

# From Marine Carbon Dioxide Removal to Circular Blue Bioeconomy: A Systematic Review of Seaweed Cultivation, Verification, and Sustainability Trade-offs

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## Key Words:

Seaweed cultivation, marine carbon dioxide removal (mCDR), blue carbon, circular blue bioeconomy, carbon accounting.

**Abstract:** Seaweed cultivation has gained global attention as a potential marine carbon dioxide removal (mCDR) strategy and as a cornerstone of the emerging circular blue bioeconomy. However, claims regarding its climate mitigation potential remain scientifically contested and unevenly governed. This systematic literature review synthesizes evidence across four interlinked dimensions: (i) carbon accounting, verification, and permanence; (ii) ecosystem and biogeochemical sustainability trade-offs; (iii) monitoring, MRV readiness, and spatial governance; and (iv) circular bioeconomy valorisation pathways.

Drawing on multidisciplinary studies spanning modeling, field measurements, life cycle assessment, remote sensing, spatial planning, and biorefinery research, the review finds that high biomass productivity does not equate to verified atmospheric CO<sub>2</sub> removal. Credible mCDR outcomes depend critically on system boundary definition, carbon fate, residence time, and conservative treatment of substitution and leakage. Ecosystem impacts are highly context-specific, with integrated mariculture systems delivering both co-benefits and feedbacks that complicate net climate claims. While monitoring and spatial planning tools have advanced rapidly, standardized MRV pipelines linking observation to verification remain underdeveloped.

The review further shows that circular valorisation pathways provide a more robust and immediate rationale for scaling seaweed cultivation than carbon offsets alone, although they face constraints related to quality, safety, logistics, and end-of-life management. Overall, this review proposes an integrative framework that positions seaweed cultivation primarily within the circular blue bioeconomy, with mCDR treated as a conditional co-benefit supported by transparent uncertainty reporting and conservative claims. This synthesis offers actionable insights for researchers, policymakers, and investors seeking responsible pathways for ocean-based climate and sustainability solutions

## Introduction

Seaweed cultivation has emerged at the intersection of marine carbon dioxide removal (mCDR), coastal ecosystem management, and the circular blue bioeconomy, positioning macroalgae as a prominent nature-based solution within contemporary climate and sustainability agendas. Globally, the expansion of seaweed farming aligns with sustainable development goals and climate mitigation efforts, as cultivated seaweeds directly assimilate CO<sub>2</sub> through photosynthesis and generate large quantities of biomass, suggesting potential scalability as a marine-based climate solution (Gao et al., 2021; Mendes et al., 2024). Beyond climate mitigation narratives, seaweed systems are increasingly valued for their multifunctional ecosystem services, including habitat provision, nutrient cycling, shoreline protection, and pollution mitigation, which strengthen their relevance within integrated coastal management and blue economy frameworks (Cotas et al., 2023; El-Gendy & Nassar, 2024).

At the same time, scientific and governance scrutiny is intensifying. While seaweed cultivation is frequently framed as carbon neutral or carbon negative, growing evidence highlights constraints related to spatial scale, biogeochemical feedbacks, and ecological trade-offs that challenge simplified claims of climate benefits (Albrecht, 2023; Arantzamendi et al., 2023). Concerns have also been raised regarding bioethics, biodiversity impacts, and social legitimacy, particularly where rapid expansion outpaces regulatory capacity or meaningful stakeholder engagement (Skondras et al., 2024; Stephenson & Damerell, 2022). Consequently, the role of seaweed cultivation within mCDR and the blue bioeconomy is increasingly understood as conditional rather than universal, requiring careful governance, monitoring, and contextual evaluation (Morone et al., 2023; Paris et al., 2025). This tension motivates a critical reassessment of prevailing assumptions that high productivity automatically translates into verified carbon dioxide removal, that co-benefits are guaranteed, or that scaling inherently ensures sustainability. Despite rapid growth in the literature, evidence linking seaweed cultivation to credible atmospheric CO<sub>2</sub> removal remains highly fragmented. Research spans multiple domains—marine biogeochemistry, aquaculture engineering, ecosystem ecology, monitoring and verification (MRV), spatial planning, and industrial valorisation yet these strands are rarely integrated. As a result, studies often adopt inconsistent system boundaries, baselines, and methodological assumptions, leading to divergent conclusions and limited comparability across regions and cultivation systems. This fragmentation undermines the robustness of claims related to carbon sequestration, sustainability co-benefits, and policy relevance, particularly in the context of

emerging carbon markets and blue growth strategies.

This systematic literature review aims to consolidate and critically synthesize current knowledge on seaweed cultivation as a component of mCDR and the circular blue bioeconomy. Specifically, the objectives are to: (i) evaluate the credibility of seaweed-based CDR claims, including accounting approaches, permanence, and leakage; (ii) assess sustainability trade-offs, encompassing ecological, biogeochemical, and biodiversity impacts; (iii) examine the role of monitoring technologies, MRV frameworks, and spatial governance in enabling responsible scaling; and (iv) synthesize evidence on circular valorisation and biorefinery pathways that link biomass production to economic resilience. Through this synthesis, the review develops an integrative framing that distinguishes short-term carbon uptake from durable atmospheric CO<sub>2</sub> removal and aligns climate mitigation claims with ecological thresholds and viable economic pathways.

The review focuses on cultivated seaweeds, encompassing nearshore, offshore, and integrated multi-trophic aquaculture (IMTA) systems. It includes a wide range of evidence types, such as modeling studies, field experiments, cultivation and industry assessments, monitoring and remote sensing applications, spatial suitability analyses, biorefinery and valorisation research, and sustainability assessments. The analytical boundaries are confined to marine and coastal environments, with explicit attention to connections between carbon accounting, ecosystem interactions, and downstream product pathways.

Guided by these considerations, this review addresses four research questions: (1). RQ1: Under what conditions can seaweed cultivation deliver verifiable atmospheric CO<sub>2</sub> removal, and what are the main constraints related to accounting and permanence?; (2). RQ2: What ecological and biogeochemical trade-offs emerge at farm-to-ecosystem scales, including within integrated mariculture systems?; (3). RQ3: How can monitoring technologies, MRV frameworks, and spatial planning enable credible and responsible scaling of seaweed cultivation?; (4). RQ4: Which valorisation pathways best support a circular blue bioeconomy while reducing incentives to overclaim CDR benefits?

The remainder of this article is organized as follows. Section 2 describes the systematic review methodology, including search strategy, eligibility criteria, and synthesis approach. Section 3 outlines the theoretical background underpinning mCDR, socio-ecological systems, and circular bioeconomy perspectives. Section 4 presents the findings across four thematic areas: CDR credibility, sustainability trade-offs, monitoring and spatial governance, and circular valorisation

pathways. Section 5 discusses cross-cutting insights, uncertainties, and implications for science, policy, and practice. The review contributes an integrated decision framework that links carbon verification, ecosystem effects, governance readiness, and circular bioeconomy strategies, offering a coherent basis for evaluating the role of seaweed cultivation in climate mitigation and sustainable blue growth.

## Research Methods

This systematic literature review was designed and conducted following established best practices in environmental and sustainability research, with particular attention to transparency, reproducibility, and methodological rigor in the rapidly evolving field of marine carbon dioxide removal (mCDR) and seaweed-based systems.

### 2.1 Search Strategy

The primary literature search was conducted using **Scopus**, selected for its broad of peer-reviewed and journals. To ensure comprehensive coverage and minimize database bias, the search was supplemented with **Web of Science**, **ScienceDirect**, **SpringerLink**, **Wiley Online Library**, and **IEEE Xplore** (particularly for studies related to monitoring technologies and remote sensing). **Google Scholar** was employed for backward and forward snowballing to identify additional relevant studies not captured in the core database searches. The combined use of these databases is widely recognized as effective for capturing the breadth of scholarship on seaweed-based mCDR and blue bioeconomy pathways (Roeschel, 2025).

Search strings were developed iteratively to balance sensitivity and specificity, drawing on prior systematic reviews and domain-specific terminology (Lovelock & Duarte, 2025; Roeschel, 2025). Illustrative keyword clusters included:

- *Seaweed* OR *kelp* OR *macroalgae* AND ("carbon dioxide removal" OR *CDR* OR "blue carbon" OR *sequestration* OR *sinking* OR *burial*)
- *Seaweed aquaculture* OR *farming* OR *mariculture* OR *IMTA* AND ("carbon accounting" OR *MRV* OR *verification* OR *permanence* OR *leakage*)
- *Seaweed* AND (*remote sensing* OR *satellite* OR *hyperspectral* OR *spectral* OR *monitoring*)
- *Seaweed* AND (*GIS* OR *suitability* OR *site selection* OR *spatial planning*)
- *Seaweed* AND (*biorefinery* OR *valorisation* OR "circular bioeconomy" OR *LCA* OR *TEA* OR *contaminants*)

Additional keywords related to ecological impacts and sustainability challenges (e.g., *blue carbon ecosystems*, *sustainable aquaculture practices*) were incorporated to capture studies addressing environmental trade-offs and governance considerations (Lovelock & Duarte, 2025; Omoto et al., 2024).

The temporal scope of the search was justified based on the evolution of seaweed cultivation and mCDR research, with emphasis on contemporary literature reflecting advances in monitoring, carbon accounting, and policy relevance. Only **English-language, peer-reviewed**

**articles** were included, alongside a limited number of high-quality reports or standards where directly relevant. Full documentation of search strings, databases queried, search dates, and result counts was maintained to ensure transparency and reproducibility, consistent with PRISMA recommendations (Roeschel, 2025).

## 2.2 Eligibility Criteria

Studies were eligible for inclusion if they were empirical, modeling-based, or review articles that directly addressed at least one of the following dimensions: (i) mCDR mechanisms, carbon fate, or accounting frameworks; (ii) ecological or biogeochemical impacts of seaweed cultivation; (iii) monitoring technologies, MRV systems, or spatial planning approaches; or (iv) valorisation, biorefinery pathways, and sustainability metrics within the blue bioeconomy. Eligible studies were required to provide a clear description of the seaweed species or system studied and report measurable outcomes, such as carbon fluxes, ecological indicators, monitoring performance, or product and supply-chain metrics (Gao et al., 2021; Sutrisno et al., 2024).

Studies were excluded if they did not involve seaweed or macroalgae cultivation contexts, lacked empirical or model-based evidence, were purely conceptual without analyzable claims, or were not aligned with the defined research objectives. Non-peer-reviewed literature, duplicate records, and studies reporting irrelevant outcomes were also excluded to maintain analytical focus and quality (Torres et al., 2024).

Quality appraisal was embedded throughout the screening and synthesis process. Methodological rigor was assessed based on clarity of system boundary definition, representativeness of study design, validation of methods or models, transparency of assumptions, and treatment of uncertainty. Where applicable, established appraisal frameworks such as **PRISMA** used to evaluate the reliability and robustness of included studies, particularly for secondary reviews (Gao et al., 2021; Torres et al., 2024).

## 2.3 Screening and Selection

All retrieved records were subjected to a structured screening workflow consisting of de-duplication, title and abstract screening, full-text eligibility assessment, and final inclusion. Where feasible, a dual-screening approach was applied, with discrepancies resolved through discussion to reduce selection bias and enhance consistency (Roeschel, 2025).

Data extraction was conducted using standardized templates designed to capture key study characteristics, including system type, geographic location, methodological approach, reported outcomes, and sources of uncertainty (Gao et al., 2021; Sutrisno et al., 2024). Extracted studies

were coded into four thematic categories corresponding to the review objectives: CDR credibility, sustainability trade-offs, monitoring and spatial governance, and circular valorisation pathways.

Synthesis was primarily qualitative, employing **narrative synthesis and thematic analysis** to integrate heterogeneous evidence from biogeochemical, ecological, technological, and economic domains (Appiah-Danquah et al., 2025). Where sufficient methodological homogeneity existed, quantitative comparisons were noted, although formal meta-analysis was limited by variability in metrics and system boundaries. This mixed-methods approach enabled a comprehensive assessment of convergence, divergence, and evidence gaps across the literature (Gao et al., 2021; Sutrisno et al., 2024).

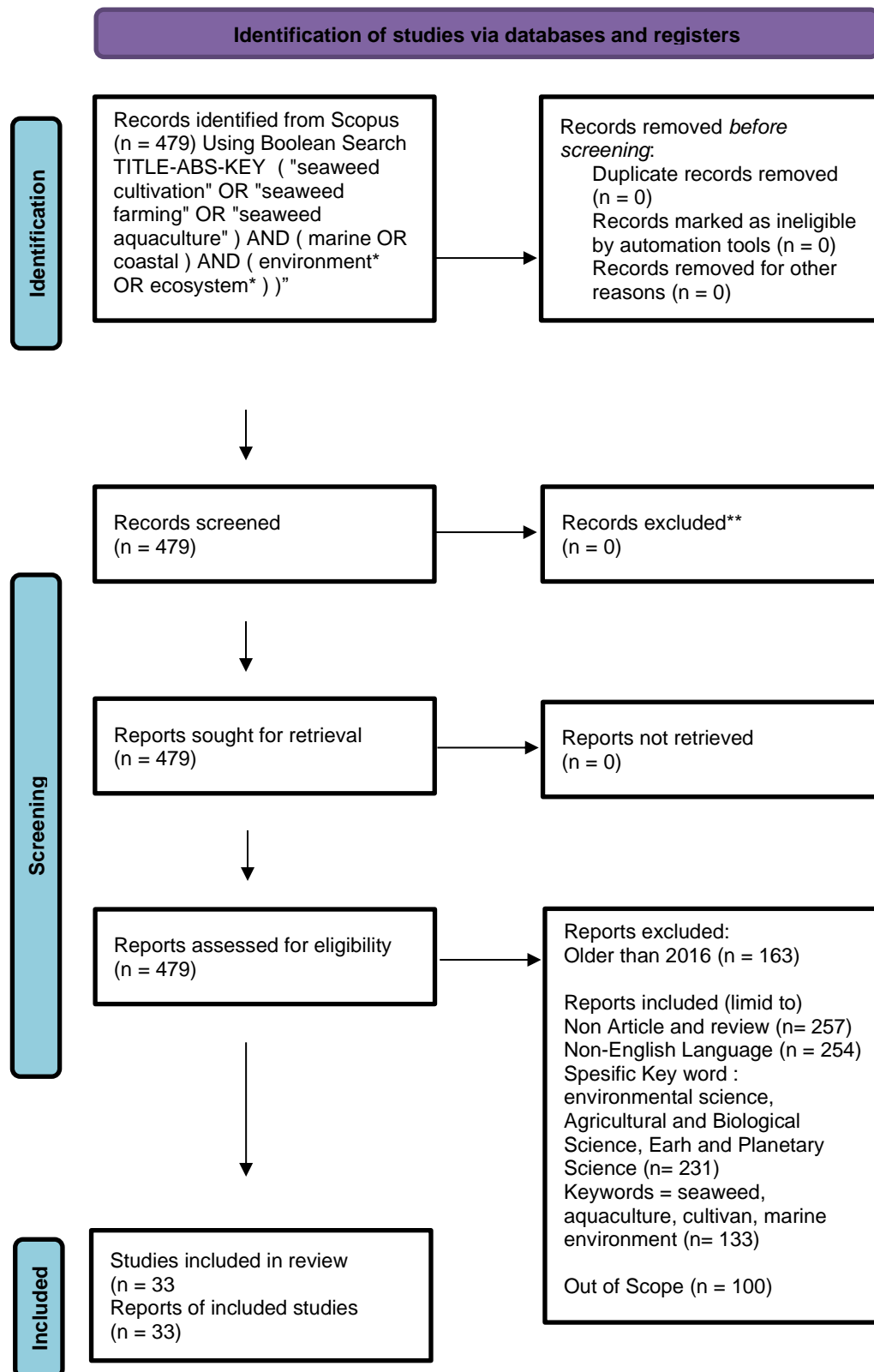


Figure 1. The PRISMA flow diagram detailing the screening and selection process of literature.

The study selection process is summarized in **Figure 1**, presented as a PRISMA flow diagram detailing the identification, screening, eligibility, and inclusion stages, including the

number of records at each step and reasons for exclusion. This visualization supports transparency and reproducibility in accordance with best practices for systematic reviews in mCDR and sustainability research (Roeschel, 2025).

## Research Results

### 4.1 CDR Credibility: Carbon Accounting, Permanence, and Verification

The literature synthesized in this theme demonstrates that the credibility of seaweed-based marine carbon dioxide removal (mCDR) hinges on how carbon uptake is translated into verifiable atmospheric CO<sub>2</sub> removal, with particular sensitivity to accounting boundaries, permanence assumptions, and monitoring and verification (MRV) approaches. Across studies, a consistent finding is that high primary productivity or large-scale biomass production does not, by itself, constitute credible CDR, echoing broader theoretical distinctions between biomass growth and atmospheric CO<sub>2</sub> drawdown articulated in earlier sections (Duarte et al., 2022; Fay et al., 2021; Macreadie et al., 2021).

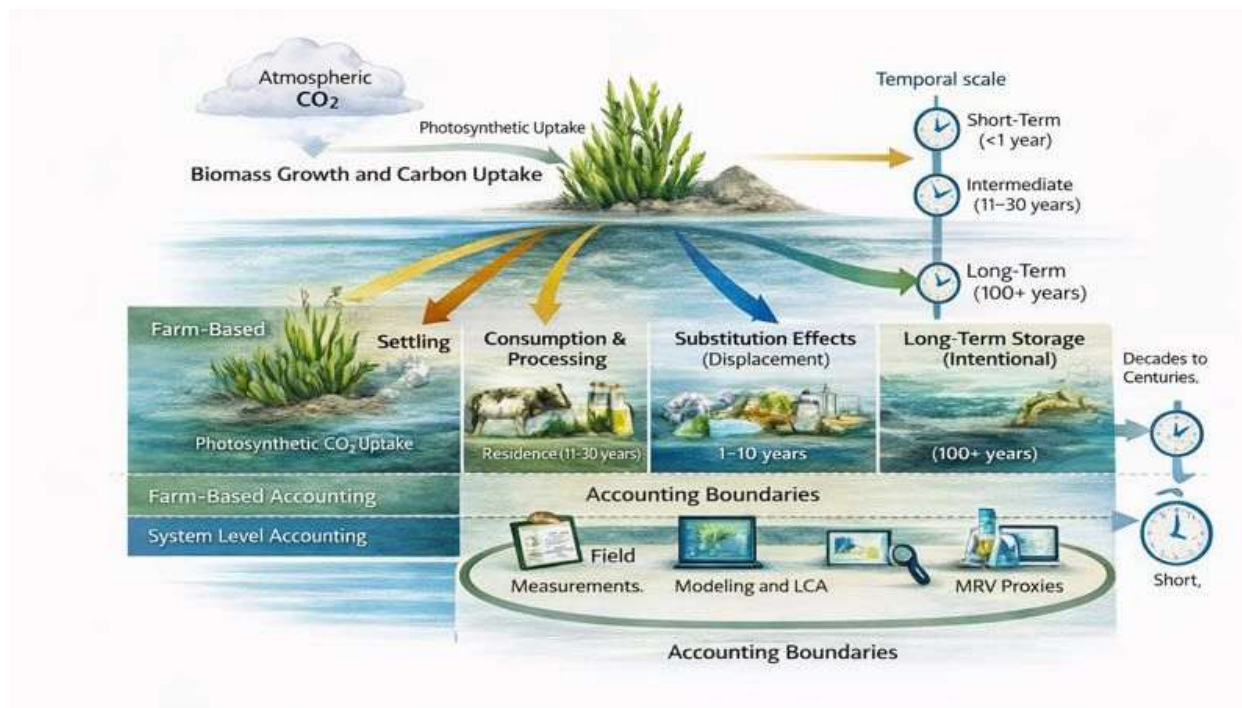


Figure 3. Carbon accounting, verification, and permanence pathways in seaweed-based mCDR

Figure 3 synthesizes the core accounting challenges underlying seaweed-based marine carbon dioxide removal by explicitly tracing alternative carbon fate pathways from initial photosynthetic uptake to potential long-term storage. The figure illustrates how carbon fixed into

seaweed biomass may follow divergent trajectories, including rapid remineralization, harvest and processing for consumption or materials, indirect displacement or substitution effects, and intentional long-term storage pathways such as deep-ocean sinking or incorporation into durable products. By overlaying farm-only, system-level, and supply-chain-inclusive accounting boundaries, the figure demonstrates that apparent climate outcomes are highly sensitive to what emissions, offsets, and feedbacks are included or excluded from assessment. Temporal scales spanning days to decades further emphasize that permanence, rather than productivity, determines whether a pathway can plausibly contribute to atmospheric CO<sub>2</sub> removal. The inclusion of monitoring, reporting, and verification (MRV) proxies such as field measurements, biogeochemical modeling, and life cycle assessment highlights how evidence is generated and where uncertainty accumulates across boundaries and time horizons. Collectively, the figure reinforces a central finding of this review: high biomass growth alone does not constitute verified mCDR, and conservative boundary definition combined with explicit treatment of carbon residence time is essential for credible climate claims.

Conceptual and expert-driven analyses emphasize that the inclusion of seaweed within carbon markets remains conditional. (Nishihara et al., 2025) synthesize expert perspectives across regions and conclude that seaweed systems can only qualify as “blue carbon” projects if MRV is demonstrably credible at the project level and if additionality is clearly established relative to background variability and policy-driven baselines. The study highlights that uncertainty in monitoring feasibility, carbon fate, and co-benefits or harms undermines legitimacy, reinforcing calls for standardized MRV protocols and explicit permanence criteria before carbon credits can be issued.

Empirical evidence further illustrates how accounting boundaries critically shape outcomes. (Liu et al., 2025), using field-based carbonate chemistry and air - sea CO<sub>2</sub> flux measurements (pCO<sub>2</sub>-derived flux rates) in Sansha Bay, China, demonstrate that macroalgae cultivation embedded within integrated mariculture can shift from an apparent CO<sub>2</sub> sink to a net source when adjacent fish farming is included in the system boundary. Their results show increased CO<sub>2</sub> outgassing associated with fish-derived dissolved inorganic carbon, quantitatively reducing and in some cases reversing the CO<sub>2</sub> removal capacity attributed to seaweed alone. This finding exemplifies leakage effects discussed in mCDR theory and underscores the necessity of ecosystem-scale rather than farm-only accounting.

Model-based assessments explore intentional long-term storage pathways but reveal strong dependence on temporal assumptions. (Ye et al., 2024) model national-scale scenarios (2020–

2050) for the deliberate sinking of surplus seaweed biomass in China and estimate that meaningful CDR outcomes depend on assumed “sink efficiency,” defined as the proportion of carbon retained after multiple decades. Their scenarios indicate that permanence is only achieved on time horizons exceeding several decades, while operational constraints such as the availability of genuine surplus biomass and logistics limit near-term deployment. These results reinforce theoretical debates on durability and the risk of conflating hypothetical long-term storage with immediate climate mitigation benefits.

At larger spatial scales, (Luo et al., 2023) estimate the carbon sink associated with seaweed cultivation along the Chinese coast between 2000 and 2019, using production-area-based carbon calculations. Their analysis explicitly separates total carbon production from the fraction plausibly sequestered, demonstrating that only a subset of cultivated biomass contributes to long-term storage. Expansion scenarios further reveal that increases in cultivated area are constrained by nearshore space availability and potential coastal ecosystem impacts, quantitatively linking CDR potential to spatial governance considerations.

Life cycle–based studies consistently show that net climate outcomes depend on supply-chain emissions and substitution assumptions. Wu et al., (2025) conduct a comparative life cycle assessment (LCA) of wakame (*Undaria pinnatifida*) and kelp (*Saccharina japonica*) cultivated on floating rafts in China and find that materials such as polyethylene cultivation lines and at-sea operations dominate environmental burdens. Sensitivity analyses indicate that small design changes can reduce impacts, but also that nutrient-removal or food-substitution credits if included can numerically exceed direct life-cycle emissions, highlighting the need for transparent and conservative offset assumptions. Similarly, (Thomas et al., 2021), analyzing the hatchery–farm preservation chain of *Saccharina latissima* in Sweden, show that while carbon uptake is measurable, it is inherently temporary unless coupled with durable storage pathways; preservation choices alone can substantially alter emissions profiles.

Techno-economic and LCA integration further underscores substitution sensitivity. (West et al., 2023) evaluate cultivation systems and end-use scenarios for *Saccharina latissima* and *Gracilaria tikvahiae* in the northeastern United States and demonstrate that drying is a dominant cost and emissions driver, while high-offset pathways such as anaerobic digestion require strong policy incentives to be viable. Their results quantitatively illustrate how displaced products (e.g., land-based vegetables, coal-based electricity, synthetic fertilizers) fundamentally determine whether a system appears climate-positive or not.

Taken together, these studies converge on a core insight: credible seaweed-based mCDR

requires explicitly defined system boundaries that encompass co-located aquaculture and supply chains, conservative treatment of substitution credits, and clear differentiation between short-lived biomass carbon and durable storage. Without such rigor, claims of carbon removal risk overstating mitigation potential, a concern repeatedly raised in both conceptual (Nishihara et al., 2025) and empirical (Liu et al., 2025; H. Wu et al., 2025) analyses.

Table 1. Carbon accounting, verification (MRV), and permanence trade-offs in seaweed-based marine CDR and blue carbon claims

No.	Ref.	Study focus (system/region)	CDR pathway / blue-carbon claim addressed	Quantification approach (MRV proxy)	Key accounting boundary & assumptions	Permanence, leakage, and sustainability trade-offs highlighted
1	(Nishihara et al., 2025)	Conceptualization of seaweed “blue carbon” projects (multi-region; expert community)	Whether/when seaweed systems qualify as “blue carbon” can be credited in carbon markets	Expert elicitation / structured survey of specialists; synthesis of consensus vs divergences	MRV must be credible at project level; boundaries must separate <i>additional</i> carbon removal from background variability and market/policy drivers	Challenges: method uncertainty, monitoring feasibility, co-benefits/harms, policy legitimacy; need standardized MRV and clear permanence criteria
2	Liu et al., (2025)	Integrated mariculture with fish farming + macroalgae in a coastal bay (Sansha Bay, China)	Seaweed cultivation as CO <sub>2</sub> sink can be offset or reversed by co-located carbon inputs	Field carbonate chemistry + air-sea CO <sub>2</sub> flux calculations (pCO <sub>2</sub> and CO <sub>2</sub> flux rates)	Treating macroalgae farm as a sink requires boundary that includes adjacent/embedded aquaculture emissions (e.g., fish-derived DIC/CO <sub>2</sub> )	Fish farming increased CO <sub>2</sub> outgassing and reduced CO <sub>2</sub> removal capacity; highlights “leakage” via co-production systems and

							the need for integrated accounting
3	Ye et al., (2024)	Strategic deployment of “sinking surplus seaweeds” to deep sea (China; national-scale scenarios 2020–2050)	Permanent sequestration via intentional sinking as an mCDR pathway	Scenario modeling across SSP–RCP pathways; estimates carbon removal potential and deployment timing	Assumes defined “sink efficiency” over time (e.g., % retained after decades) operational constraints (harvestable surplus, logistics)	a Permanence depends on long time horizons (decades+); scheduling and coastal replenishment affect feasibility; risk that near-term sinking may reduce food value unless surplus is available	
4	Luo et al., (2023)	National assessment of seaweed cultivation’s carbon sink and environmental co-benefits (China coast; 2000–2019)	Role of large-scale cultivation in carbon sequestration and potential expansion	Data-driven carbon sink estimation from cultivation area/yield; scenario of added farming area	Separates total seaweed carbon production from fraction plausibly sequestered; expansion scenarios assume suitable nearshore area and stable productivity	Highlights that only a portion of produced carbon translates into long-term sequestration; expansion pressures intersect with spatial constraints and coastal ecosystem effects	
5	Wu et al., (2025)	Comparative LCA of two farmed seaweeds (wakame <i>Undaria</i> )	Net climate value depends on farm supply-chain emissions,	Process-based LCA; sensitivity scenarios for seedling density and	Boundary includes materials/energy for cultivation; credits/offsets	Farm materials (e.g., polyethylene lines) and at-sea	

		<i>pinnatifida</i> vs not just cultivation- kelp biomass growth <i>Saccharina japonica</i> ; China; floating rafts)			from nutrient removal or food substitution require transparent assumptions	operations dominate impacts; small design changes can reduce burdens; nutrient-removal credits can dwarf life-cycle emissions and must be treated carefully
6	Thomas et al., (2021)	LCA of kelp hatchery–farm–preservation chain ( <i>Saccharina latissima</i> ; Sweden; multiple preservation methods)	“Carbon capture” and bioremediation claims must reflect temporality and storage fate	Comparative LCA including nutrient uptake and carbon capture indicators	Accounts for hatchery, grow-out, and preservation; carbon uptake considered as temporary without long-term storage	Preservation choices can shift emissions substantially; carbon removal is not permanent unless coupled to durable storage pathways (e.g., long-lived products or deep-sea sequestration)
7	Wu et al., (2023)	Techno-economic LCA evaluation of cultivation systems and end-uses	“Net benefit” + depends strongly on end-use (food vs energy/fertilizer offsets)	TEA + LCA across cultivation designs and processing/end-use scenarios	Offset accounting depends on displaced products (e.g., land-based vegetables, coal	Drying is a major cost/impact driver; high-offset pathways (anaerobic

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(Northeast U.S.; <i>Saccharina</i> <i>latissima</i> and <i>Gracilaria</i> <i>tikvahiae</i> )	electricity, synthetic fertilizer) and processing choices (drying, transport)	digestion) may need policy incentives; illustrates sensitivity of climate claims to substitution baselines
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**Note (for later manuscript use):** The studies above imply that credible mCDR claims require (i) explicitly defined system boundaries (including co-located aquaculture and supply chains), (ii) transparent baseline and substitution assumptions, and (iii) permanence treatment that distinguishes short-lived biomass carbon from durable storage pathways.

#### 4.2 Sustainability Trade-offs: Ecosystem, Biogeochemical, and Biodiversity Impacts

- The studies synthesized under this theme reveal that the sustainability outcomes of seaweed cultivation are highly context-dependent, shaped by cultivation configuration, co-located activities, and environmental baselines. Consistent with socio-ecological systems theory discussed earlier (Duarte et al., 2022; Macreadie et al., 2021), seaweed farms operate as coupled ecological - production systems that can generate both ecosystem services and disservices. As a result, ecological benefits such as nutrient removal or habitat enhancement cannot be assumed a priori, and trade-offs often emerge when systems are evaluated beyond farm-scale productivity metrics.
- At regional scales, evidence shows that structural composition of mariculture systems fundamentally alters biogeochemical outcomes. (Xiong et al., 2023), analyzing multi-year (2003–2020) flux balances of carbon, nitrogen, phosphorus, and oxygen (CNPO) across two major Chinese mariculture provinces, demonstrate that seaweed co-cultivation can either mitigate or exacerbate coastal pressures. In Fujian, where seaweed culture offsets fish-derived inputs, mariculture functioned as a net CNPO sink, whereas in Guangdong, higher fish intensity resulted in a net CNPO source relative to riverine inputs. Quantitatively, these contrasting flux directions imply elevated risks of acidification, eutrophication, and deoxygenation in systems dominated by fed aquaculture, reinforcing the need to treat “blue carbon” and sustainability claims at the system level rather than the crop level (Xiong et al., 2023).

- Seasonal and site-specific dynamics further complicate sustainability assessments. Zhu et al., (2022), drawing on a 70-year history of *Laminaria japonica* cultivation around Taohua Island, report that water quality and plankton community responses vary across seasons. During late cultivation periods (spring), cultured areas exhibited higher pH, dissolved oxygen, and salinity, alongside slightly reduced total phosphorus compared to control sites. Phytoplankton abundance was lower within cultivation areas, while Shannon–Wiener diversity indices were higher, indicating a trade-off between biomass suppression and community diversification. These findings highlight that beneficial signals (e.g., elevated DO) can co-occur with altered plankton dynamics, necessitating season-resolved monitoring frameworks rather than static assessments (Zhu et al., 2022).
- Long-term field studies emphasize the difficulty of attributing ecological change directly to seaweed farming in dynamic coastal systems. Morone et al., (2023), examining oyster–seaweed installations in Matsushima Bay over approximately four years following the 2011 tsunami, find that phytoplankton abundance tracked temperature variability rather than aquaculture presence across most stations. Nutrient enrichment was localized near canal exits, while broader bay stations showed no significant nutrient differences attributable to cultivation infrastructure. Surface-water eukaryote assemblages varied strongly by year and season, with no consistent station-level effects, underscoring the importance of distinguishing farming impacts from background environmental variability and land-based inputs (Morone et al., 2023).
- Experimental evidence under controlled conditions suggests that future climate drivers may intensify productivity - quality trade-offs. Mesocosm experiments on *Ulva lactuca* under factorial combinations of CO<sub>2</sub> (400 vs. 1000 ppm), temperature (20 vs. 24 °C), and nitrate (5 vs. 150 μmol L<sup>-1</sup>) show that maximum growth rates occurred under combined future CO<sub>2</sub>, temperature, and nitrogen conditions, while peak pigment concentrations and optimal nutritional compositions occurred under different parameter combinations (Unspecified, 2024). These results imply that climate change may enhance biomass yields while simultaneously shifting biochemical profiles, with downstream consequences for product quality, nutrient-removal efficiency, and ecosystem interactions.
- Across these studies, a consistent pattern emerges: sustainability outcomes depend not only on whether seaweed is cultivated, but how, where, and with what co-activities. Integrated mariculture can deliver nutrient-cycling benefits and improve local water quality under certain configurations, yet it can also amplify biogeochemical stressors when fed aquaculture dominates, aligning with theoretical concerns about leakage and boundary effects discussed

in earlier sections. Consequently, robust sustainability assessment requires multi-indicator monitoring—including nutrients, oxygen, carbonate chemistry, and biodiversity metrics implemented at appropriate spatial and temporal scales (Morone et al., 2023; Xiong et al., 2023; Zhu et al., 2022).

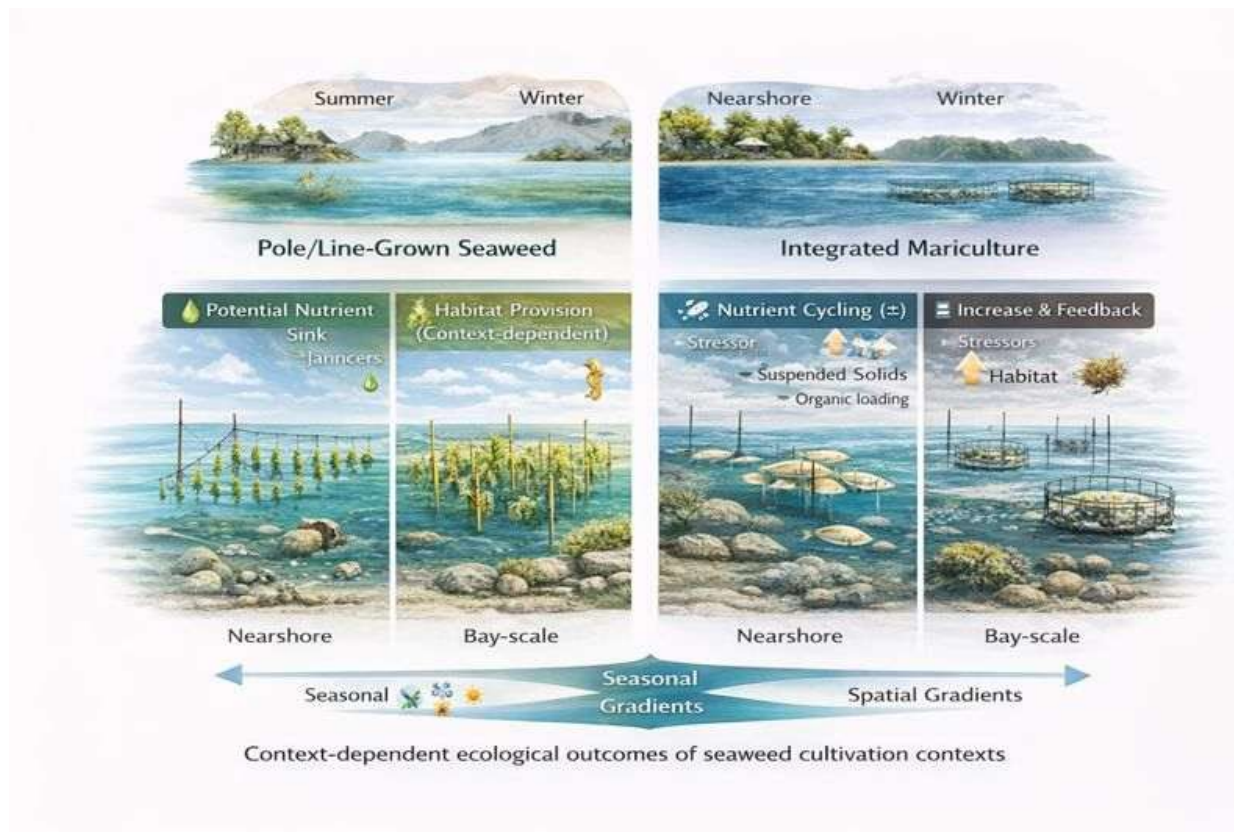


Figure 4. Ecosystem and sustainability trade-offs across cultivation contexts

Figure 4 synthesizes the context-dependent environmental sustainability trade-offs associated with seaweed cultivation and integrated mariculture across seasonal and spatial gradients. The figure contrasts pole- or line-grown seaweed systems with integrated mariculture configurations, illustrating how ecological outcomes vary between nearshore and bay-scale settings and across seasonal conditions. Seaweed-only cultivation is shown to function as a potential nutrient sink and habitat provider, with benefits that depend on local hydrodynamics, background nutrient loads, and seasonal timing. In integrated mariculture systems, nutrient cycling can be enhanced through co-location of trophic components; however, the figure also highlights the emergence of feedbacks and environmental stressors, including altered oxygen dynamics and organic loading, that may offset or complicate net sustainability gains. By explicitly visualizing both ecosystem services and potential disservices, the figure underscores that environmental outcomes cannot be generalized across systems or scales. Instead,

sustainability performance emerges from the interaction of cultivation design, co-produced species, spatial configuration, and seasonal forcing. This synthesis reinforces the central conclusion of this section: ecological benefits associated with seaweed cultivation are real but highly contingent, and responsible scaling requires system-level assessment rather than reliance on single indicators or universal claims.

Table 2. Environmental Sustainability Trade-Offs (Ecosystem, Biogeochemical, And Biodiversity Implications) Of Seaweed Cultivation and Integrated Mariculture

No.	Ref.	Study setting (region; system)	Cultivation / aquaculture configuration	Environmental indicators measured	Key sustainability trade-offs (observed effects; direction)	Governance & monitoring implications
1	Xiong et al., (2023)	China; two major mariculture provinces (Fujian vs Guangdong); coastal flux-balance perspective	Combined fish mariculture (CNP release + O <sub>2</sub> loss) and seaweed culture (CNP removal + O <sub>2</sub> generation), reconstructed from multi-year (2003–2020) data	CNPO fluxes (C, N, P, O <sub>2</sub> ); comparisons to riverine inputs (e.g., Min River, Pearl River); temporal trends	<b>Mariculture structure-dependent outcomes:</b> net CNP sink in Fujian vs net CNP source in Guangdong; net source may drive <b>acidification, eutrophication, and deoxygenation</b> risks in coastal waters	Treat “blue carbon” claims as <b>system-level:</b> seaweed co-benefits depend on co-located fish intensity and local loading; manage via <b>structural adjustment</b> (species/sector mix) and routine monitoring of <b>O<sub>2</sub>, nutrients, and carbonate</b>

						<b>chemistry proxies</b>
2	Zhu et al., (2022)	Taohua Island coastal waters; long-history Laminaria farming (~70 years); seasonal survey	Laminaria japonica culturing area compared with control area across four seasons	Water quality + plankton: temperature, Secchi depth, TN/TP, salinity, pH, DO; phytoplankton species number, density, abundance, Shannon–Wiener diversity	<b>Seasonal and site trade-offs:</b> species number/density ↑ with temperature, Secchi depth, TN; ↓ with DO; during late culturing (spring) culture increased <b>pH, DO, salinity</b> and slightly reduced <b>TP</b> ; phytoplankton abundance <b>lower</b> in culture area, while diversity <b>higher</b>	Sustainability assessment must be <b>season-resolved</b> (late-culture period can shift pH/DO and plankton structure); adopt monitoring that couples <b>water quality</b> with <b>community metrics</b> (abundance + diversity), not just nutrients
3	Morone et al., (2023)	Matsushima Bay, northeastern Honshu, Japan; post-2011 tsunami recovery context; multi-year field survey (~4 years)	Oyster/seaweed aquaculture installations (rafts; anchored and float-suspended ropes) within bay stations	Phytoplankton abundance; water temperature; nutrient concentrations across stations; surface-seawater eukaryote assemblage composition across years/seasons	<b>Attribution trade-off:</b> phytoplankton abundance tracked <b>temperature</b> ; nutrients were high near canal exit, but aquaculture installations	Highlights need to separate aquaculture signals from <b>background variability</b> and <b>land-based inputs</b> ; focus

					showed <b>no significant effect</b> on nutrients across other stations; eukaryote assemblages varied by year/season, with <b>no clear station differences</b>	monitoring on <b>hotspots</b> (e.g., canal outlets) and maintain <b>longitudinal biodiversity baselines</b> when evaluating “aquaculture impact”
4	Duarte et al., 2022; Macreadie et al., 2021)	Controlled tank cultivation; laboratory/mesocosm setting	Factorial manipulation of CO <sub>2</sub> (400 vs 1000 ppm), temperature (20 vs 24 °C), nitrate (5 vs 150 µmol/L) across six “current/future” combinations for <i>Ulva lactuca</i>	Physiological/quality metrics: growth rate; pigments (Chl a, Chl b, total Chl); nutritional composition (protein, carbohydrate, lipid)	<b>Resilience vs quality trade-off under climate forcing:</b> highest growth under future CO <sub>2</sub> + future temperature + future nitrogen; pigment maxima occurred under different combinations; nutritional composition maxima under yet another combination → future conditions may <b>boost</b>	For sustainable deployment, couple climate-adaptive farming with <b>product-specification management</b> (choose cultivation conditions to target biomass quality); include variability bands in sustainability claims when future climate drivers alter

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**productivity but shift biochemical profiles,** affecting downstream product quality and nutrient-removal performance

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#### 4.3 Monitoring, MRV, and Spatial Governance for Responsible Scaling

- The literature reviewed under this theme demonstrates that credible scaling of seaweed cultivation particularly in the context of marine carbon dioxide removal (mCDR) and the circular blue bioeconomy depends critically on the integration of monitoring technologies, MRV readiness, and spatial governance tools. Consistent with earlier theoretical discussions on system boundaries, additionality, and governance (Duarte et al., 2022; Macreadie et al., 2021), these studies show that where seaweed is cultivated can be as consequential as how it is cultivated, and that spatial misallocation or inadequate monitoring can undermine both environmental performance and social legitimacy.
- At broad spatial scales, GIS-based suitability mapping has emerged as a foundational planning instrument. Jha et al., (2025) apply multi-criteria GIS modeling across the Andaman and Nicobar Islands and identify approximately 68,659 km<sup>2</sup> of potentially suitable area for seaweed cultivation, of which 5,363 km<sup>2</sup> is classified as highly suitable within 1–50 m depth zones. By explicitly excluding coral reefs, seagrass beds, protected areas, and navigation routes, this approach illustrates how spatial planning can pre-empt ecological harm and user conflict an essential prerequisite for establishing credible MRV baselines. Similar spatial optimization is evident in Bangladesh, where Tasnim et al., (2024) employ a Generalized Additive Model (GAM) integrating in situ production data (180 plots, four species) with satellite observations. Their model achieves high predictive performance (AUC = 0.83; R<sup>2</sup> = 0.85) and identifies ~1,850 km<sup>2</sup> suitable for floating long-line systems, demonstrating how system-specific suitability mapping can inform both investment and policy decisions.
- Finer-scale planning further expands the spatial governance toolbox. Raja et al. (2024) apply a Fuzzy Analytic Hierarchy Process (FAHP) coupled with ArcGIS to rank brackishwater

environments in India, identifying 141.56 ha suitable for seaweed farming, including 91.93 ha classified as highly suitable. These results illustrate how spatial diversification beyond marine environments can reduce pressure on nearshore ecosystems and wild harvests, aligning with sustainability and livelihood objectives discussed in earlier sections. Offshore planning studies extend this logic to higher-energy systems: Medina Madariaga et al., (2025) use spatial multi-criteria evaluation to map monthly and species-specific suitability along the French Atlantic coast, identifying up to 1,847 km<sup>2</sup> suitable for *Saccharina latissima* and 461 km<sup>2</sup> for *Palmaria palmata*, with optimal windows concentrated between November and April. Such seasonal resolution is critical for managing risk and aligning cultivation with biophysical thresholds relevant to durable CDR claims.

- In complex, multi-use coastal settings, spatial planning must also address social and regulatory constraints. Wickliffe et al., (2024) demonstrate how exclusion-based geospatial analysis can identify compatible zones for shellfish and macroalgae farming within the heavily trafficked San Diego Bay, offering a replicable workflow for reducing permitting friction and social conflict. Complementary governance perspectives are provided by Coffey et al., (2025; Raja et al., (2024), whose global scoping review (240 records, 2001 - 2022) reveals strong geographic and taxonomic imbalances in research on seaweed–offshore wind co-location, as well as persistent legal and environmental gaps that constrain implementation despite policy interest.
- Monitoring and MRV readiness are equally central to responsible scaling. Chen et al., (2025) illustrate how remote sensing can close data gaps at national scales by combining Sentinel-2 imagery with Random Forest classification in Google Earth Engine to monitor seaweed extent, species composition, and production across the Korean Peninsula (2017 - 2023). Their results show near-perfect agreement between remotely sensed acreage and reported production ( $R^2 = 0.99$ ), underscoring the potential of satellite-based approaches for low-cost, scalable MRV of biomass and productivity. At smaller but operationally critical scales, Fidai et al., (2024) demonstrate how hyperspectral measurements (350–2500 nm) combined with UAV surveys enable classification of pelagic sargassum by morphotype, decomposition stage, and biochemical properties, supporting rapid decision-making for biomass handling and valorisation.
- Several studies emphasize that spatial governance must extend beyond siting to include logistics, infrastructure, and institutional responsibility. Yue et al., (2025) integrate engineering suitability coefficients with standardized carbon accounting methods (HY/T 0349–2022) to project 3,591 km<sup>2</sup> yr<sup>-1</sup> of artificial upwelling–supported seaweed expansion in

China, corresponding to an estimated 861,656 tonnes yr<sup>-1</sup> of carbon sink potential, directly linking spatial planning outputs to policy-relevant carbon reporting. In Ireland, Cerca et al., (2024) identify 40 local supply hubs and 14 optimal shared processing facilities using GIS and scenario modeling, demonstrating how post-harvest logistics can materially reduce costs and greenhouse gas emissions. Their complementary conceptual analysis further clarifies sustainability responsibilities and bottlenecks across the supply chain, highlighting governance phases such as licensing, seed supply, and timing that are often overlooked but decisive for scaling success (Cerca et al., 2023).

- Finally, design-oriented and adaptive governance perspectives stress the importance of place-based monitoring and stakeholder inclusion. Buckner et al., (2024) focusing on open-water kelp mariculture in the Salish Sea, synthesize ecological evidence and local knowledge including tribal fishing rights to propose farm design and monitoring priorities aimed at maximizing benefits while minimizing ecological and social harms. At earlier planning stages, O'Shea et al., (2024) use conceptual mapping and a modified Delphi process to identify 58 potential social ecological consequences of offshore multi-use settings, illustrating how expert-based foresight can inform risk screening before large capital investments are made.
- Collectively, these studies converge on a central insight: monitoring, MRV, and spatial governance are not auxiliary considerations but core determinants of credibility in seaweed-based mCDR and blue bioeconomy initiatives. Quantitative suitability mapping, validated remote sensing, logistics-aware planning, and inclusive governance frameworks together form the enabling infrastructure for responsible scaling. Without such integration, expansion risks repeating the boundary, leakage, and legitimacy challenges identified in earlier sections.



Figure 5. Monitoring, MRV, and spatial governance architecture for scaling

Figure 5 conceptualizes an end-to-end governance architecture that links environmental observation to verification and decision-making in seaweed-based systems. The figure illustrates how remote sensing platforms, including satellites and unmanned aerial vehicles, and in situ sensors provide complementary streams of biophysical data on biomass extent, environmental conditions, and system performance. These observations are integrated through data-processing and modeling layers, where analytical workflows translate raw measurements into interpretable indicators of production, environmental interaction, and uncertainty. Outputs from this stage feed directly into spatial planning tools, such as suitability mapping and sea-use zoning, which support evidence-based site selection and conflict-aware marine spatial planning. Crucially, the figure shows how spatial outputs and monitoring-derived indicators are connected to MRV and policy interfaces, enabling traceability from data acquisition to reported claims. Feedback loops emphasize adaptive management, whereby monitoring results inform farm redesign, re-siting, or operational adjustment over time. By visualizing these linkages, Figure 5 reinforces a key argument of this review: monitoring technologies and spatial planning are not ancillary technical components, but enabling infrastructures that underpin credibility, transparency, and governance readiness in scaling seaweed cultivation for both climate and bioeconomy objectives.

related macroalgae biomass) responsibly

<b>No.</b>	<b>Ref.</b>	<b>Geographic focus &amp; scale</b>	<b>Decision objective</b>	<b>Methods / tools</b>	<b>Key inputs / data sources</b>	<b>Main outputs</b>	<b>Verification / evaluation</b>	<b>CDR / blue-bioeconomy relevance</b>
1	Jha et al., (2025)	Andaman & Nicobar Islands (India EEZ) macro-level zoning (1–50 m depth).	Delineate potential seaweed farming zones while avoiding sensitive habitats and navigation routes.	GIS-based multi-criteria suitability modeling thematic layers + exclusion zones.	Environmental factors converted to spatial layers depth contour exclusion layers (coral reefs, seagrass, protected areas, natural habitats, navigation).	Suitability map: 68,659 km <sup>2</sup> appropriate (5,363 km <sup>2</sup> highly suitable) 63,296 km <sup>2</sup> guidance on cultivation techniques.	Internal consistency via exclusion independent ground-truth metrics reported in abstract.	Reduces siting conflict and ecological harm precondition for scalable cultivation and credible MRV baselines.
2	Tasnim et al., (2024)	Bangladesh coastal & marine territorial waters (e.g., Moheshkhali, Cox's Bazar, Teknaf, St. Martin's).	Predict habitat suitability for different cultivation systems (off-bottom long-line/netfloat line).	Generalized Additive Model (GAM) to generate habitat suitability maps for cultivation systems.	In-situ production + environmental data (180 plots 4 species) + satellite observations + model simulation key drivers include TSS and salinity.	System-specific suitability areas (e.g., floating long-line: 1,850 km <sup>2</sup> suitable) spatial hotspots in SE coast system comparison.	Model validation: AUC=0.8 3R <sup>2</sup> =0.85 (reported).	Operationalizes evidence-based scaling (where/which system) and supports investment/policy for emerging blue economy.
3	Raja et al., (2024)	Chengalpa district (India) brackishwater ecosystem	Identify and rank brackishwater areas for seaweed	Fuzzy Analytic Hierarchy Process (FAHP) +	Monthly sampling at 22 locations criteria:	Suitability map: 141.56 ha potential (91.93 ha	Field sampling across months prediction	Enables diversification of cultivation environment

		site-scale hectares.	farming expansion beyond marine sites.	ArcGIS multi-criteria spatial analysis.	water quality, environmental factors, accessibility, constraints criteria mapped in ArcGIS.	highly suitable4 9.63 ha moderate ly suitable).	accuracy metrics not reported in abstract.	nts and reduces pressure on wild harvestsup ports livelihood/i ndustry scaling.
4	Medina Mada riaga et al., (2025 )	French North Atlantic coastoffshore cultivation seasonal (monthly) suitability.	Determine offshore cultivation suitability for three macroalgae species and identify seasonal constraints.	GIS-based Spatial Multi-Criteria Evaluation (SMCE) producing a global suitability index.	Species-specific thresholds for nutrients, temperature, transparency, currents, wavelite remote sensing + model outputsocio-economic conflicts integrated.	Species-and month-specific suitability (e.g., <i>S. latissima</i> up to 1,847 km <sup>2</sup> P. palmata 461 km <sup>2</sup> )seasonal optimum (Dechigher Nov–Apr).	Sensitivity analysis (temperature, nitrate)experiment validation proposed as future work.	Supports offshore expansion planning and risk managementintegrates biophysical + socio-economic constraints relevant to durable CDR projects.
5	Wickliffe et al., (2024 )	San Diego Bay area (California, USA)port-adjacent, multi-use coastal waters.	Identify compatible locations for shellfish and macroalgae culture systems in a highly utilized maritime port.	Geospatial analyses using centralized geodatabaseexclusion analysis (multi-criteria decision) + culture-systems analysis.	Planning layers capturing existing uses/constants and environmental suitability culture-system-specific factors.	Recommended siting areas for aquaculture within/around the bayreplicable spatial planning workflow .	Rule-based exclusion + factor screening quantitative validation metrics reported in abstract.	Shows how marine spatial planning can de-risk permitting and reduce social conflict—important for scaling seaweed-based CDR/NbS in busy seascapes.
6	Chen	Korean	Monitor	Otsu-	Sentinel-2	Acreage	Reported	Provides

	et al., (2025)	Peninsular scale monitoring (2017–2023) 10 m resolution.	extent, species, and production of cultivated seaweed fill data gaps where statistics are limited.	threshold features + Random Forest classification in Google Earth Engine using Sentinel-2 imagery.	spectral time series spectral features + phenology + cultivation practices.	trends species composition (laver vs kelp) production estimation using acreage–production relationship.	correlations: acreage–production species differentiation supported by phenology/practice integration.	scalable, low-cost MRV for biomass/production and informs carbon accounting and investment planning.
7	Fidai et al., (2024)	Barbados & Ghana (Tropical Atlantic) beached biomass field + UAV scale.	Enable remote detection and characterization (morphotype/decomposition/biochemistry) of beached pelagic sargassum.	In-situ hyperspectral measurement (350–2500 nm) + UAV multispectral survey spectral profiling & decomposition mapping framework.	Field spectrometer UAV RGB/multispectral imagery and decomposition-stage observations.	Operational remote-detection framework spectral decomposition key spectral regions (e.g., 920–1080 nm absorption feature).	Cross-platform + airborne datasets used for accuracy statistics not reported in abstract.	Improves monitoring/verification for biomass handling and supports circular blue bioeconomy valorisation pathways.
8	Coffey et al., (2025)	Global literature (2001–2022) general seaweed farming vs seaweed–wind integration (more Europe-focused).	Synthesize evidence and gaps for upscaling seaweed via co-location with offshore wind energy.	Quick scoping review (240 records) + ecosystem-service and knowledge-gap analysis.	Published studies classification by region, taxa (red vs brown dominance), ecosystem services, constraints, knowledge	Identifies trends and imbalances (provisioning > cultural services) highlights environmental	Review-level synthesis (no empirical validation).	Clarifies research and governance priorities needed to responsibly scale seaweed–wind multi-use and reduce permitting

					gaps.	constraint s and legal gaps in wind- focused work.		risk.
9	O'Shea et al., (2024)	Hypothetical offshore case-co-location of seaweed + wind farm expert-based assessment.	Anticipate social-ecological consequences and uncertainty of offshore multi-use settings (MUS).	Conceptual (cognitive) mapping + modified Delphi with 14 expert sim pact tables.	Expert elicitation across social/environmental objectives synthesis into causal maps and consequence lists.	Five cognitive maps + 58 potential consequence flags both risks (e.g., mortality, conflict) and potential benefits (e.g., provisioning, habitat functionality).	Expert consensus process/qualitative structural outputs rather than predictive performance.	Offers early-stage decision support for risk screening and integrative modelling before large capital deployment.
10	Yue et al., (2025)	Coastal China (5 provinces; 8 cities; 11 counties/districts) scenario 2022–2027.	Map optimal (5 AU) project zones and quantify additional seaweed area and carbon sink potential.	Engineering-suitability coefficient (K_AU) + predictive model selection + carbon sink accounting (HY/T 0349–2022).	Engineering constraints predictive modelling of AU-supported area (E_AU) area-to-yield conversion national carbon sink accounting method.	Projected AU expansion 3,591 km <sup>2</sup> /yr projected carbon sink 861,656 tonnes/yr Zhejiang and Porphyra dominate contributions.	Model selection among four candidate field validation approach not described in abstract.	Links spatial planning to standardized carbon accounting—core to scalable mCDR assessment and policy reporting.
11	Cerca et al., (2024)	Ireland rural/remote coastal landscapes	Plan post-harvest logistics and shared	Multi-method analysis: GIS +	Empirical spatial data on licenses/in	40 local supply hubs identified	Scenario-based cost/GHG	Improves net climate performance by

		licensed areas + existing infrastructure network.	infrastructure for emerging kelp supply chains.	mathematical modelling + qualitative content analysis.	infrastructure scenarios assumption on moisture reduction and payload.	14 optimal shared processing facility locations scenarios to reduce cost and GHG emissions	comparisons noted (preservation methods on-market values).	reducing supply-chain emissions and supports circular bioeconomy scaling.
1 2	Cerca et al., (2023)	Ireland macroalgae cultivation upscaling across operational and institutional levels.	Define sustainability responsibilities and bottlenecks in cultivated macroalgae supply systems.	Interdisciplinary sustainability management - socioecological responsibility mapping.	Qualitative assessment of responsibilities (environment, communities, local actors, customers) highlights phases (site selection, licensing, seed supply, timing).	Identifies uncertainties/bottlenecks and expanded supply-chain phases vs wild harvest.	Conceptual/empirical synthesis (no performance metrics).	Clarifies governance and social-license prerequisites for responsible scaling and certification readiness.
1 3	Buckner et al., (2024)	Salish Sea (Washington State, USA) open-water native kelp mariculture.	Provide farm design guidance and monitoring/research priorities to maximize benefits and minimize harms.	Evidence synthesis + adaptive management guidance locally specific design and monitoring agenda.	Local ecological/social context incorporates tribal concerns and treaty-protected fishing access.	Actionable design guidance prioritised monitoring and research gaps for regulators and growers.	Adaptive management framework relies on future monitoring.	Strengthens sustainability safeguards and monitoring expectations— supports credible scaling and reduced ecological trade-offs

#### 4.4 Circular Valorisation and Biorefinery Pathways

The literature reviewed in this theme demonstrates that circular blue bioeconomy pathways provide a more immediate and defensible rationale for scaling seaweed cultivation than carbon dioxide removal alone, while also shaping the credibility of any associated climate claims. Across valorisation studies, a consistent finding is that economic viability, environmental performance, and social legitimacy depend on how biomass is processed, what products are prioritized, and how quality and safety risks are managed rather than on biomass quantity alone. This aligns with earlier theoretical perspectives emphasizing cascading use, co-product optimization, and system-level sustainability assessment through life cycle analysis (LCA) and techno-economic analysis (TEA).

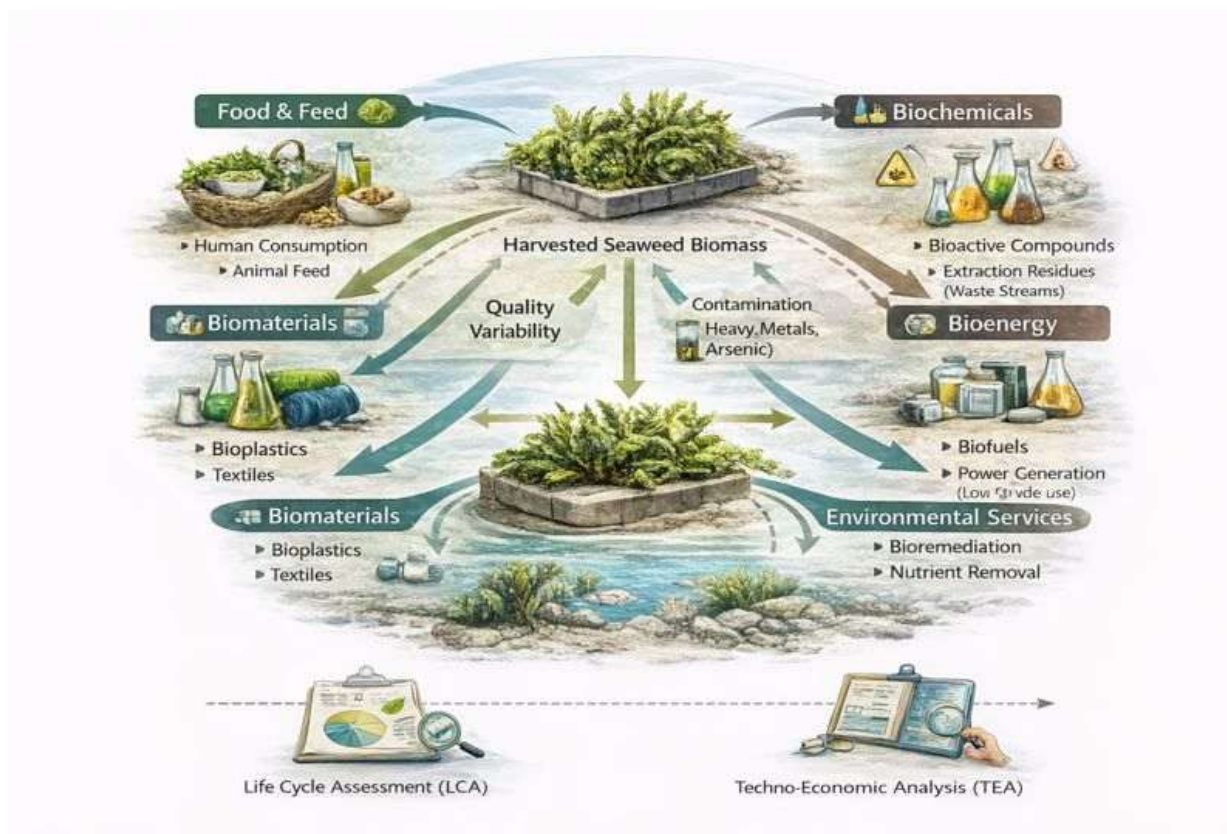


Figure 6. Circular valorisation pathways and sustainability constraints

Figure 6 synthesizes the major circular blue bioeconomy valorisation pathways branching from harvested seaweed biomass, while explicitly visualizing the sustainability constraints that condition their environmental and climate performance. The figure illustrates how seaweed biomass can be directed toward multiple end uses, including food and feed, biomaterials, biochemicals, bioenergy, and environmental services, through processing and biorefinery pathways that enable cascading use and co-product generation. Importantly, the figure overlays key constraints such as quality variability, contamination by heavy metals and arsenic, energy

demand, logistics and storage requirements, and end-of-life management across all pathways, emphasizing that value creation is neither uniform nor risk-free. Lower-grade uses such as bioenergy are shown to be strongly constrained by processing intensity and energy inputs, while higher-value biochemical and food pathways are conditioned by strict quality and safety thresholds. By integrating life cycle assessment (LCA) and techno-economic analysis (TEA) as cross-cutting evaluative tools, the figure reinforces that circular bioeconomy outcomes must be assessed holistically rather than inferred from biomass production alone. This synthesis supports a central conclusion of this section: circular valorisation provides a more defensible rationale for scaling seaweed cultivation than carbon offsets alone, but only when sustainability constraints are transparently acknowledged and managed.

At the industry and supply-chain level, multiple studies emphasize upgrading governance and coordination as prerequisites for circular value creation. (Rahmadi et al., 2025), focusing on Eucheumatoid seaweed systems in Indonesia, highlight that carrageenan-oriented industry development can generate livelihoods and industrial upgrading only when post-harvest handling, quality consistency, and market access are addressed across the cultivation - processing - market chain. Their review identifies fragmented supply chains and price volatility as dominant constraints, underscoring that circular-economy benefits are contingent on institutional and technological readiness rather than cultivation expansion alone. Similar conclusions emerge from Hermalena et al., (2025), who analyze carrageenan production centers in South Sulawesi and show that environmentally integrated supply-chain coordination ensuring raw material continuity and stakeholder alignment is essential for sustaining processing capacity and reducing inefficiencies.

At the process and product - innovation scale, biorefinery-oriented studies illustrate how value density and functional outputs shape sustainability outcomes. Dumraliya et al., (2025) demonstrate laboratory-to-pilot feasibility for producing the rare sugar L-rhamnose from green-seaweed ulvan via catalytic hydrolysis using carbon-embedded sulfonated resins. The reported reusability of catalysts across multiple cycles provides a quantitative indicator of process efficiency, yet the study also highlights feedstock variability and downstream purification demands as critical scaling barriers. At a more integrated systems level, Fang et al., (2023; Leadbeater et al., (2022) propose a hybrid solar - seaweed biorefinery capable of co-producing biochemicals, biofuels, electricity, and freshwater. Their thermodynamic modeling combined with LCA and cost - benefit analysis illustrates the potential of multi-output systems to improve overall resource efficiency, while simultaneously revealing high capital intensity and logistical

complexity as non-trivial trade-offs.

Emerging circular materials pathways further expand the valorisation landscape. Leadbeater et al., (2022) use genome-led in silico screening to identify bacteria capable of degrading seaweed polysaccharides and producing bioplastics such as polyhydroxyalkanoates (PHAs). Although situated at the discovery stage, this work underscores how microbial conversion pathways could transform low-value biomass into higher-value circular materials, provided that subsequent wet-lab validation and bioprocess optimization confirm scalability and economic feasibility.

Quality enhancement and safety assurance repeatedly appear as binding constraints on circular bioeconomy claims. Huang et al., (2021) show that controlled artificial lighting can significantly enhance photosynthetic pigment and soluble protein content in cultivated seaweed, improving suitability for nutraceutical or functional food markets. However, these gains come with higher energy demand and limited scalability relative to open-water systems, illustrating a classic yield–quality–footprint trade-off. Food-safety studies reinforce this point: Park et al., (2025) quantify how environmental factors influence proximate composition and heavy metal concentrations in *Pyropia* spp., demonstrating that contamination risks vary spatially and must be actively managed to maintain food-grade quality. Lin et al., (2021) further show that nutrient conditions specifically phosphorus availability alter arsenic uptake and speciation in *Porphyra haitanensis*, directly linking cultivation practices to toxicological risk and regulatory compliance. Environmental service-oriented valorisation pathways introduce additional trade-offs. Luo et al., (2023) assess the heavy-metal removal capacity of *Gracilaria lemaneiformis* and explicitly pair remediation benefits with evaluation of secondary pollution risks, emphasizing that contaminated biomass requires careful handling to avoid re-release of pollutants. This risk is further substantiated by Luo et al., (2023), who experimentally demonstrate differential heavy-metal accumulation and release during decay of dried versus fresh *Gracilaria* litter, highlighting end-of-life management as an often-overlooked but quantitatively significant component of sustainability assessment.

Monitoring-enabled valorisation approaches bridge production and processing decisions. Fidai et al., (2024) combine hyperspectral measurements across the 350–2500 nm range with UAV-based multispectral surveys to classify pelagic sargassum by morphotype, decomposition stage, and inferred biochemical properties. Such spectral differentiation enables rapid sorting of biomass for appropriate processing or disposal pathways, reducing waste and improving the feasibility of circular utilization under time-sensitive conditions.

Collectively, these findings demonstrate that circular blue bioeconomy outcomes are governed by product specification, contamination control, logistics, and end-of-life management, rather than by biomass growth alone. Across studies, circular valorisation emerges as a pathway that can internalize environmental constraints and reduce incentives to overstate carbon removal benefits. In this sense, circular bioeconomy pathways do not replace the need for rigorous mCDR accounting, but they provide a more resilient and evidence-grounded justification for scaling seaweed cultivation when carbon removal remains uncertain or conditional.

Table 4. From Biomass To Value: Circular Blue Bioeconomy Valorisation Pathways, Processing Routes, And Quality/Safety Constraints In Seaweed Systems

<b>No.</b>	<b>Ref.</b>	<b>Valorisation pathway (what value is created?)</b>	<b>Processing / biorefinery route (how?)</b>	<b>Key outputs &amp; co-products</b>	<b>Sustainability / quality / safety metrics reported</b>	<b>Scale / readiness signal</b>	<b>Key constraints / risks (trade-offs)</b>
1	Rahmadi et al., (2025)	<b>Carrageenan-oriented industry development</b> from Eucheumatoids (Indonesia): livelihoods + industrial upgrading	Review + strategic recommendations across cultivation–postharvest–market chain	Carrageenan-grade raw dried seaweed; improved farm practices and chain coordination	Identifies constraints affecting <b>quality consistency</b> , market access, and governance/technology gaps	Practice-to-policy roadmap (sector-level readiness)	Price volatility, fragmented supply chain, limited technology access, and climate risks can reduce circular-economy gains
2	Hermalena et al., (2025)	<b>Carrageenan production centers:</b> upgrading local processing capacity and sustainability of supply chains	Environmental-based supply chain integration (coordination, stakeholder alignment, raw material assurance)	Carrageenan products + improved logistics/coordination	Supply-chain environmental integration (raw material continuity, waste/efficiency considerations)	Community/cluster readiness (institutional/organizational)	Raw material inconsistency, limited collaboration, and weak governance can

							undermin e processin g-center performa nce
3	Dumr aliya et al., (2025)	<b>High-value biochemicals</b> (rare sugar platform) from green- seaweed polysacchari des	Catalytic hydrolysis of crude <b>ulvan</b> using carbon- embedded sulfonated resins (reusable catalyst)	<b>L- rhamnose</b> (target product) + hydrolysat e streams (potential co- products depending on fractionati on)	Reusability reported (e.g., catalyst retains activity across multiple cycles) as an efficiency indicator	Lab-to- pilot chemistr y pathway (process proof- of- concept)	Feedstoc k variabilit y, downstre am purificati on burden, catalyst lifetime, and process scaling/e nergy trade-offs
4	Fang et al., (2023)	<b>Integrated biorefinery:</b> co-produce biochemicals + biofuels + electricity + water (multi- output circularity)	Hybrid <b>solar- seaweed biorefinery</b> concept; thermodyna mic integration + LCA + cost- benefit framing	Biochemi cals + biofuels + electricity + freshwater (co- productio n)	Explicit <b>life- cycle assessment</b> + <b>cost-benefit</b> elements; thermodynami c efficiency framing	System- level concept with decision -grade modellin g	Capital intensity; dependen ce on stable biomass supply; logistical emissions ; integratio n complexi ty and market coupling
5	Leadb eater et al., (2022)	<b>Bioplastic production</b> enabled by seaweed- degrading	In silico genome-led identification of bacteria capable of	Candidate microbial “bioplasti c producer”	Computational evidence (genome mining / pathway	Discover y-stage (requires wet-lab validatio	Translati on risk from computat ional

		microbes (circular materials)	seaweed degradation and bioplastic (e.g., PHA) production	strains; pathway blueprint from polysaccharides → bioplastic	inference) as pre-validation metric	n and bioprocess engineering)	prediction; pretreatment needs; strain performance and scale economics
6	Huang et al., (2021)	<b>Pigment and protein enhancement</b> for higher-value biomass (nutraceutical/functional ingredients)	Controlled <b>artificial lighting</b> selection/optimization for growth and biochemical enrichment	Increased photosynthetic pigments + soluble protein (quality improvement)	Growth rate + pigment/protein measurements (quality indicators for product specification)	Controlled-environment production strategy	Energy demand and cost; scale limits vs open-water systems; optimizing for quality may reduce yield or increase footprint
7	Park et al., (2025)	<b>Food-grade quality assurance</b> for high-value laver (Pyropia spp.)	Empirical assessment linking environmental factors to proximate composition and heavy metal content	Raw laver with quantified nutritional composition + contamination profile	Proximate components + <b>heavy metal contents</b> as safety/quality metrics; environmental drivers identified	Production management / safety control relevance (farm-level)	Contamination risk varies with environment; requires monitoring/traceability; safety constraints can limit market access
8	Lin et	<b>Food safety</b>	Experiments	Arsenic	Arsenic	Risk-	Nutrient

	al., (2021)	<b>and risk management</b> for edible Porphyra	on nutrient uptake (P) effects on <b>arsenic uptake &amp; speciation</b> at environment ally relevant concentratio ns	uptake and biotransfo rmation profiles (risk-relevant outputs)	species/uptake dynamics + nutrient interaction insight as safety metric	science readines s for cultivati on guidelin es	managem ent can alter arsenic risk; standards and site selection must consider trace-element dynamics
9	Luo et al., (2022)	<b>Bioremediat ion service</b> (heavy-metal removal) with attention to secondary pollution	Evaluate heavy-metal removal capacity of <b>Gracilaria lemaneifor mis</b> and assess secondary pollution risks	Removal capacity estimates + risk evaluation for contamina ted biomass	“Removal capacity” paired with <b>secondary pollution risk</b> framing (what happens to metals biomass)	Operatio nally relevant for environ mental manage ment in farming bases	Disposal/handling of contamin ated biomass; decay-driven releases; trade-off between remediati on service and contamin ation managem ent
10	Luo et al., (2023)	<b>End-of-life / waste management</b> for seaweed litter in mariculture zones	Experiments contrasting decay of dried vs fresh <b>Gracilaria</b> litter and associated heavy-metal release	Heavy-metal accumulatio n + release profiles during decay	Release dynamics as an environmental risk metric informing waste handling	Manage ment-relevant evidence for maricult ure zones	Litter/dec ay can re-mobilize contamin ants; requires coordinat ed harvestin g, litter preventio

							n, and disposal standards
1	Fidai et al., (2024)	<b>Valorisation enablement</b> for stranded pelagic biomass (sorting by quality for processing)	Hyperspectral (350–2500 nm) + UAV multispectral characterization to infer biochemical/phenotypic properties	Spectral profiles + decomposition-stage maps (supports logistics and processing selection)	Spectral features linked to decomposition/biochemistry as quality proxies	Field-to-operational monitoring pathway (decision support)	Calibration/transferability across sites; decomposition heterogeneity; operational logistics and rapid-response constraints

How this table supports Theme 4 synthesis (for later drafting): The evidence base spans (i) biorefinery process innovation, (ii) supply-chain and industrial upgrading, and (iii) quality/safety constraints (heavy metals, arsenic, decomposition). Together, these show why circular blue bioeconomy claims must be tied to *product specification, contamination control, logistics, and end-of-life management* not biomass growth alone.

## Discussion

This review provides several cross-cutting insights when carbon accounting, ecosystem impacts, monitoring capacity, and valorisation pathways are analyzed together. Across the literature, seaweed cultivation is consistently shown to achieve high biomass productivity, yet verified atmospheric CO<sub>2</sub> removal remains conditional on carbon fate, residence time, and explicit air–sea CO<sub>2</sub> equilibration dynamics rather than on growth rates alone (Hurd et al., 2022, 2023; Nishihara et al., 2025). Studies reviewed in Tables 1 and 2 demonstrate that rapid biomass turnover, remineralization, and co-located emissions can substantially weaken net CDR outcomes, even where primary production is high.

A dominant source of uncertainty is the definition of system boundaries. What is included

or excluded such as adjacent fish farming, downstream processing, or displaced products often determines whether a seaweed system appears as a net sink or source of CO<sub>2</sub> (Liu et al., 2025; H. Wu et al., 2025; J. Wu et al., 2023). This finding reinforces theoretical arguments that credibility in mCDR depends more on boundary transparency and additionality than on biological performance per se (Duarte et al., 2022; Macreadie et al., 2021). Unclear or narrow boundaries undermine the legitimacy of seaweed-based CDR claims and complicate their alignment with climate policy and carbon markets (Hurd et al., 2023; Macreadie et al., 2022). Evidence from integrated mariculture systems reveals genuine nutrient-recycling and local water-quality benefits, but also highlights carbonate chemistry feedbacks and respiratory emissions that can offset or reverse climate benefits under certain configurations (Liu et al., 2025; West et al., 2023; Xiong et al., 2023). Ecological effects are therefore highly context-dependent: farms may function as habitat or biodiversity attractors, yet cumulative impacts and threshold behavior remain poorly understood at seascape scales (Morone et al., 2023; Zhu et al., 2022).

Monitoring technologies ranging from spectral remote sensing to in situ measurements are advancing rapidly and enable large-scale biomass tracking and spatial governance (Chen et al., 2025). However, the literature converges on a key gap: the absence of standardized MRV pipelines that translate monitoring outputs into verification-grade carbon accounting (Hurd et al., 2022; Nishihara et al., 2025). Similarly, while GIS-based spatial planning demonstrates technical feasibility, governance application requires stronger integration of ecological constraints, stakeholder values, and permitting realities (Cerca et al., 2023).

Finally, findings from Table 4 indicate that circular valorisation pathways including food, biochemicals, materials, and bioremediation provide a more robust near-term justification for scaling seaweed cultivation than carbon offsets alone. Nonetheless, supply-chain variability, contamination risks, and end-of-life management remain limiting factors (Luo et al., 2023; Park et al., 2025). Taken together, the most defensible pathway forward is a dual legitimacy strategy: prioritize circular bioeconomy value creation while treating mCDR as an evidence-gated co-benefit, supported by conservative claims and transparent uncertainty reporting.

## **Conclusion**

This systematic literature review synthesizes fragmented evidence on seaweed cultivation across marine carbon dioxide removal (mCDR), ecosystem sustainability, monitoring and spatial governance, and circular blue bioeconomy valorisation. The review demonstrates that while

seaweed systems can achieve substantial biomass productivity, credible atmospheric CO<sub>2</sub> removal is not an automatic outcome. Instead, it remains conditional on carbon fate, residence time, and explicit treatment of air–sea CO<sub>2</sub> equilibration, permanence, additionality, and leakage. Across the literature, uncertainty is driven less by biological growth rates than by how system boundaries are defined and operationalized.

Evidence from ecosystem and integrated mariculture studies shows that seaweed cultivation can deliver meaningful co-benefits, including nutrient recycling, localized water-quality improvements, and habitat provision. However, these effects are highly context-dependent and can be offset by carbonate chemistry feedbacks, respiratory emissions, or cumulative impacts when cultivation is scaled without adequate system-level assessment. Threshold behavior and seascape-scale ecological responses remain insufficiently studied, representing a critical gap in the literature.

Advances in monitoring technologies and GIS-based spatial planning demonstrate strong technical feasibility for scaling seaweed cultivation responsibly. Remote sensing, in situ sensing, and multi-criteria spatial analysis can support biomass estimation, site selection, and governance processes. Nevertheless, the review identifies a persistent gap between monitoring outputs and verification-grade MRV frameworks capable of supporting robust carbon accounting and market claims.

Finally, circular valorisation pathways including food, biochemicals, materials, and environmental services emerge as a more defensible near-term justification for scaling seaweed cultivation than carbon offsets alone. Yet, these pathways are constrained by supply-chain variability, contamination risks, logistics, and end-of-life management challenges. Taken together, this review advances a dual legitimacy strategy: prioritizing circular blue bioeconomy value creation while treating mCDR as an evidence-gated co-benefit. This framing aligns climate ambition with ecological thresholds, governance realities, and economic viability, providing a coherent decision framework for future research, policy, and investment.

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