profits (USD year^{-1}) for combined systems: 6,039.831; 5,182,726; 5,639.662 (values reproduced as written in abstract).		n can meet feasibility criteria (R/C > 1); however, some numeric formatting in abstract is ambiguous (comma/dot separators), so full-text verification is needed.
7	Hinge et al., (2025)	Global-catastrophe scenario: economic viability of producing seaweed (focus on Gracilaria; supply at large scale)	Cost modeling under severe nuclear-winter benchmark; compares capital-intensive vs labor-intensive models (as stated)	Scale-up logistics; capital vs labor intensity; yield projections and input cost assumptions	Reported that seaweed costs would range between ~$400 and (upper bound not visible in exported abstract); production potentially up to 250 million tonnes annually (as stated)	Not stated	Scenario-specific (disaster resilience), not representative of normal market conditions; useful as a boundary-case for cost structure under extreme constraints.

4.3. Environmental risks, impacts, and mitigation linked to cultivation-system design

Evidence shows environmental risks/impacts in seaweed aquaculture are shaped by cultivation method, system design, scale, and the assessment framework; therefore, environmental performance cannot be generalized but reflects trade-offs among local ecological interactions, biogeochemical processes, and management capacity.

Figure 5 synthesizes the environmental evidence reviewed in Section 4.3 by visualizing environmental risk as a set of pathways that link cultivation-system design to assessment approaches and mitigation options. Rather than treating environmental performance as an inherent property of seaweed farming, the figure emphasizes that risks emerge from interactions among hazards, exposure pathways, and management capacity. Nearshore longline and raft systems are associated primarily with benthic interaction, biofouling, and disease pathways, reflecting their proximity to coastal habitats and high biological connectivity. Offshore systems shift risk toward gear loss, monitoring constraints, and conditional carbon dynamics, where exposure-driven benefits coexist with heightened uncertainty and access limitations. Land-based systems concentrate risks around effluent management and energy use, while simultaneously enabling controlled nutrient capture and biosecurity interventions. The figure also highlights how environmental evidence is fragmented across the literature, as different studies rely on monitoring, EIA-style indicators, LCA/LCC, or risk-scoring approaches, each illuminating distinct aspects of sustainability. By explicitly connecting hazards to mitigation levers—such as site suitability mapping, biosecurity protocols, material choices, harvest timing, and IMTA integration—Figure 5 reinforces the central argument of this section: environmental risk in seaweed aquaculture is best understood and managed as a design- and governance-dependent process, rather than a binary outcome of cultivation method choice.

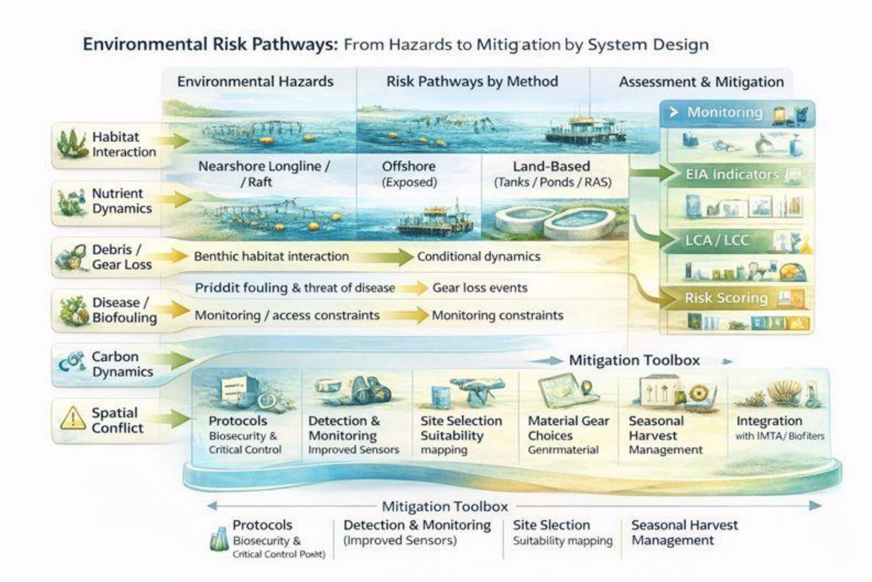

Figure 5. Environmental Risk Pathways: From Hazards to Mitigation by System Design

Risk pathway diagram mapping method-specific environmental hazards (habitat interaction, nutrient dynamics, debris/gear loss, disease/biofouling, carbon dynamics, spatial conflict) to assessment approaches and mitigation levers across seaweed cultivation systems.

Land-based and integrated systems highlight environmental service functions (nutrient and carbon mitigation) while shifting burdens toward energy use and effluent management. Outdoor IMTA integrating *Gracilaria* spp. with shrimp under RAS reduced nutrients (NO_3^- 7 - 39% ambient; 8–31% warming), lowered CO_2 up to 41%, and stored 8 -12.4 g C m^{-2} in dry biomass (Borburema et al., 2026). Land-based *Ulva* using fishpond effluents removed >65% NH_4^+ within 3 h, and over longer periods removed up to 94.8% NH_4^+ and >85% NO_3^-, with higher effluent concentrations enhancing growth and protein (Massocato et al., 2022). In integrated biofloc systems (*Ulva lactuca* + shrimp + tilapia), macroalgae reduced nitrate by 57% and phosphate by 47%, although fertilization regimes strongly influenced outcomes (Carvalho et al., 2024). Thus, land-based/IMTA systems can mitigate nutrient pollution, but benefits depend on design and operational controls.

Nearshore cultivation exhibits localized ecological risks (habitat modification, biofouling, disease). Long-term *Kappaphycus alvarezii* farming in India altered sedimentation, organic enrichment, and macrobenthic functional diversity, indicating benthic change even when water-column effects were less pronounced (Bhowmik et al., 2025). Monitoring of *Kappaphycus striatus* showed PCR detected pests in 25.7% of samples versus 20.0% by visual inspection, implying routine under-detection (Faisan et al., 2025). Farmer biosecurity implementation was low (36.1–40.6%) in Malaysia (Kambey et al., 2021), yet HCCAP biosecurity reduced ice-ice and pests by 60–75% (*K. malesianus*) and 29–71% (other *Kappaphycus* spp.) (Rustam & Wamnebo, 2021) Suitability mapping for longlines in North Kalimantan classified 86.5% of area as S2 and 0.30% as S1, indicating higher risk when farms operate outside optimal envelopes (Maradhy et al., 2021).

Ecosystem-scale studies show benefits and risks can coexist. Multi-species monitoring found farms increased pH up to 0.10 and reduced pCO_2 by 58.7 ± 15.9 µatm, creating temporary refugia, but also increased pH variability (0.14–0.30) that may stress organism Xiao et al., (2021). Mesocosms showed kelp can shift from CO_2 sink to source late in growth, with pCO_2 increases 20–37 μatm and pH declines (−0.03 to −0.04) driven by microbial mineralization (Xiong et al., 2024). Large-scale models and comparisons highlight cumulative and methodological risks: Dutch bay carrying-capacity models caution against over-intensification (Jiang et al., 2022); Chinese surveys show system-specific effects on phytoplankton and water quality (L. Zhu et al., 2023); biodiversity studies found no clear habitat/invertebrate gains near temperate kelp farms (Schutt et al., 2023); and epibiont dynamics (PERMANOVA $F_{4,25} = 100.56$, $p < 0.001$) can render kelps commercially unviable late season (Corrigan et al., 2023).

Life-cycle perspectives extend impacts beyond farms. A Chinese kelp LCA reported 57.5 kg CO_2-eq per ton FW, with operational streamlining as a key lever (Li et al., 2023). Ropes/anchors dominate impacts through replacement, while carbon credits contribute only ~5% of revenue (Collins et al., 2022). Processing hotspots include freezing and heated-air drying; alternatives (e.g., ensiling) can reduce impacts when nutrient/carbon services are considered (Thomas et al., 2021), but inconsistent inventories still limit comparability (Thomas, 2025).

Overall, risks/benefits are context- and method-dependent: land-based/IMTA systems mitigate nutrients but add energy/infrastructure burdens; nearshore systems face biological and habitat risks moderated by siting and biosecurity; and offshore/large-scale operations add monitoring, gear-loss, and cumulative-impact challenges reinforcing the need to link environmental-risk assessment explicitly to cultivation-system design.

Table 3. Environmental Risks, Impacts, and Mitigation

No.	Study (Author–Year)	Cultivation method / system (as stated)	Risk / impact category	Assessment approach (as stated)	Indicators / metrics reported (from abstract)	Direction / level of risk or impact (from abstract)	Mitigation practices reported from abstract)
1	Borburema et al., (2026)	Land-based/outdoor IMTA with shrimp (*Penaeus vannamei*) in recirculating aquaculture systems (RAS); ambient vs warmed conditions; *Gracilaria* spp.	Nutrient & carbon mitigation; climate-stress resilience	Outdoor IMTA experiment under ambient vs future-warming scenario	Nutrient reductions: NO_3^- 7–39% (ambient) / 8–31% (warmed); NH_4^+ 4–33% (ambient) / 5–21.5% (warmed); PO_4^{3-} 1–18% (ambient) / 1–17% (warmed). CO_2 reduced by 41% (ambient) and 27% (warmed). Carbon stored 8–12.4 g C m^{-2} (dry biomass).	Seaweed IMTA reduced dissolved nutrients and CO_2 under both current and warmed conditions; indicates environmental co-benefits alongside production.	Integration of seaweed into shrimp RAS (IMTA) as mitigation; shows continued effectiveness under warming.
2	Massocato et al., (2022)	Land-based/outdoor cultivation of Ulva spp. in fishpond effluents (50% vs 100% effluent)	Effluent bioremediation; nutrient pollution	Pilot-scale outdoor experiments; physiological monitoring	Removed >65% NH_4^+ in 3 h; up to 94.8% NH_4^+ removed by end; >85% NO_3^- removed after 5 days at 50% effluent; overall ≥82% NO_3^- removed across treatments (as stated).	Strong nutrient-removal capacity; higher effluent concentration increased growth and protein content	Using seaweeds as biofilters in aquaculture effluents; no additional mitigation beyond integration described.

						(qualitatively stated).	
3	Carvalho et al., (2024)	Integrated biofloc systems with Ulva lactuca + shrimp (*P. vannamei*) + tilapia (*O. niloticus*); chemoautotrophic vs heterotrophic fertilization	Water-quality management; nutrient accumulation risk in intensive systems	45-day recirculating integrated-culture experiment	Nitrate removal 57% and phosphate removal 47% during cultivation; tanks and volumes described (4 m^3 shrimp, 0.7 m^3 tilapia, 0.35 m^3 macroalgae).	Integrated Ulva improved nutrient removal; fertilization regime influenced growth and water-quality performance.	System design lever: choice of fertilization regime + integration of macroalgae; heterotrophic treatment reported better water-quality maintenance (qualitative).
4	Bhowmik et al., (2025)	Long-term nearshore seaweed aquaculture of Kappaphycus alvarezii (India)	Habitat modification; benthic ecosystem functioning; macrobenthic diversity risk	Field ecological assessment (long-term cultivation impacts)	Reported impacts framed as changes in sedimentation, organic enrichment, particle trapping, and shifts in abundance/functional diversity of macrobenthic assemblages (qualitative in abstract).	Indicates cultivation can modify habitat and benthic resources; macrobenthic functional diversity differs and is linked to K. alvarezii-mediated enrichment (qualitative).	Not specified in abstract (primarily impact characterization).
5	Faisan et al., (2025)	Sea-based farming area for Kappaphycus striatus	Biological risk: epiphytic pest outbreaks; farm losses	Temporal monitoring + visual vs PCR detection comparison	Monitoring over June 2019–Feb 2020; PCR detection 25.7% vs visual 20.0% ($p<0.001$) for epiphytic filaments (as stated).	Molecular detection identified higher pest presence than visual checks; supports under-detection risk in routine monitoring.	Mitigation lever implied: improved detection/monitoring (visual + molecular) to support early control.
6	Kambey et al., (2021)	Seaweed aquaculture industry (Malaysia), farm-level biosecurity	Biosecurity risk governance: disease/pest spread; outbreak control	Knowledge–Attitude–Practice (KAP) survey + policy implementation evaluation	Farmer biosecurity knowledge/attitude 55.7–64.1% (fair); practice implementation 36.1–40.6% (poor). Extension officer knowledge 57.9% (moderate); attitude 76.9% (good).	Highlights implementation gap: acceptable awareness/attitude but weak practices—elevating outbreak risk.	Policy-level mitigation recommended (biosecurity prevention), but specific farm practices not detailed in abstract.

7	Rustam & Wamnebo, (2021)	On-farm biosecurity management in a commercial Kappaphycus farm (sea-based)	Disease/pest risk: ice-ice syndrome and pest outbreaks	Biosecurity assessment using Hazard and Critical Control Point (HCCAP) approach	Reported outbreak reductions: ice-ice and pest outbreak decreased 60–75% for *K. malesianus* and 29–71% for another *Kappaphycus* (as stated in abstract).	Indicates structured biosecurity management can substantially reduce outbreaks.	HCCAP-based biosecurity management measures (critical control points) as mitigation.
8	Maradhy et al., (2021)1	Nearshore cultivation of Kappaphycus alvarezii using longline planting (Tarakan/North Kalimantan context)	Environmental suitability risk (site selection; water quality constraints)	Water-suitability evaluation (multi-parameter)	Suitability categories: S3 13.20%, S2 86.50%, S1 0.30%; potential cultivation area 33,896.73 ha (as stated).	Indicates most area is "suitable" but little "very suitable"; suggests site constraints that may elevate production risk if ignored.	Site selection via suitability mapping; mitigation through matching longline sites to water-quality classes.
9	Xiao et al., (2021)	Seaweed farms (multiple species: Saccharina japonica, Gracilariopsis lemaneiformis, Porphyra haitanensis)	Climate/chemistry benefit and variability risk: ocean acidification buffering vs pH variability	Field monitoring comparing farm vs control waters	Buffering: ΔpH up to 0.10 (*S. japonica*), 0.04 (*G. lemaneiformis*), 0.03 (*P. haitanensis*). pH variability range 0.14–0.30 units (within farms). pCO_2 deficit vs controls 58.7 ± 15.9 µatm (range 27.3–113.9 µatm).	Farms can create refugia (higher pH / lower pCO_2), but with strong temporal pH fluctuations—potentially a stressor for co-occurring organisms.	Mitigation not specified; implication for monitoring and farm management under future variability.
10	Jiang et al., (2022)	Saccharina latissima cultivation in a Dutch coastal bay (system type not specified in abstract)	Ecosystem carrying-capacity risk: nutrient/light limitation; density/space planning	Mechanistic kelp model + bay-scale modelling assessment	Model-based estimation (specific numeric outputs not visible in abstract export) focusing on seasonal growth and environmental interactions.	Provides carrying-capacity framing to avoid overexpansion that could reduce yields and alter ecosystem dynamics.	Mitigation implied: setting cultivation intensity/extent based on carrying-capacity modelling.
11	Zhu et al., (2023)	Comparative coastal aquaculture systems: seaweed (Gracilaria lemaneiformis),	Water-quality & plankton community impacts; eutrophication risk	Spatiotemporal field survey (June–Sept 2020)	Indicators include phytoplankton community composition and water-quality comparisons across systems	Suggests different culture systems shape phytoplankton and water quality differently;	Mitigation not specified; implication for integrated coastal planning

		shellfish (Mytilus coruscus), cage fish (China)			(specific numeric outcomes not visible in abstract export).	highlights need to account for system-specific externalities.	and monitoring.
12	Schutt et al., (2023)	Temperate kelp farms (Saccharina spp.; method not specified in abstract)	Ecosystem service claims vs evidence: habitat & biodiversity provisioning	Biodiversity assessment (farm vs control) including small invertebrates	Small invertebrates assessed using mesh settling devices at kelp-line depth (2 m). Abstract notes no observed habitat provisioning or increased biodiversity relative to expectations (qualitative).	Challenges assumption that farms always increase biodiversity; indicates context-dependent outcomes and risk of over-claiming benefits.	Mitigation not specified; implication for monitoring design and ecosystem-service reporting standards.
13	Corrigan et al., (2023)	European kelp farming (Saccharina latissima; schedule/harvest variations)	Biofouling/epibiont risk affecting crop quality & ecosystem interactions	Monitoring across farming schedules and harvesting techniques	Significant increases in epibiont abundance (PERMANOVA $F_{4,25}=100.56$, $p<0.001$) and diversity (PERMANOVA $F_{4,25}=27.25$, $p<0.001$); taxonomic richness ~9 phyla per kelp by late summer (August).	Epibionts increase over season; heavy fouling can make kelps not commercially viable (as stated).	Partial harvesting maintained or increased epibionts (i.e., limited mitigation effectiveness in abstract).
14	Xiong et al., (2024)	Seaweed farming environment (kelp late-growth/aging stage; mesocosm cultivation)	Carbon-cycle risk: farms may become CO_2 source due to microbial mineralization of released DOC	In-situ mesocosm + ecosystem process inference	During late-growth/aging stage: pCO_2 increased 20–37 μatm; pH shift from increase (+0.02–0.08) to decline (−0.03–0.04); buffering effects can offset within 3 days (as stated).	Indicates CO_2 sink assumption can fail seasonally; late-stage DOC release and respiration can exceed photosynthetic uptake, shifting system to CO_2 source.	Mitigation not specified; implies need for seasonal accounting/ management (harvest timing; monitoring).
15	Li et al., (2024)	Large commercial kelp farm (Shandong, China; 400 ha, 60,000 tons/yr; method not specified in abstract)	Life-cycle environmental impacts (GHG footprint, hotspots across supply chain)	Life Cycle Assessment (LCA) using primary farm data	Functional unit 1 ton FW kelp; farm size benchmark; climate impact reported 57.5 kg CO_2-eq (as stated).	Indicates mature, streamlined production can lower impacts; provides benchmark for large-scale operations and LCA comparability.	Mitigation lever implied: streamlining operations; improvements to production processes (qualitative).

16	Collins et al., (2022)	Brown algae cultivation system (Ireland; method not specified in abstract)	Environmental footprint + economics; carbon-credit revenue reliability	Economic + environmental assessment using life cycle costing (LCC) (and environmental analysis)	LCC over 20-year lifespan; carbon assimilation revenue contributes only ~5% of revenue (as stated). Ropes and anchors highlighted as major impact shares due to replacement (as stated).	Suggests long-term feasibility depends on biomass markets; carbon credits alone unlikely to drive viability; gear replacement influences impacts.	Mitigation lever implied: extending gear lifespan/replacement strategy; market development.
17	Thomas et al., (2021)	Saccharina latissima supply chain: hatchery + cultivation + preservation (outdoors, heated air-cabinet drying, ensiling, freezing)	Life-cycle environmental impacts; preservation hotspots; accounting for carbon/nutrient services	Comparative environmental LCA across stages and preservation options	Includes accounting for nutrient bioremediation and carbon capture; identifies major impact shares from freezing and air-cabinet drying (as stated).	Shows environmental outcomes depend strongly on processing/preservation choice; with carbon capture and nitrogen uptake, more impacts may be (temporarily) absorbed than emitted (as stated).	Mitigation lever: choose lower-impact preservation routes; account for ecosystem services in LCA boundaries.
18	Thomas et al., (2024)	Kelp aquaculture (inventory-data harmonization; *Saccharina latissima* referenced)	Assessment-method risk: non-standardized data causes inconsistent environmental conclusions	Harmonized recalculation / meta-LCA method development	Emphasizes lack of standardized methods for inventory data collection and reporting; proposes harmonized recalculation for comparability (qualitative).	Highlights methodological risk: inconsistent data can mislead technology comparisons and policy decisions.	Mitigation: standardized data collection, harmonized recalculation, improved data-sharing practices.

4.4. Integrated trade-offs and decision frameworks for technology selection

Integrated evidence across productivity, cost efficiency, and environmental risk indicates that no single cultivation method consistently dominates all criteria; reviewed studies instead point to context-dependent trade-offs where improvements in one dimension often require compromises in others. Table 4 consolidates this evidence into a decision-relevant comparison linking cultivation-system design to yield potential, cost structure, and environmental-risk profiles.

Figure 6 operationalizes the integrated synthesis by translating the review evidence into a structured, decision-ready workflow that supports technology selection under context-specific constraints. The figure emphasizes that method choice should begin with explicit context profiling considering exposure, logistics, energy availability, governance capacity, and species or market objectives before narrowing options to a shortlist of cultivation classes. This framing aligns with the evidence that no single method consistently dominates across productivity, cost, and environmental risk dimensions. The trade-off compass in Figure 6 makes these tensions explicit, reinforcing that improvements along one axis often require compromises along others. Importantly, the figure foregrounds design and management levers as mechanisms for shifting trade-offs, rather than treating performance as an inherent property of a cultivation method. By pairing this workflow with an MCDA-ready matrix template, the figure provides a transparent structure for comparing methods using consistent criteria, including cost-boundary assumptions, environmental-risk profiles, and evidence strength.

Figure 6. Decision Matrix for Best-Fit Technology Selection
Caption: Decision-oriented visual synthesis translating the SLR evidence into a best-fit selection workflow: context profiling, method shortlist, trade-off appraisal, design/management levers, aligned with an MCDA-ready decision matrix.

This approach directly supports the review's central argument that robust decision-making in seaweed aquaculture depends on aligning system design, techno-economic boundaries, and environmental-risk management within specific ecological and institutional contexts, rather than relying on universal rankings or single-metric optimization.

Nearshore longlines illustrate this logic. Nearshore kelp can achieve viable harvests (e.g., 12.7 kg m^{-1} over an ~8-month period at exposed sites using low-cost designs), while *Kappaphycus* density optimization shows higher stocking maximizes final biomass but reduces growth efficiency (Mulyani & Cahyono, 2025). However, conventional single-layer longlines are among the more expensive options (USD 4.44 kg^{-1} dw) unless redesigned to improve space efficiency (Wu et al., 2023). Environmentally, longlines face persistent biofouling and disease risks, with epibiont dynamics showing strong seasonal effects (PERMANOVA $F_{4,25} = 100.56$, $p < 0.001$) that can render biomass commercially unviable, alongside benthic modification and biosecurity vulnerabilities (Bhowmik et al., 2025; Corrigan et al., 2023; Rustam & Wamnebo, 2021). Longlines are therefore most suitable where fouling is manageable, biosecurity is effective, and governance reduces spatial conflict.

Raft systems show stronger economic indicators but thinner productivity and environmental datasets. Techno-economic projections suggest rafts outperform tube-nets under supportive policy, achieving IRRs of 35.29%, payback of ~0.7 years, and higher NPVs across Indian coastal states, but only with 40% capital subsidies and explicit labor costing (Ramalingam et al., 2025). Environmental risks are largely inferred from broader nearshore evidence (biofouling, habitat interaction, spatial competition), leaving uncertainty about long-term performance at scale.

Offshore systems prioritize spatial expansion in high-energy environments. Engineering studies show offshore kelp structures can withstand waves (Hs > 2 m; max ~5.9 m), supporting technical feasibility (Moscicki et al., 2024), but yield and cost-efficiency benchmarks remain sparse. Carbon-cycle synthesis further complicates benefit claims: kelp can shift from CO_2 sinks to sources late in growth, with pCO_2 increases of 20–37 μatm (Xiong et al., 2024). Offshore systems may suit regions with ample capital, engineering capacity, and robust monitoring, but require cautious interpretation of economic and environmental advantages.

Land-based systems (tanks, ponds, RAS, IMTA) provide the most controlled but capital- and energy-intensive profile. Productivity can be high (e.g., ~9.9% day^{-1} in nutrient-enriched *Gracilaria* and 4.19–5.78% day^{-1} in *Kappaphycus* nurseries) (Gacura et al., 2026; Suriya Narayanan & Ruben Sudhakar, 2025). They also deliver mitigation services NO_3^- reductions up to 39%, CO_2 reductions up to 41%, and carbon storage (8–12.4 g C m^{-2}) supporting nutrient management and biosecurity (Borburema et al., 2026). Yet life-cycle evidence shows energy use, drying/freezing, and infrastructure replacement can dominate footprints and costs, with large farms reporting 57.5 kg CO_2-eq per ton FW and downstream processing as a hotspot (Thomas et al., 2021).

Overall, evidence strength varies by method and dimension: nearshore work provides extensive ecological/biosecurity data but inconsistent economic boundaries; raft systems have scenario-based economic evidence but limited environmental specificity; offshore systems are dominated by engineering/modeling rather than yield benchmarks; and land-based systems show robust mitigation evidence but fragmented cost reporting. Table 4 therefore functions as a decision matrix rather than a ranking, enabling stakeholders to match technologies to objectives while accounting for uncertainty, scale, and context.

Table 4. Integrated Trade-offs and Decision-Relevant Synthesis

No.	Ref.	Cultivation method (category)	Productivity profile (evidence from dataset)	Cost-efficiency profile (evidence from dataset)	Environmental risk / impact profile (evidence from dataset)	Context suitability (best-fit conditions)	Strength of evidence (within dataset)	Design / management levers (reported)
1	Wu et al., (2023)	Longline (nearshore)	Low-cost nearshore kelp (*S. latissima*) system: 12.7 kg m^{-1} harvested over ~8 months (St-Gelais et al., 2022). Productivity varies with platform/gear design and stocking density (e.g., *Kappaphycus* density trials; numerical detail is often incomplete in abstracts).	Multi-platform TEA indicates single-layer longlines have relatively high cultivation costs: ~USD 4.44 kg^{-1} dw (Wu et al., 2023). Low-cost nearshore systems target low capital access and report ~8% returns (St-Gelais et al., 2022).	Key risks: strong seasonal biofouling/epibiont dynamics that can make biomass commercially unviable (Corrigan et al., 2023). Benthic effects include altered sedimentation and enrichment under long-term *Kappaphycus* farming (Bhowmik et al., 2025). Biosecurity/disease (ice-ice, pests) require controls (Rustam et al., 2021; Kambey et al., 2021; Faisan et al., 2025). Farms can increase pH and reduce pCO_2 but also increase pH variability	Best fit for nearshore/coastal areas with easy logistics; community to commercial scales; clear zoning/governance. Performance is sensitive to seasonality, currents/nutrients, and fouling/disease pressure.	High for risk evidence (biofouling, benthic, biosecurity) and medium for cost metrics (TEA is system-specific). Monitoring/field evidence is substantial, but productivity metrics are inconsistently reported.	Platform redesign (layering/strip configurations) to reduce costs; harvest timing to reduce fouling; HCCAP/biosecurity to reduce outbreaks; molecular monitoring to improve epiphyte detection.
2	Ramalingam et al., (2025)	Raft (nearshore; platform-based)	Raft-specific productivity evidence in this dataset is limited in extracted abstracts (often reported as	National-scale projections (India) show rafts outperform tube-nets under supportive	Environmental risks are likely similar to other nearshore platforms (space conflicts, habitat interaction, fouling/disease), but the extracted	Best fit for sheltered–moderate coastal settings with adequate labor and	Medium for economic evidence (clear TEA/NPV/IRR), low–medium for productivity	Subsidy structure and labor-cost treatment as primary feasibility levers;

			economic context rather than yield outcomes).	policy: IRR 35.29% (raft) vs 28.57% (tube-net); payback 0.7 vs 0.8 years (Ramalingam et al., 2025). Positive NPVs occur only with 40% capital subsidy and explicit labor costing (Ramalingam et al., 2025).	abstracts do not consistently quantify raft-specific impacts.	investment support where business models depend on subsidy structures.	and raft-specific environmental risk (dependent on full-text and yield-focused studies).	integration of biosecurity and fouling management practices adapted from nearshore literature.
3	Moscicki et al., (2024)	Offshore (exposed / open-water)	Productivity evidence is often sparse, but structural survivability is reported: offshore kelp systems can withstand storms (Hs > 2 m; max wave ~5.9 m) yet face operational issues and poor holdfast attachment (Moscicki et al., 2024). Open-sea gear studies show trade-offs: higher DGR in monoline but higher yield per meter in tube-nets (Kavale et al., 2021).	Direct offshore cost evidence is limited in abstracts, but platform and LCA/LCC evidence indicates gear/anchor replacement can dominate long-term impacts and costs (e.g., Collins et al., 2022).	Offshore-specific risks include monitoring/access constraints, gear loss and storm damage, and navigation/space-use conflicts. Climate-benefit claims are conditional: mature kelp can shift from CO_2 sink to source (pCO_2 +20–37 μatm) due to DOC mineralization	Best fit where offshore space, engineering and vessel capacity, and monitoring capability exist; relevant to large-scale expansion and multi-use offshore planning, requiring strong governance and safety standards.	Low–medium for productivity/cost (engineering/pilot dominated), medium for process-based environmental evidence (CO_2 dynamics) and gear-related concerns.	Mooring/anchor design and tension control; gear selection (monoline vs tube-net) to balance DGR vs yield; harvest timing and seasonal accounting for CO_2 claims.
4	Suriya Narayanan & Ruben Sudhakar, (2025)	Land-based (tanks/pond/RAS; incl. IMTA & biofloc)	Controlled settings often yield strong productivity evidence: *Gracilaria edulis* under PMES reached DGR 9.9 ± 0.9% day^{-1} and 202.5 ± 12.6 mg DW L^{-1} (Suriya Narayanan & Ruben Sudhakar,	Land-based costs are commonly driven by energy/water and infrastructure; abstracts emphasize drying/freezing as major cost and impact hotspots in supply chains (Thomas et al.,	Strong evidence for ecosystem services: IMTA/RAS reduces nutrients and CO_2 (e.g., NO_3^- 7–39% ambient; CO_2 −41%) and stores carbon (Borburema et al., 2026). *Ulva* in effluents rapidly removes NH_4^+ and achieves high NO_3^- removal (Massocato et al., 2022). In biofloc, *Ulva* reduced	Best fit for contexts with reliable energy and infrastructure; high biosecurity needs (seedstock/propagules); integration with intensive aquaculture	Medium–high for nutrient-removal/bioremediation evidence; medium for productivity (lab/pilot DGR results); low–medium for pure cultivation cost evidence	Nutrient/media optimization to reduce inputs; IMTA integration to convert waste streams into ecosystem services; preservation choices (e.g.,

	2025). Land nurseries for *Kappaphycus* reported 4.19–5.78% day^{-1} (Gacura et al., 2026). Systems can also prioritize propagule output (Oyarzo et al., 2021).	2021; Wu et al., 2023). Cost per kg for land-based cultivation is often not fully reported in abstracts.	nitrate 57% and phosphate 47% (Carvalho et al., 2024). Key risks include energy/water footprints and effluent burdens (inferred from LCA/preservation evidence).	(IMTA/biofloc); or where marine space is constrained.	(often missing in abstracts).	ensiling vs drying/freezing) to reduce downstream i

V. DISCUSSION

The synthesis of evidence across productivity (Section 4.1), cost efficiency (Section 4.2), environmental risks (Section 4.3), and integrated trade-offs (Section 4.4) demonstrates that seaweed aquaculture systems are characterized by systematic trade-offs rather than linear performance hierarchies. Across cultivation methods, higher productivity is frequently associated with increased resource inputs, technological complexity, or spatial expansion, which in turn elevate cost and/or environmental risk. This pattern is evident in land-based and IMTA systems, where high growth rates and nutrient-removal benefits are achieved through controlled inputs and infrastructure, but at the expense of higher operational costs and energy demand (Tables 1, 3, and 4), consistent with broader observations that intensification can amplify environmental and economic pressures if not carefully managed (Costa et al., 2021; Guo et al., 2025).

Contextual conditions strongly mediate these trade-offs. Nearshore longline and raft systems benefit from lower capital requirements and accessibility, yet their productivity and effective cost efficiency are highly sensitive to seasonality, biofouling, disease pressure, and governance arrangements (Tables 1–4). Offshore systems illustrate a contrasting profile: exposure and improved water exchange may support growth potential, but higher CAPEX/OPEX, engineering demands, and monitoring challenges constrain economic and environmental robustness (Coleman et al., (2022); Tables 2 and 4). Land-based systems perform best under conditions of strong infrastructure, energy access, and biosecurity, but their scalability is limited where such inputs are constrained (Guo et al., 2025). These findings reinforce that “best” cultivation methods are context-specific, shaped by exposure, scale, species, logistics, and institutional capacity (Nobre et al., 2025).

A major barrier to stronger comparative conclusions lies in methodological inconsistency. Differences in productivity metrics (wet vs dry weight), cost boundaries (CAPEX/OPEX inclusion, labor valuation), and environmental indicators complicate cross-study synthesis and can distort perceived performance advantages (Coleman et al., 2022; Gao et al., 2021; Hurd et al., 2022). Nevertheless, the reviewed literature also provides evidence that technology design and management levers such as IMTA integration, platform redesign, biosecurity protocols, and data-driven monitoring can partially mitigate yield, cost, risk trade-offs when aligned with local conditions (Kou et al., 2022; Satyam & Patra, 2024); Tables 2–4).

Given these complexities, the value of integrated decision frameworks becomes clear. Evidence mapping, MCDA, and decision matrices such as the synthesis presented in Table 4 offer transparent tools for aligning cultivation technologies with policy goals and site-specific constraints (McGurrin et al., 2023; Moreira et al., 2021; Subbiah et al., 2023). However, persistent research gaps remain, particularly the lack of standardized metrics and harmonized assessment protocols, as well as limited attention to socio-economic outcomes at community scale (Pausch et al., 2024; Rodrigues et al., 2025; Ross et al., 2022). Addressing these gaps is essential for enabling scalable, comparable, and sustainable seaweed aquaculture development..

VI. CONCLUSION

This systematic literature review provides a comprehensive, method-focused synthesis of evidence on seaweed cultivation technologies, comparing longline, raft, offshore, and land-based systems through the integrated lenses of productivity, cost efficiency, and environmental risk. Across the reviewed literature, no cultivation method emerges as universally superior. Instead, performance outcomes are shaped by context-dependent trade-offs, where improvements in productivity are often accompanied by higher costs, increased operational complexity, or elevated environmental risks.

The review demonstrates that land-based and integrated systems (e.g., RAS and IMTA) offer high controllability, stable growth rates, and strong nutrient-mitigation potential, but frequently shift burdens toward energy use, infrastructure, and operating costs. Nearshore longline and raft systems remain attractive for their lower capital barriers and accessibility, yet they are highly sensitive to seasonality, biofouling, disease, and spatial conflicts, which can undermine both productivity and cost efficiency. Offshore systems present opportunities for spatial expansion and exposure-driven growth advantages, but evidence remains dominated by engineering feasibility rather than robust productivity and economic benchmarks, while environmental benefits—particularly related to carbon dynamics—are more conditional than often assumed.

A central contribution of this SLR lies in highlighting that limitations in comparability across studies, rather than a lack of evidence, constrain robust technology assessment. Inconsistent productivity metrics (wet vs dry basis, normalization by area or time), heterogeneous techno-economic boundaries (CAPEX/OPEX treatment, labor valuation, depreciation), and fragmented environmental-risk frameworks reduce the transferability of findings. To address these challenges, this review advances an integrated decision-oriented framework that explicitly links cultivation-system design to yield potential, cost drivers, environmental risks, and contextual suitability.

Future research should prioritize head-to-head comparisons of cultivation methods under comparable environmental conditions, standardized reporting of productivity and cost metrics, and integrated assessments that combine techno-economic analysis with environmental-risk and life-cycle perspectives. Such efforts are essential for enabling scalable, transparent, and sustainable development of seaweed aquaculture aligned with both industry needs and environmental governance objectives.

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