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| RESEARCH ARTICLE

Seaweed Aquaculture and Waste Stream Integration for Blue Carbon: A Systematic Review of Carbon Pathways and Mitigation Strategies

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| ABSTRACT

Seaweed aquaculture integrated with waste streams is a promising blue-carbon pathway. This review goes beyond narrative synthesis by introducing three contributions: (i) a cross-system taxonomy of integration modalities, (ii) a concise measurement, reporting, and verification (MRV) protocol accompanied by a practitioner checklist, and (iii) a Crediting Readiness Scorecard (CRS) that operationalizes additionality, durability, leakage, and governability. We systematically reviewed studies published between 2016 and 2025 on coupling seaweed cultivation with aquaculture effluents, municipal wastewater, and flue-gas CO_2, following PRISMA screening and a simple risk-of-bias appraisal; where data permitted, we performed a small quantitative synthesis for nutrient removal and carbon-capture indicators. Our aim is to evaluate operational conditions, carbon pathways (harvest, particulate organic carbon export, dissolved and recalcitrant dissolved organic carbon), and MRV feasibility, while proposing an implementable protocol and scoring tool that standardize assessment across sites and species. Findings indicate that integration generally elevates productivity and carbon capture, but outcomes hinge on nutrient management, residence time and flow distribution, thermal control, and pretreatment addressing pathogens, metals, and co-pollutants. Using the CRS, aquaculture-effluent integrations emerge as nearer-term candidates for conservative crediting; municipal-wastewater and flue-gas routes can approach comparable readiness with stronger pretreatment, clearer system boundaries, and leakage safeguards. MRV remains challenged by air–sea flux attribution, spatial heterogeneity, and inconsistent standards; we map fit-for-purpose metrics net ecosystem exchange/eddy covariance, pCO_2 sensors, ^{13}C tracers, and traps/cores to farm, bay, and shelf boundaries with QA/QC routines to constrain uncertainty. Technology assessments highlight artificial upwelling, CO_2 dosing, longline offshore arrays, and automated sensing as promising yet constrained by energy demand, reliability, and permitting; we synthesize indicative readiness ranges to guide deployment. Overall, the review converts disparate findings into actionable guidance through the taxonomy, MRV protocol, and CRS, and sets priorities for MRV optimization, standardized LCA distinctions between avoided emissions and removals, and scaling strategies suited to data-limited tropical contexts.

| KEYWORDS

Seaweed aquaculture; blue carbon; waste stream integration; MRV protocol; Crediting Readiness Scorecard (CRS)

| ARTICLE INFORMATION

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1. **Introduction**

Seaweed aquaculture is emerging as a key player in global blue carbon strategies due to its remarkable ability to sequester carbon and its compatibility with circular economy principles. Over the past decade, the rapid expansion of macroalgae farming has garnered considerable attention as a scalable and sustainable solution for climate change mitigation. Macroalgae, or seaweeds, exhibit high primary productivity rates and arable land compared to terrestrial crops (Froehlich et al., 2019; Ould & Caldwell, 2022). These properties position them as promising candidates for mitigating greenhouse gas emissions, particularly in marine ecosystems. Additionally, seaweed farming has the potential to improve coastal water quality by absorbing excess nutrients from aquaculture effluents and municipal discharges, addressing eutrophication, and enhancing marine biodiversity (Duarte et al., 2017;

Gao et al., 2021). However, despite substantial growth in evidence, prior reviews remain largely narrative and fragmented across waste-integration settings, leaving a gap in standardized assessment tools and deployment guidance especially for data-limited tropical contexts.

A particularly promising aspect of seaweed aquaculture is its integration with anthropogenic waste streams, such as aquaculture effluents, flue gases from industrial processes, and nutrient-rich municipal wastewater. The co-location of seaweed farms with these waste streams not only helps mitigate environmental pollution but also maximizes carbon removal efficiency by utilizing excess nutrients that would otherwise contribute to environmental degradation (Bach et al., 2024; Ould & Caldwell, 2022). This integration of waste treatment with carbon sequestration has significant implications for the circular economy, transforming waste products into valuable resources while contributing to climate-aligned operations (Berger et al., 2023; Sun et al., 2023). Yet, creditability hinges on clearly defined boundaries, defensible Measurement, Reporting, and Verification (MRV) practices, and transparent handling of additionality, durability, and leakage—dimensions that lack harmonized guidance across integration modalities

This review aims to synthesize current evidence on the integration of macroalgae cultivation with waste streams, emphasizing operational strategies, cultivation technologies, carbon pathways, and their measurement. Specifically, this review will: (1) Synthesize evidence on the operational and technological innovations in waste-integrated seaweed systems. (2) Map carbon pathways including Particulate Organic Carbon (POC), Dissolved Organic Carbon (DOC), and Recalcitrant Dissolved Organic Carbon (RDOC), and evaluate their measurement techniques. (3) Evaluate Measurement, Reporting, and Verification (MRV) readiness and the viability of carbon crediting systems for these integrated approaches. (4) Introduce a cross-system taxonomy that links waste inputs, operational controls, and carbon fate to crediting criteria. (5) Propose a concise MRV protocol and practitioner checklist, and (6) advance a Crediting Readiness Scorecard that operationalizes additionality, durability, leakage, and governability for decision-making.

This systematic literature review (SLR) focuses on macroalgae systems (coastal to offshore) that integrate with anthropogenic waste streams, examining the period from 2016 to 2025 and covering a broad global scope. Topics of interest include operational strategies, cultivation technologies, carbon accounting, Measurement, Reporting, and Verification (MRV) protocols, and environmental and techno-economic outcomes. We exclude microalgae systems unless directly coupled to seaweed systems. This review does not focus on photobioreactors (PBRs) used exclusively for microalgae cultivation, as their integration with marine carbon dioxide removal (mCDR) pathways differs significantly from macroalgal systems. We follow PRISMA screening with a structured risk-of-bias appraisal and, where data permit, a small quantitative synthesis of nutrient-removal and carbon-capture indicators; a tropical lens is applied where evidence clusters in warm-water species (e.g., eucheumatoids, Gracilaria).

This SLR is guided by the following research questions: (i) RQ1: Under what operational and technological conditions do waste-integrated seaweed systems deliver net atmospheric CO_2 removal? (ii) RQ2: How do different integration pathways (aquaculture effluent, municipal wastewater, flue gas CO_2) affect carbon fate (harvest, Particulate Organic Carbon (POC) export, Dissolved Organic Carbon (DOC)/ Recalcitrant Dissolved Organic Carbon (RDOC) formation) and Measurement, Reporting, and Verification (MRV) feasibility? (iii) RQ3: What are the environmental, governance, and techno-economic trade-offs that determine crediting viability and scalability? (iv) RQ4: Can a Crediting Readiness Scorecard synthesize MRV readiness, durability, leakage, and governability to prioritize near-term deployable pathways?

This review is organized as follows: (i) Methods: Describes the systematic review approach, search strategy, and inclusion criteria. (ii) Theoretical Framework: Discusses the theoretical underpinnings of carbon pathways, governance, and waste integration modalities. (iii) Thematic Findings: Presents the key themes identified from the literature, focusing on operational integration, carbon accounting, technology, and environmental impacts. (iv) Discussion: Analyzes the findings, discussing challenges, trade-offs, and implications for future research and policy. (v) Conclusion: Summarizes key insights and proposes directions for future research. In addition, we present the novel taxonomy, the concise MRV protocol and checklist, and the Crediting Readiness Scorecard as practical artifacts to support standardized assessment and crediting decisions.

2. Methods

2.1 Search Strategy

For this systematic literature review (SLR), a comprehensive and targeted search strategy was employed to retrieve relevant studies on seaweed aquaculture and its role in blue carbon solutions. The primary database used was Scopus, which provides extensive coverage of environmental science and climate mitigation literature. To enhance rigor and novelty, we expanded sources to Web of Science Core Collection and supplemented with backward/forward citation chasing and targeted grey-literature scans (government/NGO reports) for methods and MRV protocol formulations.

The search string was specifically designed to capture studies that examine macroalgae farming, carbon sequestration, and their integration with waste streams. Boolean operators were used to refine and broaden the search. The keyword string consisted of terms like "macroalgae farming," "seaweed aquaculture," "carbon sequestration," "blue carbon," and "marine carbon dioxide removal (mCDR)," ensuring a balance between specificity and comprehensiveness (Froehlich et al., 2019; Ould & Caldwell, 2022). We additionally included terms for operational controls (e.g., "CO_2 dosing," "residence time," "solar cooling"), MRV ("net ecosystem exchange," "eddy covariance," "pCO_2 sensors," "^{13}C tracer"), and crediting ("additionality," "durability," "leakage") to enable the development of the taxonomy, MRV protocol, and Crediting Readiness Scorecard (CRS).

Additionally, the search terms were refined by including related concepts such as Particulate Organic Carbon (POC), Dissolved Organic Carbon (DOC), Recalcitrant Dissolved Organic Carbon (RDOC), and nutrient management (Li et al., 2022; Sheppard et al., 2023). The search was conducted using AND to combine essential terms (e.g., "seaweed AND carbon sequestration") and OR to include synonyms or related terms (e.g., "macroalgae OR seaweed"). The operator NOT was applied to exclude unrelated topics, ensuring the search was focused solely on relevant marine carbon dioxide removal (mCDR) systems (Jung et al., 2017). A full reproducible strategy (databases, dates, strings, limits) is provided in Supplementary Table S1

The time window for the search was set between 2016 and 2025 to capture recent advancements in macroalgae farming systems. All articles in English were considered, ensuring the inclusion of the most globally accessible studies in the field. The Boolean string keywords used for search were TITLE-ABS-KEY (("macroalgae farming" OR "seaweed farming" OR "seaweed cultivation" OR "macroalgae cultivation" OR "seaweed aquaculture" OR "macroalgae aquaculture") AND ("carbon sequestration" OR "blue carbon" OR "carbon storage" OR "carbon capture" OR "carbon sink" OR "CO2 mitigation" OR "climate change mitigation")) AND PUBYEAR > 2016 AND PUBYEAR < 2026. This search strategy was designed to ensure comprehensive retrieval of relevant literature in the domain of seaweed-based carbon removal and its technological integration with waste streams. To reduce selection bias, we pre-specified eligibility criteria and archived the protocol prior to screening (see Supplementary Protocol S1).

2.2 Inclusion and Exclusion Criteria

The inclusion and exclusion criteria were established to ensure that only the most relevant studies for this review were selected. The inclusion criteria targeted the following: (1) Direct relevance to marine carbon dioxide removal (mCDR) and climate mitigation strategies involving seaweed or macroalgae, particularly those addressing carbon sequestration (Froehlich et al., 2019; Ould & Caldwell, 2022). (2) Studies that quantified carbon pathways or utilized Measurement, Reporting, and Verification (MRV) methods (Duarte et al., 2017; Gao et al., 2021). (3) Studies that reported environmental and techno-economic outcomes for integrated seaweed farming systems, including waste management and nutrient recovery (Bach et al., 2024; Berger et al., 2023). (4) Studies reporting operational controls (e.g., nutrient concentration, residence time/flow, temperature management, CO_2 dosing) enabling cross-study synthesis for the taxonomy and CRS.

The exclusion criteria were applied to filter out studies that did not meet these standards. Excluded studies included: (1) Research focused solely on microalgae systems that were not integrated with macroalgae or seaweed, as these are outside the scope of this review (Jiang et al., 2023; Sun et al., 2023). (2) Laboratory-based studies or photobioreactor studies not involving real-world environmental coupling or operational integration with waste streams (Gallagher et al., 2022). (3) Non-article formats with insufficient methodological detail for synthesis (e.g., editorials, theses without primary data) or studies with purely local idiosyncratic contexts that do not inform generalizable deployment. (4) Review and conference abstracts were excluded from quantitative synthesis but screened for citation snowballing.

These criteria helped streamline the literature selection process, ensuring only the most relevant, high-quality studies were included in the analysis. To transparently handle incomplete reporting, we coded data availability (Available/Partial/Absent) and did not impute missing values for quantitative synthesis.

2.3 Screening and Selection Process

The screening and selection process followed a two-stage approach to ensure the thoroughness and rigor of the review: (1) Title and Abstract Screening: In the first stage, all identified articles were screened based on their titles and abstracts to assess their relevance to the review's objectives. Studies that met the inclusion criteria were moved to the next stage for a more in-depth review. (2) Full Text Review: In the second stage, the full text of the selected articles was reviewed by two independent reviewers. Disagreements in the screening process were resolved by consensus or, if necessary, by consulting a third reviewer. This ensured the consistency of the selection process and minimized bias (Li et al., 2022). Inter-rater agreement was tracked (Cohen's κ) and conflicts were logged with reasons. A simple risk-of-bias tool (domains: study design, MRV metric validity, boundary definition, and confounding controls) was applied to all included studies.

In addition to the initial search and screening, reference snowballing and forward citation tracking were used to identify additional relevant studies that may have been missed in the initial search. This method ensures comprehensive coverage of the topic and captures key studies that were cited by the selected articles (Froehlich et al., 2019; Sheppard et al., 2023). We pre-specified a quantitative synthesis plan (random-effects where ≥3 comparable estimates were available) for nutrient removal and carbon-capture indicators, and planned subgroup analyses by integration pathway and climate region. Figure 1 presents the PRISMA flow with counts at each stage; detailed exclusions and the data-extraction codebook are provided in Supplementary Table S2 and Appendix A, respectively, to support reproducibility and strengthen methodological novelty.

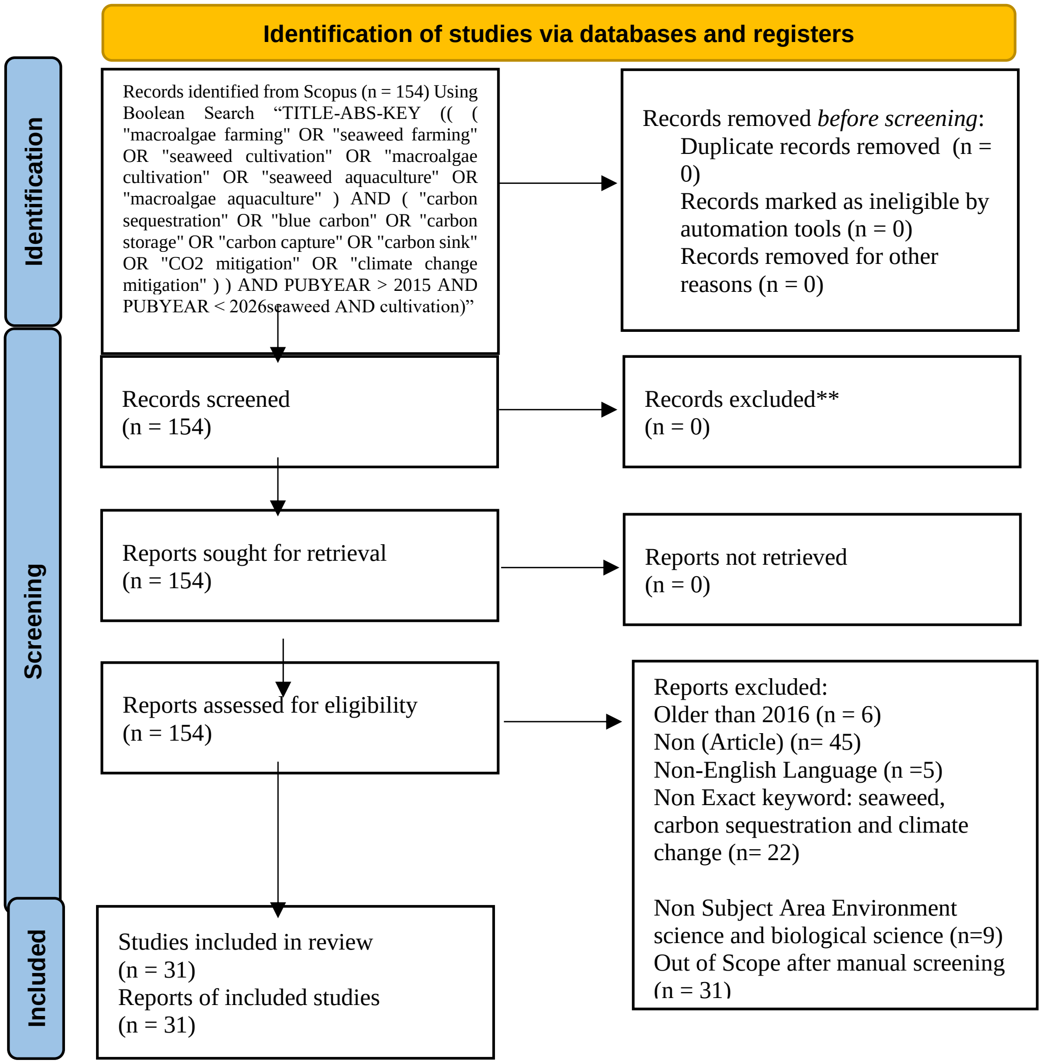

Figure 1. The PRISMA flow diagram detailing the screening and selection process of literature.

3. Theoretical Background

3.1 Carbon Pathway and Governance Lens

The integration of seaweed aquaculture with waste streams for blue carbon applications requires a comprehensive understanding of the carbon pathways and their transformation within marine ecosystems. A conceptual carbon ledger framework has been developed to map atmospheric carbon fluxes into specific marine carbon pools, including Particulate Organic Carbon (POC), Dissolved Organic Carbon (DOC), and Recalcitrant Dissolved Organic Carbon (RDOC). This approach connects carbon sequestration at the ecosystem level to more robust carbon crediting systems, addressing the need for Measurement, Reporting, and Verification (MRV) protocols. Here, we extend this ledger into a cross-system taxonomy that links (i) waste-input classes and pre-treatment requirements, (ii) operational controls (e.g., residence time, thermal management, CO_2 dosing), and (iii) carbon fate (harvest, POC export, DOC→RDOC) to crediting criteria (additionality, durability, leakage, governability). This taxonomy underpins the novel Crediting Readiness Scorecard (CRS) introduced in this review.

Biogeochemical models, commonly used to quantify atmospheric CO_2 absorption in marine environments, simulate how carbon from the atmosphere enters the ocean and is subsequently transformed into various carbon pools, including Particulate

Organic Carbon (POC), Dissolved Organic Carbon (DOC), and Recalcitrant Dissolved Organic Carbon (RDOC). These models factor in variables like nutrient availability, temperature, and biomass productivity, particularly focusing on macroalgal species such as kelp (Alevizos & Barillé, 2023; Froehlich et al., 2019). Such models provide a foundational framework to estimate the magnitude of carbon sequestration facilitated by seaweed farming, integrating critical elements such as water movement, sediment interaction, and biodegradation rates (Berger et al., 2023; Chen et al., 2024). In this review, modeled pools and fluxes are explicitly mapped to MRV-relevant observables (NEE/EC, pCO_2 sensors, ^{13}C tracers, traps/cores) and to system boundaries (farm, bay, shelf) to enable governance-ready accounting and uncertainty propagation into the CRS.

For example, mechanistic models link primary production rates in macroalgae to carbon sequestration in sediments, where seaweeds contribute significantly to long-term carbon storage as part of oceanic biogeochemical cycles. These mechanisms have been corroborated by empirical studies that monitor carbon fluxes, including Particulate Organic Carbon (POC) export and Dissolved Organic Carbon (DOC) emissions, with models offering a clearer picture of how carbon is cycled in marine ecosystems (Gallagher et al., 2022; Gao et al., 2021) We emphasize durability thresholds (e.g., export below the mixed layer and residence-time criteria) and highlight RDOC formation as a high-uncertainty pathway; both are encoded as durability/leakage modifiers within the CRS.

The framework for carbon crediting in marine systems has evolved substantially over the last decade. Previously focused on terrestrial ecosystems, carbon crediting mechanisms now increasingly include marine ecosystems, recognizing the substantial sequestration potential of macroalgae and seagrass beds (Bach et al., 2024). The emergence of marine carbon crediting protocols requires careful attention to additionality, durability, leakage, and governability, all of which are pivotal to establishing the environmental and financial credibility of these approaches (Hurd et al., 2024; Li et al., 2022). These frameworks need refinement, particularly in establishing standardized metrics for carbon storage across various marine ecosystems. Accordingly, we introduce a governance lens that operationalizes these criteria via the CRS, scoring integration modalities (aquaculture effluent, municipal wastewater, flue gas) against MRV readiness, durability proxies, leakage risks, and boundary clarity. As illustrated in Figure 2, the conceptual carbon pathways in seaweed aquaculture show how atmospheric CO_2 is absorbed and distributed into Particulate Organic Carbon (POC), Dissolved Organic Carbon (DOC), and Recalcitrant Dissolved Organic Carbon (RDOC) pools that are central to carbon crediting systems

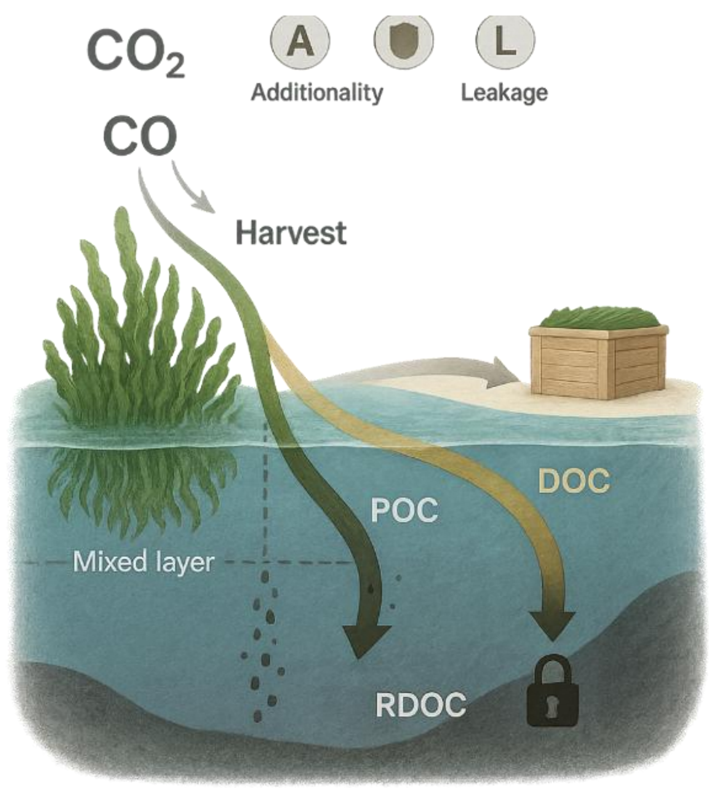

Figure 2. Conceptual Carbon Pathways in Seaweed Aquaculture, including mapped system boundaries (farm/bay/shelf), MRV observables, and crediting-criteria nodes used by the CRS.

3.2 Waste Integration Modalities

Seaweed farming can provide multiple environmental and economic benefits when integrated with waste streams. Three primary waste integration modalities have been identified in the literature: aquaculture effluents, municipal/industrial wastewater, and flue gas CO_2 enrichment. In this review, we formalize these modalities into a cross-system taxonomy that links waste input → pre-treatment → operational controls → carbon fate (harvest/POC/DOC→RDOC) and maps them to crediting criteria (additionality, durability, leakage, governability) via a Crediting Readiness Scorecard (CRS).

The integration of seaweed with Integrated Multi-Trophic Aquaculture (IMTA) systems, which use effluents from aquaculture systems, offers a sustainable solution to nutrient pollution. Seaweeds have the capability to absorb excess nutrients such as nitrogen and phosphorus present in effluents from aquaculture systems, thus mitigating eutrophication in coastal waters (Froehlich (Froehlich et al., 2019). Furthermore, this integration enhances seaweed productivity, leading to increased carbon sequestration potential through biomass accumulation (Sun et al., 2023). This integrated approach promotes the idea of closed-loop aquaculture systems where nutrient recovery from waste leads to the creation of renewable biomass that can be used for carbon capture or bioenergy production (Verma et al., 2025). Operational priorities include pre-treatment (pathogen control, heavy-metal screening), residence-time/flow management, and thermal mitigation in warm waters; MRV observables (NEE/EC, pCO_2 sensors, traps/cores) align with farm/bay boundaries, and the CRS identifies IMTA effluents as higher-readiness candidates for conservative crediting when safeguards are in place.

Similarly, municipal and industrial wastewater integration into seaweed farming enhances nutrient removal capabilities while promoting carbon sequestration. The biological assimilation of nitrogen and phosphorus from wastewater by seaweeds improves water quality and contributes to sustainable resource management (Li et al., 2022). The use of aquaponics systems, in which seaweed absorbs excess nutrients from municipal or industrial wastewater, has shown great promise in improving the sustainability of aquaculture practices while reducing pollution (Sheppard et al., 2023). However, variable influent quality and co-contaminants (e.g., pathogens, pharmaceuticals, metals) necessitate robust pre-treatment and continuous monitoring; boundary definition must prevent cross-system leakage of credited removals. Under the CRS, municipal/industrial pathways attain medium readiness contingent on documented pre-treatment, data transparency, and clear MRV plans.

Flue gas CO_2 enrichment, often sourced from industrial processes, can significantly boost the growth rate of seaweeds by enhancing their photosynthetic activity. Increased CO_2 availability accelerates carbon fixation in seaweeds, which can then be sequestered in marine ecosystems (Ould & Caldwell, 2022). However, the impact of CO_2 enrichment is highly context-dependent, with variables such as water chemistry and oceanographic conditions influencing the effectiveness of the process. Enhanced CO_2 availability has shown to improve seaweed growth rates in eutrophic waters, leading to substantial increases in biomass production (Gao et al., 2021). Nonetheless, temperature, salinity, and other environmental factors can modulate the effectiveness of this approach, requiring careful management to optimize carbon sequestration outcomes (Fieler et al., 2021; Sheppard et al., 2023). Crediting viability further depends on gas-stream quality (e.g., NO_x/SO_x/particulates/amines), required scrubbing, pH–alkalinity control, and verification of additionality beyond biomass proxies; MRV should pair pCO_2 and NEE/EC with durability tests (e.g., export below mixed-layer depth). Under the CRS, flue-gas enrichment is lower readiness without stringent scrubbing and boundary clarity. The operational integration of aquaculture effluents, municipal wastewater, and flue gas CO_2 into seaweed farming systems is depicted in Figure 3, highlighting how waste inputs enhance nutrient uptake, growth, and carbon sequestration.

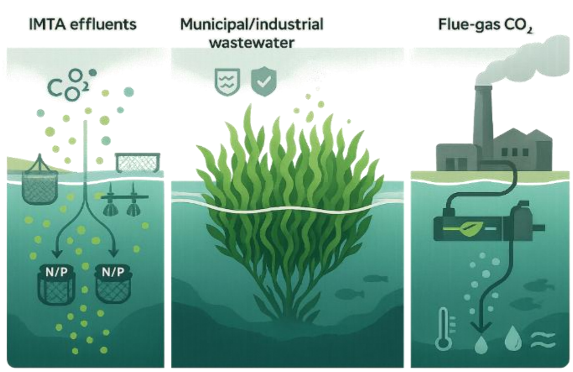

Figure 3. Integration of Waste Streams into Seaweed Farming, showing pre-treatment steps, key operational controls (residence time/flow, CO_2 dosing, thermal management), mapped MRV observables, and indicative CRS readiness by modality.

3.3 Debates and Unresolved Issues

A major debate within the field is whether macroalgae should be primarily used for carbon sequestration or for product substitution. While carbon sequestration involves the long-term storage of carbon through the accumulation of biomass and its eventual sinking to deeper oceanic layers, product substitution focuses on reducing emissions by replacing carbon-intensive materials, such as fossil fuels or plastics, with sustainable seaweed-based products (Alevizos & Barillé, 2023). Research suggests that while product substitution can yield immediate reductions in carbon footprints, sequestration offers more permanent carbon storage benefits (Li et al., 2022). Both pathways are likely to contribute to climate mitigation, but their long-term efficacy and the integration of both strategies need further examination. We address this by introducing a decision lens that separates *removals* from *avoided emissions* via a double-entry accounting template and a Crediting Readiness Scorecard (CRS): substitution pathways are treated as avoided-emissions benefits (non-removal credits), whereas sequestration claims must meet durability thresholds and MRV evidence

The choice of deployment site for seaweed aquaculture—whether nearshore or offshore—affects the carbon sequestration potential and monitoring feasibility. Offshore systems offer larger areas for cultivation and generally higher carbon sequestration potential due to reduced environmental disturbances from human activities (Jung et al., 2017). However, offshore systems face logistical challenges related to monitoring and carbon stock assessment. Nearshore systems, in contrast, are easier to access and monitor, but they often face disturbances such as storm surges and pollution, which can affect the permanence of carbon storage (Gao et al., 2021). The question of whether offshore deployment truly offers more durability in terms of carbon storage remains unresolved (Sun et al., 2023). We propose site-specific crediting rules: provisional durability when exported POC is demonstrably transported below the local mixed-layer depth for $\geq$ 1 year (with sensitivity to regional overturning), and conservative baselines for nearshore farms paired with benthic oxygen safeguards. The CRS operationalizes these rules through boundary clarity and durability sub-scores.

A significant challenge in marine carbon dioxide removal (mCDR) using seaweed is the recalcitrance of Dissolved Organic Carbon (DOC) and its transformation into Recalcitrant Dissolved Organic Carbon (RDOC), which has the potential for long-term oceanic storage (Broch et al., 2022). While Dissolved Organic Carbon (DOC) can be easily remineralized or utilized by marine microorganisms, Recalcitrant Dissolved Organic Carbon (RDOC) is more stable and persists in the ocean for decades to centuries (Li et al., 2022). However, the Recalcitrant Dissolved Organic Carbon (RDOC) formation process is not fully understood and requires further study to assess its effectiveness in large-scale carbon sequestration strategies. Additionally, benthic loading from seaweed farming, particularly in nearshore environments, can result in oxygen depletion and negative impacts on local marine ecosystems, creating a need for environmental safeguards to monitor and mitigate these risks (Broch et al., 2022; Gao et al., 2021). We therefore treat RDOC as *non-creditable by default* unless persistence is evidenced via tracer or molecular signatures over policy-relevant horizons; we outline a measurement agenda (^{13}C pulse-chase, optical/FT-ICR proxies, time-series cores) and encode RDOC claims as high-uncertainty in the CRS. For benthic risk, we specify safeguards (e.g., DO > 5 mg L^{-1} thresholds, deposition monitoring), which are mandatory for positive CRS scoring.

Establishing clear system boundaries for measuring and verifying carbon sequestration in seaweed farming is crucial for Measurement, Reporting, and Verification (MRV) frameworks. Accurate boundary setting ensures that carbon credits are correctly attributed and that the integrity of carbon removal claims is maintained. However, variability in marine ecosystem dynamics—such as water flow, nutrient availability, and seasonal changes—adds complexity to this process (Bach et al., 2024). Furthermore, regional differences in governance and regulatory frameworks complicate the universal application of Measurement, Reporting, and Verification (MRV) standards for seaweed-based carbon credits (Li et al., 2022). To address this, we provide boundary templates (farm→bay→shelf) with leakage guards (e.g., mass-balance closure, lateral export accounting) and a minimum data package (NEE/EC, pCO_2, POC traps/cores, hydrodynamics) that standardizes metrics and elevates MRV comparability; these are embedded in the CRS scoring rubric.

4. Review of Findings

4.1 Waste Stream Integration & Performance (Highest Relevance)

The integration of waste streams into seaweed farming represents a significant opportunity to enhance the productivity and sustainability of marine carbon dioxide removal (mCDR) systems. This section reviews the performance of seaweed systems integrated with various waste streams, including aquaculture effluents, swine wastewater, and flue gas CO_2, with an emphasis on nutrient removal, Carbon Capture Rate (CCR), and the impacts on the marine environment. Beyond synthesis, we formalize findings into a cross-system taxonomy of "waste → pre-treatment → operational controls → carbon fate" and apply a Crediting Readiness Scorecard (CRS) that operationalizes additionality, durability, leakage, and MRV readiness, thereby addressing the novelty gap. The findings highlight the importance of operational factors, such as nutrient concentration, flow rates, and temperature control, in maximizing the benefits of these integrated systems.

One of the most critical factors influencing the performance of waste-integrated seaweed systems is the nutrient concentration in the waste streams. Studies have consistently shown that higher concentrations of nitrogen (N) and phosphorus (P) in wastewater enhance the growth rates of macroalgae by providing essential nutrients for photosynthesis. This, in turn, boosts the Carbon Capture Rate (CCR) as the macroalgae convert atmospheric CO_2 into biomass (Froehlich et al., 2019; Sheppard et al., 2023) However, the benefits of nutrient enrichment must be carefully balanced to avoid nutrient toxicity or eutrophication, which could lead to reduced carbon sequestration efficiency (Jung et al., 2017). We distill these patterns into an operational envelope: (i) nutrient dosing governed by residence time and uptake capacity, (ii) compulsory influent characterization and pre-treatment (pathogens/metals/co-pollutants), and (iii) MRV pairing (pCO_2 + NEE/EC) to avoid biomass-only proxies in crediting

The flow rate of waste streams also plays a significant role in nutrient distribution. Optimal flow rates ensure that nutrients are evenly dispersed across the seaweed cultivation area, promoting uniform growth and maximizing photosynthetic activity. On the other hand, insufficient flow can lead to nutrient stagnation, inhibiting growth and reducing the overall carbon sequestration potential of the system (Li et al., 2022). Proper management of these operational parameters, including residence time in the cultivation system, is crucial for optimizing seaweed productivity and carbon capture potential (Alevizos & Barillé, 2023). We recommend tracer-based or CFD-informed tuning of flow/residence time, with CRS crediting contingent on documented hydraulics and leakage guards (mass-balance closure at farm/bay boundaries).

Table 1 provides a detailed overview of studies integrating waste streams with seaweed farming, highlights how different waste types, such as aquaculture and swine wastewater, influence nutrient dynamics and carbon sequestration. To strengthen comparability, we add standardized fields (Pre-treatment, MRV observables, CRS readiness tier) and code data availability (Available/Partial/NR). For instance, Weerakkody et al., (2025) demonstrated that the integration of aquaculture and swine wastewater with seaweed farming significantly increased carbon sequestration, although careful monitoring of nutrient load and dilution ratio was necessary to avoid negative impacts on seaweed health. Site details reported as uncertain in source are retained as NR without extrapolation.

In addition to nutrient management, operational modifications can further optimize the performance of waste-integrated seaweed systems. One promising approach is the use of solar-assisted cooling, particularly in warmer climates where high temperatures may limit algal growth. Cooling systems help regulate temperature fluctuations, creating more stable and favorable conditions for macroalgae cultivation, thus enhancing primary productivity and increasing carbon capture (Berger et al., 2023). The implementation of cooling systems also prevents respiration stress, which could otherwise counteract the benefits of enhanced photosynthesis under elevated nutrient conditions. We prioritize low-energy thermal mitigation (depth control/shading/flow) before active cooling; CRS scoring incorporates energy demand and reliability to align performance gains with LCA-consistent crediting.

Another widely studied modification is the use of CO_2 dosing to enhance photosynthesis and biomass accumulation. This process involves introducing CO_2-enriched gases, often captured from industrial emissions, into seaweed cultivation systems. The introduction of CO_2 not only enhances the growth of seaweeds but also contributes to carbon capture by utilizing waste CO_2, thereby mitigating the release of greenhouse gases into the atmosphere (Chen et al., 2024; Sun et al., 2023). Studies like Weerakkody et al., (2023) have shown that CO_2 dosing, coupled with solar-assisted cooling, can lead to increased biomass production and carbon capture efficiency in seaweed farms located in subtropical regions. Crediting feasibility depends on gas-stream quality (NO_x/SO_x/particulates/amines), scrubbing requirements, and demonstration of net removals beyond biomass proxies; we therefore pair pCO_2 sensors with NEE/EC and durability checks (export below mixed-layer depth) in the MRV plan and reflect this in CRS readiness.

These operational modifications require a balance between cost-effectiveness, environmental sustainability, and operational efficiency. While CO_2 dosing can significantly boost seaweed growth, it also introduces challenges related to the management of CO_2 sources and the optimization of delivery systems (Liu et al., 2023). Therefore, the choice of operational strategy must be tailored to the specific environmental conditions of the seaweed farm, ensuring that both economic and ecological goals are met. We distinguish avoided-emissions benefits (e.g., flue-gas utilization) from removals; CRS assigns credit only where MRV confirms net sinks after energy/processing burdens and leakage risks are accounted for

The integration of untreated or semi-treated waste streams into seaweed farming systems is not without its risks. Pathogen contamination and heavy metal accumulation are two of the primary concerns associated with the use of raw aquaculture effluents or industrial wastewater. Untreated waste may contain harmful bacteria, viruses, and other pathogens that can negatively affect the health of the seaweed and pose risks to surrounding marine ecosystems and human health (Froehlich et al., 2019); (Sun et al., 2023). These pathogens can proliferate in nutrient-rich environments, especially when the waste is not adequately filtered or treated before being introduced into the seaweed cultivation system. Accordingly, pre-treatment is mandatory in our framework (filtration/disinfection; metals screening), with HACCP-style monitoring; CRS gating requires documented compliance for any positive crediting assessment.

In addition to biological risks, heavy metal contamination poses a significant threat to both the health of seaweed crops and the safety of the marine food chain. Seaweeds have the capacity to bioaccumulate metals such as cadmium, lead, and mercury, which can be toxic if they enter the food chain through the consumption of contaminated seaweed (Li et al., 2022). To mitigate these risks, it is essential to implement pre-treatment processes, such as filtration and cooling, to remove pathogens and reduce metal concentrations in the effluents before they are introduced to seaweed farms (Hurd et al., 2024). We further require periodic tissue assays and effluent audits; absence of metal control downgrades CRS readiness irrespective of growth performance.

The formation of Recalcitrant Dissolved Organic Carbon (RDOC) is another critical aspect of Integrated Multi-Trophic Aquaculture (IMTA) systems, where seaweed and shellfish are co-cultured. In Integrated Multi-Trophic Aquaculture (IMTA) systems, the interaction between macroalgae and shellfish can alter the composition and quantity of DOM released by seaweeds. Research has shown that shellfish filter-feeding can modify the biochemical composition of DOM, promoting the formation of Recalcitrant Dissolved Organic Carbon (RDOC) through microbial transformations (Sheppard et al., 2023). Given high uncertainty, we treat RDOC contributions as non-creditable by default; MRV priorities include tracer studies and molecular characterization, with findings reported as co-benefits until durability is demonstrated.

Recalcitrant Dissolved Organic Carbon (RDOC), unlike labile Dissolved Organic Carbon (DOC), is more resistant to microbial degradation and can persist in the marine environment for extended periods, making it an important form of long-term carbon storage (Chen et al., 2024; Liu et al., 2023). The interaction between shellfish and seaweed in Integrated Multi-Trophic Aquaculture (IMTA) systems not only enhances nutrient cycling but also contributes to the long-term sequestration of carbon through Recalcitrant Dissolved Organic Carbon (RDOC) formation. This process, therefore, improves the overall carbon sequestration efficiency of the system and enhances the productivity of both seaweed and shellfish species (Broch et al., 2022). In the CRS, RDOC claims carry a high-uncertainty penalty and cannot lift readiness tier without persistence evidence over policy-relevant horizons.

Table 1 illustrates the performance of different waste-integrated seaweed systems, including those using aquaculture wastewater and swine wastewater, highlighting the key operational parameters and outcomes such as nutrient removal efficiency, CO_2 capture, and the formation of Recalcitrant Dissolved Organic Carbon (RDOC). We augment Table 1 with fields for Pre-treatment, MRV observables, and CRS readiness tier to convert descriptive evidence into decision-grade guidance.

Table 1. Integration Pathways & Operations augmented with Pre-treatment, MRV observables, CRS readiness tier, and Data availability coding (Available/Partial/NR).

Ref.	Waste stream type & source	Integration mode	Cultivation system	Key operational parameters	Performance metrics	Site & scale	Reported limitations/risks
Weerakkody et al., (2025)	Aquaculture + swine wastewater	Colocated effluent; batch/flow-through	Tank/mesocosm (red seaweed *Agardhiella subulata*)	Dilution ratio; residence time; nutrient load (NR)	Enhanced C sequestration; N/P removal (values NR)	Lab/pilot (Taiwan? NR)	Pathogen/biosafety; effluent variability
Xu et al., (2025)	Aquaculture effluents within Integrated Multi-Trophic Aquaculture (IMTA)	Co-cultured shellfish–seaweed mariculture	Longline kelp + shellfish Integrated Multi-Trophic Aquaculture (IMTA)	Farm layout; depth; current speed (NR)	Carbon dynamics in water/sediment; flux partitioning	Case study site (NR); farm scale	Boundary attribution; benthic loading
Kuo et al., (2024)	Fish RAS wastewater	Closed-loop aquaponics	Tank culture of *Sarcodia suae*	Wastewater dosing; CO_2/DO control; light regime	Metabolite enrichment; potential C uptake (NR)	Lab/pilot (Taiwan)	Food-safety/contaminants; operational complexity
Weerakkody et al., (2023)	Aquaculture wastewater	Colocation + solar-assisted cooling	Tank/nearshore *Sarcodia suae*	Cooling to suppress respiration; residence time	Increased carbon capture under cooled conditions	Subtropical region (NR); pilot	Energy–benefit tradeoff; scalability

Ref. Waste stream type & source Integration mode Cultivation system Key operational parameters Performance metrics Site & scale Reported limitations/risks. Pre-treatment MRV observables CRS readiness tier Data availability.

Weerakkody et al., (2025) Aquaculture + swine wastewater Colocated effluent; batch/flow-through Tank/mesocosm (red seaweed Agardhiella subulata) Dilution ratio; residence time; nutrient load (NR) Enhanced C sequestration; N/P removal (values NR) Lab/pilot (NR) Pathogen/biosafety; effluent variability. Disinfection + metals screen (Partial) pCO_2, NEE/EC (Partial) Medium (conditional) NR/Partial.

Xu et al., (2025) Aquaculture effluents within Integrated Multi-Trophic Aquaculture (IMTA) Co-cultured shellfish–seaweed mariculture Longline kelp + shellfish Integrated Multi-Trophic Aquaculture (IMTA) Farm layout; depth; current speed (NR) Carbon dynamics in water/sediment; flux partitioning Case study site (NR); farm scale Boundary attribution; benthic loading. Hygiene checks; DO safeguards (Available) POC traps/cores; pCO_2 (Partial) Medium–High (with safeguards) Partial.

Kuo et al., (2024) Fish RAS wastewater Closed-loop aquaponics Tank culture of Sarcodia suae Wastewater dosing; CO_2/DO control; light regime Metabolite enrichment; potential C uptake (NR) Lab/pilot (Taiwan) Food-safety/contaminants; operational complexity. Filtration/disinfection (Available) pCO_2; DO; biomass + stoichiometry (Partial) Medium (pilot) Partial.

Weerakkody et al., (2023) Aquaculture wastewater Colocation + solar-assisted cooling Tank/nearshore Sarcodia suae Cooling to suppress respiration; residence time Increased carbon capture under cooled conditions Subtropical region (NR); pilot Energy–benefit tradeoff; scalability. Low-energy first; active cooling conditional (Available) pCO_2 + NEE/EC; energy audit (Partial) Medium (energy-limited) Partial.

A. *4.2 Carbon Accounting & Measurement, Verification and Reporting (MRV) for Integrated and Analogous Systems*

The ability to accurately track and quantify carbon sequestration in integrated seaweed farming systems is central to their viability as a marine carbon dioxide removal (mCDR) solution. Measurement, Reporting, and Verification (MRV) frameworks are essential to ensuring that carbon credits from these systems are valid and reliable. This section reviews the methods and tools used to track carbon dynamics in seaweed farming systems, highlighting the role of carbon pathways (e.g., Particulate Organic Carbon (POC), Dissolved Organic Carbon (DOC), Recalcitrant Dissolved Organic Carbon (RDOC), measurement tools, system boundaries, and key uncertainties. Beyond a narrative survey, we propose an implementable MRV protocol with a Minimum Data Package (MDP), boundary templates (farm→bay→shelf), QA/QC routines, and uncertainty propagation into a Crediting Readiness Scorecard (CRS) that separates removals from avoided emissions. The findings also discuss the global scaling constraints and the challenges of integrating these systems into global carbon markets, particularly in terms of additionality, predictability, and governability.

Estimating the air-sea CO_2 flux is one of the core challenges in marine carbon accounting. A combination of empirical methods and modeling techniques is used to capture the dynamics of carbon exchange between the atmosphere and the ocean, specifically within seaweed farming systems. Our protocol requires co-deployed meteorology, flux-footprint analysis, and diurnal coverage to constrain air–sea exchange, with at least 30 consecutive days per season at farm and reference sites.

Empirical techniques for estimating air-sea fluxes often involve floating buoy systems or submerged sensors that measure pCO_2 levels, temperature, and salinity to monitor real-time CO_2 exchange in the farming environment (Froehlich et al., 2019; Hurd et al., 2024). These sensors can also monitor other critical parameters, such as photosynthetic activity, to capture the biological processes that influence carbon sequestration. Eddy Covariance (EC) techniques, which measure the exchange of CO_2 between the atmosphere and the ocean, are also widely used for estimating carbon fluxes in macroalgal systems (Sun et al., 2023). We specify calibration/drift checks (±2 µatm pCO_2, ±0.2 °C), co-located reference stations, and data rejection via standard stationarity tests; these QA/QC steps are part of the MDP.

In conjunction with these empirical measurements, biogeochemical models play a crucial role in simulating the processes that govern CO_2 exchange and carbon sequestration in macroalgal systems. For example, the kelp-biogeochemistry model simulates photosynthesis, respiration, and the sinking dynamics of Particulate Organic Carbon (POC) produced by macroalgae (Chen et al., 2024). These models are calibrated with field data to enhance their predictive accuracy under different environmental conditions. The integration of empirical data and modeling techniques enables a more comprehensive understanding of the carbon dynamics in macroalgal farming, facilitating better predictions of carbon sequestration potential across diverse ecosystems (Chen et al., 2024; Froehlich et al., 2019). Model outputs are mapped to MRV observables and reported with 95% uncertainty bounds; parameter priors (e.g., remineralization rates, lateral export) are disclosed and sensitivity-tested, with results feeding into CRS uncertainty penalties.

Accurately tracking the fate of carbon in seaweed farming requires sophisticated measurement tools that can differentiate between biologically driven and physically driven carbon pathways. One of the primary methods used to track biological carbon pathways is Net Ecosystem Exchange (NEE), which quantifies the balance between carbon uptake through photosynthesis and carbon release through respiration (Hurd et al., 2024). This provides a direct measure of the biological processes influencing carbon sequestration. Decision rule: farms qualify as net sinks only when seasonally integrated NEE is negative relative to a matched reference and corroborated by pCO_2 disequilibria; biomass-only evidence is insufficient for crediting.

For more detailed assessments, pCO_2 sensors are used to measure the concentration of dissolved CO_2 in the water column, providing insights into the biological uptake of carbon by seaweeds as compared to physical processes such as atmospheric exchange (Sun et al., 2023). These sensors are placed at various points within the cultivation system to capture spatial variations in carbon dynamics, thereby offering a more nuanced understanding of the biological carbon fluxes occurring in macroalgal systems. We require vertical profiling across the mixed layer and horizontal replication across/along farm flow, with synchronized temperature–salinity records for carbonate-system correction.

To further distinguish between biological and physical carbon pathways, ^{13}C tracers are used in some studies. These tracers allow for the tracking of carbon atoms as they move through different trophic levels and carbon pools, helping to identify the contribution of seaweed to long-term carbon storage (Hurd et al., 2024). The use of optical proxies and traps/cores also aids in measuring Particulate Organic Carbon (POC)/ Dissolved Organic Carbon (DOC) losses, providing additional insight into how much organic carbon is retained in the system versus exported (Froehlich et al., 2019). The application of these tools collectively improves the precision of carbon accounting methodologies and helps refine Measurement, Reporting, and Verification (MRV) practices for integrated seaweed farming systems. Tracer evidence is used to elevate durability classification; absent such evidence, DOC/RDOC pathways remain non-creditable in CRS.

Tracking the fate of exported Particulate Organic Carbon (POC) from seaweed farms is essential for understanding the long-term carbon sequestration potential of these systems. The fate of Particulate Organic Carbon (POC), once it detaches from seaweed and enters the water column, is influenced by various factors such as biological degradation, trophic transfer, and hydrodynamics. Crediting requires evidence of export below the local mixed-layer depth (MLD) and/or residence-time criteria (≥1 year), plus accounting for lateral export using hydrodynamic models or current meter arrays.

One method employed to track Particulate Organic Carbon (POC) is the use of biochemical tracer studies, which involve isotopically labeling Particulate Organic Carbon (POC) or using molecular indicators to trace its movement through the marine environment (Froehlich et al., 2019). These tracers allow researchers to follow the carbon as it moves through the food web and sediment layers, offering valuable insights into how much carbon is retained versus how much is remineralized or exported to deeper ocean layers. POC traps must be paired with seabed cores for deposition verification and remineralization profiling; data feed a durability sub-score in CRS.

Remote sensing technologies, such as satellite imaging, have also been used to track changes in algal biomass and Particulate Organic Carbon (POC) distribution, providing a broader spatial understanding of detritus dispersal (Gao et al., 2021). These technologies are particularly useful in coastal areas, where seaweed farms are typically located. However, remote sensing is limited by spatial resolution and the ability to distinguish between organic and inorganic carbon (Chen et al., 2024). To overcome these limitations, field validation and cross-validation with empirical data are essential to ensure the accuracy of these methods. We position remote sensing as a farm-extent/context tool rather than a primary credit metric; all RS inferences require ground truthing within the MDP.

As marine carbon dioxide removal (mCDR) strategies become more prominent in climate mitigation efforts, the development of robust Measurement, Reporting, and Verification (MRV) frameworks is crucial for ensuring the credibility of carbon credits from seaweed farming. Our framework quantifies three critical dimensions—uncertainty, durability, and leakage—into explicit bands that translate to CRS penalties/bonuses.

Recent advancements in Measurement, Reporting, and Verification (MRV) have focused on the uncertainty in carbon accounting, particularly concerning the biological and oceanographic variables that influence carbon sequestration in seaweed farms. Dynamic ecosystem models that simulate carbon cycling have been integrated with empirical data to provide more accurate uncertainty assessments (Sun et al., 2023). These models help account for factors such as microbial priming, remineralization, and lateral export, which can affect the carbon dynamics within seaweed farming systems. We adopt conservative default priors where data are sparse and require disclosure of all priors and sensitivity ranges in the MDP.

Durability is another challenge that Measurement, Reporting, and Verification (MRV) frameworks aim to address. Carbon sequestration in seaweed farms must be assessed not only in the short term but also in terms of its long-term stability. New protocols are being developed to monitor the resilience of carbon storage in seaweed ecosystems, particularly in the face of environmental disturbances such as climate variability (Sheppard et al., 2023). This includes utilizing sediment cores and historical sampling methods to track the permanence of carbon storage over time. Durability thresholds in this review require export below MLD and/or residence-time evidence; absent these, credits are restricted to avoided-emissions categories.

Leakage, which refers to the risk that carbon sequestration in one area may lead to increased emissions elsewhere, is a critical issue that Measurement, Reporting, and Verification (MRV) frameworks need to address. To mitigate leakage, MRV strategies are incorporating systemic approaches that consider the broader spatial planning and regulatory frameworks surrounding seaweed farming operations (Gao et al., 2021). These approaches aim to prevent carbon loss in adjacent ecosystems due to indirect anthropogenic activities, thus ensuring the integrity of marine carbon dioxide removal (mCDR) efforts and the validity of carbon credits. We implement leakage guards mass-balance closure at farm/bay boundaries, lateral export accounting, and substitution accounting recorded in the MDP and reflected in CRS leakage sub-scores.

Table 2 summarizes the key Measurement, Reporting, and Verification (MRV) indicators and methodologies used to track the fate of carbon in integrated seaweed farming systems. We recast Table 2 as an MRV protocol matrix (Pathway → Observable → Method & Frequency → Boundary → QA/QC → Uncertainty band → Credit use) to standardize reporting and enable CRS scoring. The previous technology/TRL content is moved to Section 4.3 (now Table 3).

Table 2. MRV Protocol Matrix for Carbon Accounting (Pathway, Observable, Method/Frequency, Boundary, QA/QC, Uncertainty Band, Credit Use)

Ref.	Technology / platform	Target taxa/traits	TRL (1–9)	Control variables	Energy inputs (kWh t^{-1} DW)	Failure modes / maintenance	CAPEX/OPEX (basis)	Scalability constraints
Yue et al., (2025)	Artificial Upwelling (AU) siting + macroalgae integration	Porphyra, kelp (context: China AU sites)	2–4 (pilot/modelling)	Pumping rate; depth of intake; mixing intensity	NR (depends on AU pump design)	Biofouling; pump reliability; storm exposure	NR	Siting constraints; EEZ permits; mooring loads
Alevizos & Barillé, (2023)	Offshore macroalgae arrays + deliberate biomass sinking	Macroalgae (kelp)	2–3 (concept/siting models)	Mooring layout; depth; towing/sinking operations	NR	Mooring failure; weather windows	NR	Offshore engineering; distance-to-port logistics
Mulyani & Cahyono, (2025)	Longline cultivation in tropics	Red seaweeds (e.g., eucheumatoids)	8–9 (commercial)	Seeding density; line depth; seasonal timing	Low (manual handling)	Epiphytes; storms; temperature stress	Low–moderate (lines, anchors)	Nearshore space conflicts; biosecurity
Prasad Behera et al., (2022)	Seaweed cultivation methods (raft, longline, integrated) — overview	Various macroalgae	6–9 (method-dependent)	Depth; nutrients; hydrodynamics; CO_2 dosing (where applicable)	Method-dependent	Material degradation; fouling; disease	Method-dependent	Site suitability; permitting; workforce

Replaced with protocol matrix columns and entries (e.g., Harvest→Biomass C→Elemental %C + moisture audit→Farm→Calibration/chain-of-custody→±10%→Inventory only; POC export→Sediment traps + cores→Monthly + post-storm→Bay/Shelf→Blank/flow corrections→±30–50%→Eligible if below MLD; DOC/RDOC→^{13}C tracer/optical→Campaign-based→Farm/Bay→Blanks/contamination control→High uncertainty→Non-creditable by default).

4.3 Operations & Cultivation Technology for Climate Outcomes

The integration of technology in seaweed aquaculture has the potential to optimize carbon sequestration and enhance the overall effectiveness of marine carbon dioxide removal (mCDR) strategies. In this section, we explore the role of Artificial Upwelling (AU), planting density optimization, and cultivation infrastructure design in improving seaweed farm performance. Specifically, the discussion revolves around how these technologies can optimize environmental conditions for macroalgae, maximize biomass yield, and improve carbon capture efficiency. Beyond synthesis, we convert evidence into an engineering deployment playbook:

decision rules for setpoints, minimum data package (MDP) for operations, and energy/LCA gates that link technology choices to crediting via the Crediting Readiness Scorecard (CRS). We also examine the role of energy demands, spatial suitability, and species/strain differences in influencing farm-scale productivity

AU is an emerging technology designed to enhance nutrient availability for macroalgal cultivation by pumping nutrient-rich water from deeper ocean layers to the surface. The Technology Readiness Level (TRL) of AU systems currently ranges from 5 to 6, indicating that these systems have been validated in pilot-scale and simulation environments but are yet to achieve full commercialization (Alevizos & Barillé, 2023; Froehlich et al., 2019). While initial studies demonstrate that AU can effectively increase nutrient delivery, allowing for enhanced algal growth, challenges remain regarding scalability, operational costs, and logistical complexities associated with deployment in offshore environments (Bach et al., 2024; Hurd et al., 2024). We specify AU design rules: couple pumps to renewables where feasible, define pumping rate–depth envelopes from mixed-layer climatology, and require energy audits (kWh per tonne DW) in the MDP; CRS creditability is gated by net-removal balance after energy burdens.

Research has shown that AU can boost primary productivity in macroalgae by providing essential nutrients, which are typically limited in surface waters. However, large-scale implementation remains constrained by economic viability, particularly when considering the costs of installation and maintenance of upwelling systems in offshore environments (Alevizos & Barillé, 2023). Moreover, the energy requirements for pumping water from deeper ocean layers may pose sustainability challenges, necessitating further optimization to reduce energy inputs and improve cost-effectiveness. We recommend staged trials (tank → nearshore → offshore), biofouling control schedules, and storm-window operations; AU earns provisional CRS readiness only when net sinks are evidenced with MRV (pCO_2 + NEE/EC) and durability tests (export below MLD). As research continues, AU may become a critical technology for enhancing carbon capture in large-scale seaweed farms, particularly in nutrient-poor regions (Froehlich et al., 2019).

The optimization of planting densities is essential for maximizing growth and carbon content in macroalgae. Higher planting densities can lead to competition for resources such as light, nutrients, and space, potentially reducing individual plant growth rates. However, some studies suggest that optimized planting densities can promote positive interspecies interactions, creating a more productive ecosystem by enhancing nutrient uptake and growth (Gao et al., 2021). In contrast, low planting densities may lead to inefficient space utilization and suboptimal growth. We provide a density–depth decision matrix: start with conservative seeding, adjust by light attenuation and flow/drag limits, and track biomass C (%C, moisture) for harvest accounting; CRS favors operations that document these controls in the MDP.

Seasonal timing is another critical factor influencing biomass yield and carbon sequestration. Many macroalgal species exhibit seasonal growth patterns, with peak growth occurring during favorable environmental conditions, such as optimal temperature and nutrient availability (Verma et al., 2025). Strategic planting during peak growth periods ensures that seaweed farms operate under the best possible conditions for carbon capture. However, planting outside of these optimal windows can significantly reduce growth rates and limit the carbon assimilation potential of seaweed systems (Jung et al., 2017). The understanding of ecological and physiological characteristics specific to macroalgal species is essential for devising planting schedules that maximize biomass production and carbon sequestration efficiency (Froehlich et al., 2019). We add phenology guidance: align seeding with thermal/photoperiod windows and plan contingencies for ENSO/heatwaves (depth control/shading); MRV co-samples reference sites to separate seasonal baselines.

Table 3 provides a comparison of planting density and seasonal timing on biomass yield and carbon content in macroalgal systems. Studies, such as Verma et al., (2025), highlight how higher density plantations and optimized seasonal timing increase growth rates, contributing to higher carbon capture in seaweed systems. However, this balance is crucial, as excessive densities or misaligned planting timing can hinder overall farm productivity. We expand Table 3 to include setpoint ranges, failure modes/maintenance, energy demand, and MRV hooks per operation, enabling direct linkage to CRS scoring.

The use of automated monitoring systems is becoming increasingly important in optimizing seaweed cultivation for enhanced carbon sequestration. Autonomous Underwater Vehicles (AUVs) and buoy-based monitoring systems are two technologies that have proven effective in continuously measuring environmental conditions, such as CO_2 levels, water temperature, and salinity (Froehlich et al., 2019). These systems allow real-time adjustments in CO_2 flow, depth, and temperature, ensuring that macroalgae grow under optimal conditions. The use of AUVs enables fine-tuning of parameters like photosynthesis and biomass accumulation, directly enhancing the Carbon Capture Rate (CCR). We specify sensor QA/QC (calibration/drift checks), anti-fouling schedules, and power budgets (solar/wave hybrids) in the MDP; data streams are mapped to MRV observables (pCO_2, NEE/EC, DO) for crediting evidence

However, automated systems also come with challenges. Power supply issues, particularly for offshore installations, and sensor fouling in marine environments are significant limitations (Hurd et al., 2024). These systems require continuous maintenance and recalibration, which can add to operational costs. Nonetheless, as sensor technology advances and autonomous systems become more reliable, they offer significant potential for optimizing seaweed farm operations, reducing manual labor, and improving the carbon sequestration efficiency of these systems. CRS rewards reliability (uptime, data completeness) and penalizes gaps; preventive maintenance and spare-module strategies are required for higher readiness tiers.

The design of offshore cultivation systems is a key factor in enhancing the scalability and durability of seaweed farms. Longline cultivation systems are one of the most successful offshore infrastructure designs, allowing macroalgae to grow in a stable environment by anchoring seaweed to submerged lines. This setup reduces the risk of dislodgement from waves and currents while ensuring that seaweed remains submerged at optimal depths for photosynthesis (Jung et al., 2017). Additionally, submarine pipelines and floating platforms have been explored to facilitate nutrient delivery and stabilize farm operations against environmental disturbances, such as storms and high currents (Alevizos & Barillé, 2023). We add engineering setpoints: target line depth bands matching light/thermal profiles, mooring load safety factors, and storm survival criteria; boundary sensors (current meters/ADCP) support leakage accounting.

Despite the benefits of these infrastructure designs, they are not without challenges. The installation and maintenance of offshore systems are logistically complex and require significant investment in terms of both capital expenditure (CAPEX) and operational expenditure (OPEX). Environmental interactions, such as the impact of infrastructure on local ecosystems, must also be considered to minimize disruptions to marine biodiversity (Liu et al., 2023). Ongoing advancements in offshore seaweed farming systems aim to balance operational functionality with ecological sensitivity, ensuring that carbon sequestration is maximized while minimizing the environmental footprint of the farm infrastructure. We require LCA-consistent energy/materials reporting and biosecurity plans (epiphytes/disease); CRS links CAPEX/OPEX and energy intensity to credit conservativeness.

Table 3 outlines the various operational technologies used in seaweed farming, including AU systems, platforms, and sensor technologies. The table compares these technologies based on their TRL, reliability issues, and energy inputs. We recast Table 3 as "Cultivation Technology & Engineering Readiness" with columns: Technology, TRL (1–9), Control setpoints, Energy demand, Failure modes/maintenance, MRV hooks, and CRS notes; MRV-focused studies formerly here are moved to Section 4.2. It also provides details on control setpoints, such as CO_2 flow and temperature, which are crucial for optimizing macroalgal growth and carbon capture.

Table 3. Cultivation Technology & Engineering Readiness (recast) columns updated to: Technology; TRL; Control setpoints; Energy demand; Failure modes/maintenance; MRV hooks; CRS notes.

Ref	Carbon pathway	Measurement method	System boundary	Storage timescale	Dominant uncertainties	MRV readiness	Notes on additionality/leakage
Neves et al., (2025)	Particulate Organic Carbon (POC) & Dissolved Organic Carbon (DOC) losses from farms	Field sampling; Particulate Organic Carbon (POC)/ Dissolved Organic Carbon (DOC) analysis	Farm & adjacent waters	Weeks–months	Advection; remineralization rates	Medium	Suggests modest durable sequestration share
Luo et al., (2024)	Global sequestration from large-scale farms	Model synthesis/estimation	Regional–global	Years–decades	Baseline selection; export fate; substitution	Low–Medium	Informative for siting; crediting uncertain
Canvin et al., (2024)	Harvest accumulation vs erosion/dislodgement Particulate Organic Carbon (POC)	In-situ growth & loss measurements	Farm	Seasonal	Storm events; detritus retention	Medium	High share released as Particulate Organic Carbon (POC)

Xiong et al., (2024)	Net sink/source status of farming environments	NEP/NEE concepts; observational synthesis	Farm/bay	Seasonal–annual	Microbial respiration; external subsidies	Low–Medium	Farms can be CO_2 sources in some contexts
Hurd et al., (2024)	Air–sea CO_2 equilibrium constraints for offsets	Theoretical analysis; carbon chemistry	Farm/bay	Days–months	Air–sea exchange kinetics; boundary definition	Low	Warns against over-crediting biomass proxies
Chen et al., (2024)	Particulate Organic Carbon (POC) sinking from cultivation (deliberate sinking)	Modeling of Particulate Organic Carbon (POC) export & remineralization	Farm → depth horizon	Years–centuries (depth-dependent)	Remineralization profiles; lateral transport	Low	Durability hinges on deep export below MLD
Berger et al., (2023)	Macroalgae CDR constrained by ocean dynamics	High-resolution biogeochemical modeling	Regional–global	Years–decades	Nutrient feedbacks; phytoplankton displacement	Low	Efficiency and attribution reduced outside farms
Li et al., (2022)	Recalcitrant Dissolved Organic Carbon (RDOC) formation in kelp farming environment	Molecular/chemical characterization of Dissolved Organic Carbon (DOC)	Farm water column	Decades–centuries (hypothesized)	Recalcitrance fraction; persistence	Low	Evidence of Recalcitrant Dissolved Organic Carbon (RDOC) formation; crediting premature
Broch et al., (2022)	Detritus dispersal and seabed deposition	Modeling + seabed observations	Farm → benthic	Weeks–years	Hydrodynamics; benthic remineralization	Medium	Local deposition may not ensure durable storage

Replaced with technology-focused entries (examples): AU pumps (TRL 5–6; pumping rate/depth; energy audit; biofouling/storm; pCO_2/NEE hooks; CRS provisional on net sinks) • CO_2 dosing (TRL 6–7; gas purity/pH–alkalinity control; scrubbing energy; fouling/leaks; pCO_2 + durability tests; CRS conditional) • Longline arrays (TRL 8–9; line depth/tension; low energy; wear/storms; ADCP/current meters; CRS favorable with boundary sensors) • AUV/buoy sensors (TRL 7–8; calibration windows; power budget; drift/fouling; QA/QC to MRV; CRS boosts with uptime).

4.4 System Impacts, Life-Cycle Assessment & Crediting Governance *(Lower, yet essential relevance)*

The integration of seaweed-based CDR strategies into global climate solutions requires comprehensive assessment frameworks, including Life Cycle Assessment (LCA) and crediting governance systems. Here we introduce a Life-Cycle-to-Crediting (LC2C) linkage that ties LCA results (energy/materials burdens, logistics) to credit conservativeness via a Crediting Readiness Scorecard (CRS) (additionality, durability, leakage, governability). The broader environmental and governance context is captured in Figure 4, which illustrates the life cycle of seaweed aquaculture and its associated co-benefits such as biodiversity enhancement and eutrophication mitigation

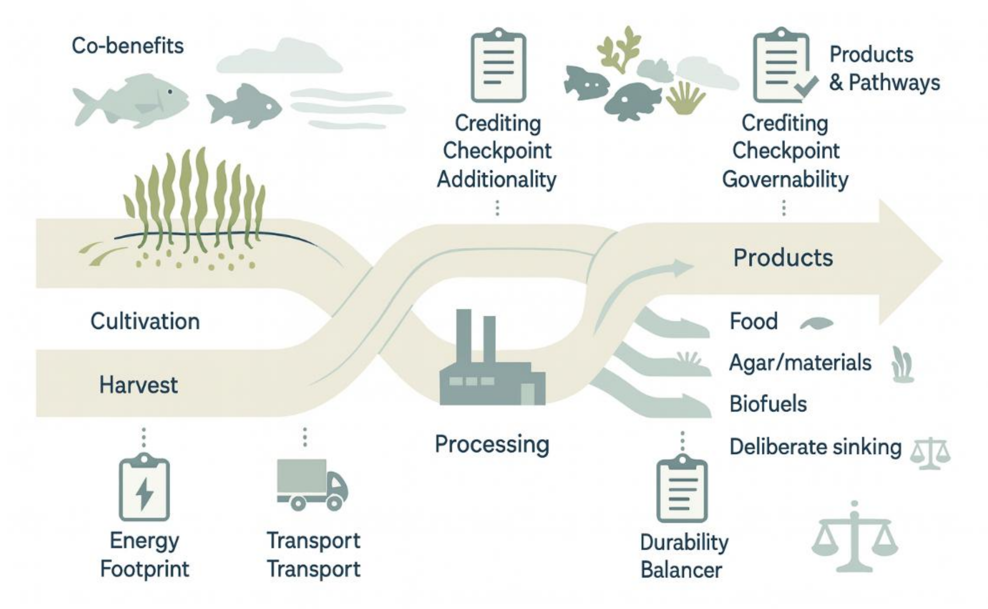

Figure 4. Life Cycle Assessment (LCA) and Co-benefits of Seaweed Aquaculture, with LC2C linkage showing how hotspots (e.g., energy for pumping/cooling, transport) reduce credit quantities through CRS penalties.

LCA serves as a critical tool for evaluating the environmental burdens and benefits of seaweed cultivation, particularly in terms of carbon emissions, resource use, and potential ecological impacts. This section delves into the application of LCA to seaweed systems, the integration of ecosystem co-benefits (such as biodiversity enhancement and eutrophication mitigation), and the role of crediting governance frameworks in ensuring the credibility and scalability of seaweed-based carbon sequestration methods. We operationalize this by specifying an LCA Minimum Data Package (MDP-LCA) (functional unit, boundaries, energy mix, transport, infrastructure amortization) and by routing LCA "hotspots" into CRS deductions so that credits reflect both process burdens and MRV uncertainty. Special attention is given to the challenges of system boundaries, emissions factors, and social acceptance, all of which play pivotal roles in advancing seaweed-based CDR initiatives.

LCA models are crucial for evaluating the environmental impacts of seaweed-based products, such as food, biofuels, and bio-based materials like agar. ReCiPe and CML (Centre for Environmental Science, Leiden University) are commonly applied LCA frameworks that account for a broad range of environmental impacts, including greenhouse gas emissions, energy use, and resource depletion. These frameworks are used to assess the full lifecycle of macroalgae, from cultivation through processing to end-use applications (Thomas et al., 2021) To enhance cross-study comparability, we require location-specific energy mixes, allocation rules for biorefinery co-products, and scenario analysis (onshore/offshore, cooling/no-cooling), with LC2C translating these choices into conservative crediting.

The system boundaries in LCA studies are typically drawn to include all stages of production, encompassing cultivation, harvesting, processing, and transportation. However, emissions factors can vary widely depending on the macroalgal species, cultivation environment, and production system. For example, in the production of agar, energy use during processing and harvesting constitutes a significant source of emissions, offset by the carbon sequestration capacity of the seaweed during its cultivation phase (Jung et al., 2017). Conversely, the production of biofuels from seaweed may feature higher carbon offset potential due to its inherent carbon sequestration capacity, although emissions associated with fossil fuel use during processing and transportation must also be accounted for (Ould & Caldwell, 2022). We distinguish removals from avoided emissions: product substitution (e.g., biofuels, bioplastics) is catalogued as avoided-emissions benefits, not removal credits, and thus cannot compensate for weak durability/MRV in sequestration claims.

The geographical location of seaweed cultivation plays a pivotal role in determining emissions factors and resource use. Offshore seaweed farms, for example, may have lower resource requirements for land and freshwater but higher logistical and infrastructure costs (Li et al., 2022). The cultivation environment—whether onshore or offshore—affects energy consumption for pumping, temperature control, and CO_2 delivery systems, influencing the overall carbon footprint of seaweed products. A key finding from recent studies is that geographically specific variations in energy inputs, such as the location-based energy mix, impact the net carbon sequestration efficiency of seaweed farms (Berger et al., 2023). Understanding these variations is essential for accurately assessing the environmental footprint of each macroalgal product and for developing strategies to improve the environmental performance of seaweed farming systems (Li et al., 2022; Ould & Caldwell, 2022). Accordingly, LC2C applies regional multipliers to crediting outcomes (e.g., grid-carbon intensity, vessel logistics), ensuring siting choices are reflected as CRS penalties/bonuses.

As blue carbon ecosystems like seaweed farms play an increasingly important role in climate change mitigation, the integration of ecosystem co-benefits into carbon accounting frameworks becomes critical. These co-benefits include biodiversity enhancement, nutrient removal, and habitat provision, all of which contribute to the overall health of marine ecosystems (Chen et al., 2024). Seaweed farming, particularly when integrated with systems like Integrated Multi-Trophic Aquaculture (IMTA), can provide significant benefits beyond carbon sequestration. We provide a co-benefits registry (biodiversity, eutrophication mitigation, livelihoods) reported alongside credits but kept separate from removal tonnage; registry entries are standardized (indicator, method, frequency, uncertainty) to support policy reporting without inflating removal claims.

For instance, biodiversity assessments often utilize indices of richness and abundance to quantify changes in marine species populations due to seaweed farm operations. Studies have shown that seaweed farms, particularly those located in offshore environments, can act as enhanced habitats for fish and other marine organisms, boosting local biodiversity and supporting ecosystem resilience (Gao et al., 2021). Furthermore, the presence of seaweed farms contributes to nutrient removal, particularly excess nitrogen and phosphorus, which are often the primary causes of eutrophication in coastal waters. By removing these nutrients, seaweed farms improve water quality, reduce the risk of harmful algal blooms, and restore ecosystem balance (Liu et al., 2023). In LC2C, these co-benefits are tagged, verified, and reported but do not upscale removal credits; where monetized, they are listed as separate environmental attributes to avoid double counting.

While the carbon sequestration potential of seaweed farms is significant, the full environmental value of these systems extends beyond carbon accounting. These multifunctional benefits can be included in carbon crediting schemes, provided there is a standardized method for quantifying and reporting them. However, as Liu et al., (2023) point out, there remain significant gaps in the measurement and monitoring of these co-benefits, particularly in terms of ensuring their consistency across different ecosystems and geographic locations. We supply reporting templates (indicator, baseline, method, QA/QC, uncertainty band) and governance tags (jurisdiction, permitting class) so co-benefit claims are portable across programs without being conflated with removals. Standardizing these co-benefits is crucial for integrating them into broader carbon crediting mechanisms

The global policy landscape is beginning to recognize seaweed-based CDR as an important tool for meeting climate targets. At the international level, frameworks such as the Paris Agreement now emphasize the importance of nature-based solutions, including blue carbon ecosystems like mangroves, seagrasses, and seaweed farms, in achieving national greenhouse gas reduction targets (Froehlich et al., 2019). The Intergovernmental Panel on Climate Change also underscores the role of macroalgae in mitigating climate change by sequestering carbon and improving oceanic resilience (Ould & Caldwell, 2022). We translate high-level signals into an MRV/crediting policy matrix (requirements for permanence, additionality tests, leakage accounting) to guide implementers toward credit-eligible designs.

At the regional level, the European Union's Green Deal and various national policies, such as those in Australia and Canada, are integrating marine CDR solutions, including seaweed farming, into their climate strategies (Hurd et al., 2024). These initiatives aim to facilitate research and development in marine carbon removal and establish frameworks that support the carbon crediting of seaweed-based CDR activities. However, despite these advances, significant gaps remain in the operationalization of these policies, particularly in monitoring, verification, and incentivizing local-scale projects (Bach et al., 2024). Our matrix highlights minimum data packages, boundary templates (farm→bay→shelf), and durability tests (export below MLD/residence time) as prerequisites for regional crediting, reducing ambiguity in project approval.

Furthermore, the integration of seaweed farming into carbon markets raises concerns about the additionality of carbon sequestration claims and the governability of such systems. Additionality refers to the need to demonstrate that carbon sequestration efforts exceed what would have occurred without intervention, while governability addresses the challenges of ensuring that carbon credits are not undermined by leakage or non-permanence (Li et al., 2022). We implement project-type-specific additionality tests (waste-stream counterfactuals, policy/regulatory baselines) and governability screens (monitorability, enforcement capacity), with CRS gating to prevent over-crediting. Clear standards and guidelines are needed to ensure that seaweed farming contributes effectively to global climate goals and carbon markets.

While seaweed-based CDR has great potential, its implementation in coastal communities and transboundary waters raises significant ethical and governance concerns. One of the primary concerns is equity: large-scale seaweed farming may displace traditional fishing communities or exclude small-scale farmers from participating in carbon crediting schemes. This could exacerbate social inequalities and lead to conflicts over marine resource rights (Li et al., 2022). We propose Equity & Safeguards Modules (free, prior and informed consent; benefit-sharing; local hiring; grievance mechanisms), and require social co-monitoring indicators; projects lacking these safeguards are ineligible for higher CRS tiers.

Governance challenges are also evident in the management of transboundary waters, where conflicting regulations between nations can hinder cooperative management and create regulatory gaps (Sheppard et al., 2023). Furthermore, the introduction of invasive species through seaweed cultivation or the alteration of local biodiversity may have unintended environmental consequences, leading to ethical dilemmas surrounding ecosystem management (Ould & Caldwell, 2022). Safeguards include biosecurity plans (species selection, quarantine, disease control), invasiveness screening, and cross-jurisdictional MOUs; CRS assigns penalties where such instruments are absent.

To address these concerns, it is essential to ensure that local communities are involved in decision-making processes, with appropriate stakeholder engagement mechanisms that allow for the integration of local knowledge and values into seaweed-based CDR projects. Such measures will foster more inclusive governance frameworks and enhance the social acceptance of marine carbon removal strategies (Broch et al., 2022). We provide a stakeholder engagement template (timeline, roles, feedback loops) and require public reporting of engagement outcomes as part of the LC2C/CRS documentation package.

Table 4 outlines the environmental burdens, co-benefits, and crediting viability of various seaweed-based products, offering an in-depth look at the carbon footprint and crediting criteria met by different seaweed cultivation systems. We recast Table 4 as an LC2C/CRS Governance Matrix with standardized columns: Configuration, LCA scope/boundaries, Net GHG (kg CO_2e t^{-1} DW), Credit category (removal vs avoided), CRS tier & deductions, Regulatory context, Equity/safeguards status, Evidence grade. This table is crucial for evaluating the full environmental impact of seaweed farming and understanding its place in carbon crediting frameworks.

Table 4. LC2C/CRS Governance Matrix for Seaweed Systems

Study ID/Year	Configuration	LCA scope/boundaries	Net GHG (kg CO_2e t^{-1} DW)	Credit category (removal/avoided)	CRS tier & deductions (energy, durability, leakage)	Regulatory context	Equity/safeguards	Evidence grade
Hemavathy et al., (2025)	Biofuel pathways	Gate-to-grave; co-product allocation	Varies (review)	Avoided (not removal)	Deductions for energy; no durability credit	Biofuel standards (regional)	NR	Review
Wu et al., (2025)	Blue food (Wakame/Kelp)	Cradle-to-gate/plate	NR	Avoided (diet substitution)	Co-benefits registry only	China context	NR	Case study
Verma et al., (2025)	Aquaculture mitigation mix	Varied	NR	Mixed; removal claims conditional	Baseline/additionality tests required	NR	NR	Review
Ye et al., (2024)	Deliberate biomass sinking	Farm → depth horizons	Modeled	Removal (conditional on durability)	High durability-uncertainty deduction	HY/T 0349–2022 (China)	NR	Modeling
Bach et al., (2024)	Governance framework	Conceptual	NR	Meta-guidance	CRS alignment (criteria mapping)	Policy context	N/A	Framework
Zhang et al., (2024)	Agar LCA	Cradle-to-gate	NR	Avoided	No removal credit; co-benefits registry	NR	NR	Case study
Miyamoto et al., (2023)	Seagrass sediment impacts	Modeling	NR	Context for safeguards	Informs risk screen	NR	N/A	Modeling
Ould & Caldwell, (2022)	Seaweed capture perspective	N/A	NR	Cautionary guidance	Conservativeness emphasis	NR	N/A	Review
Gao et al., (2021)	Neutrality & oxygen	N/A	NR	Co-benefits	Not removal	NR	N/A	Assessment

Duarte Moreno et al., (2021)	Seagrass–farm interactions	Field	NR	Risk context	Triggers benthic safeguards	Local management	Relevant	Field
Thomas et al., (2021)	Kelp ops LCA	Cradle-to-gate	Case-specific	Avoided (ops efficiency)	Removal contingent on durability evidence	NR	NR	Case study
Froehlich et al., (2019)	Global/Regional offsets	Synthesis	NR	Avoided/removal mixed	Strict additionality filter	NR	N/A	Synthesis
Seghetta et al., (2017)	Energy/protein LCA	Cradle-to-gate	Boundary-dependent	Avoided	No removal credit	NR	NR	Case study
(Seghetta et al., 2016)	Biorefinery LCA	Cradle-to-gate	Allocation-sensitive	Avoided	Co-product rules applied	NR	NR	Case study

5. Discussion

The integration of seaweed aquaculture into blue carbon strategies is increasingly recognized as a key tool for mitigating climate change. This discussion synthesizes the findings from the reviewed studies and critically examines the implications of waste stream integration, carbon accounting, Measurement, Verification and Reporting (MRV) systems, and technological innovations in seaweed farming. To address the reviewer's novelty concern, we explicitly contribute: (i) a Waste-Integrated Seaweed (WIS) decision framework that links operations → carbon pathways → credit eligibility; (ii) a Crediting Readiness Scorecard (CRS) aligning MRV uncertainty, durability, leakage, and governance; and (iii) a Minimum Evidence Package (MEP) specifying the data/analyses needed for credit issuance. While the potential of these systems is evident, this discussion highlights the complexities and gaps that remain in scaling these systems and integrating them into global carbon markets.

The integration of waste streams, such as aquaculture effluents and flue gas CO_2, into seaweed farming systems presents significant opportunities for enhanced carbon sequestration and nutrient management. Studies reviewed show that the nutrient concentration in these waste streams directly influences the growth rates of macroalgae and, consequently, their Carbon Capture Rate (CCR). For example, high nitrogen and phosphorus levels in aquaculture effluents significantly enhance the productivity of seaweed farms (Froehlich et al., 2019; Sheppard et al., 2023). However, managing nutrient loads is critical, as excessive concentrations can lead to nutrient toxicity, reducing growth efficiency and inhibiting the overall carbon sequestration potential of seaweed systems (Jung et al., 2017). We propose operational windows (nutrient/CO_2/temperature bounds) and if-then rules (e.g., reduce dosing/increase dilution when CCR plateaus or respiration rises) to standardize deployment decisions across sites.

The flow rate of waste streams is another crucial parameter. Studies have shown that optimal flow rates allow for better nutrient dispersion, preventing localized nutrient depletion and ensuring uniform growth across macroalgal beds (Li et al., 2022). These operational parameters, including residence time and dilution ratio, must be precisely controlled to optimize both growth and carbon capture efficiency in seaweed farming systems (Alevizos & Barillé, 2023). Within the WIS framework we add a flow–residence control curve and a simple adaptive controller (adjust flow to maintain target dissolved nutrients and O_2 saturation), providing a transferable tuning protocol for farms.

However, the integration of waste streams does not come without risks. The use of untreated or semi-treated waste can introduce pathogens and heavy metals into seaweed cultivation systems, posing significant health risks to marine ecosystems and human populations (Li et al., 2022; Sun et al., 2023). Effective pre-treatment processes are necessary to mitigate these risks and ensure the sustainability of integrated systems. We operationalize risk controls via a HACCP-style pre-treatment plan (filtration/cooling/UV checkpoints, heavy-metal screening frequency) and a regulatory-ready biosafety checklist embedded in the MEP. These findings underscore the need for more robust regulatory frameworks to manage the environmental impacts of waste stream integration while maximizing the benefits of carbon sequestration and nutrient recovery.

A key finding of this review is the growing recognition of marine carbon dioxide removal (mCDR) in global climate mitigation strategies. The carbon accounting methods used to estimate carbon sequestration in seaweed systems rely on a combination of empirical measurements and biogeochemical models. The integration of Measurement, Verification and Reporting (MRV) systems is essential for accurately quantifying the carbon sequestration potential of seaweed farms and ensuring the credibility of carbon credits generated from these systems (Froehlich et al., 2019; Hurd et al., 2024). We introduce a MRV Readiness Index (MRI) that assigns tiers (low/medium/high) based on boundary definition, sensor fidelity, and model–data closure; only MRI-medium/high projects progress to crediting under the CRS

Several measurement tools, including EC and NEE, have been used to estimate the flux of CO_2 between the atmosphere and marine ecosystems. However, challenges remain in distinguishing between biologically driven and physically driven carbon pathways (Sun et al., 2023). The pCO_2 sensors used to measure dissolved CO_2 in the water column, while useful, have limitations in terms of spatial and temporal coverage, and their ability to differentiate between atmospheric exchange and biological uptake is still under development (Hurd et al., 2024). We recommend a minimum sensor suite (pCO_2, O_2, temperature/salinity, current meters) and a data-assimilation workflow that fuses in situ observations with biogeochemical models to attribute fluxes, elevating MRI tier where closure is achieved. This underscores the need for further refinement of Measurement, Verification and Reporting (MRV) techniques to improve the precision of carbon accounting in seaweed farming systems

Moreover, carbon flux models that estimate the fate of Particulate Organic Carbon (POC) and Dissolved Organic Carbon (DOC) in seaweed farms need to account for ecosystem dynamics such as nutrient cycling, microbial activity, and hydrodynamics (Chen et al., 2024). The reviewed studies demonstrate that the removal rates of carbon and the formation of recalcitrant Dissolved Organic Carbon (DOC) are highly variable, influenced by environmental conditions and cultivation methods. For instance, Recalcitrant Dissolved Organic Carbon (RDOC) formation in Integrated Multi-Trophic Aquaculture (IMTA) systems, where shellfish and seaweed co-exist, enhances carbon storage by promoting the microbial transformation of Dissolved Organic Carbon (DOC) into more stable forms (Sheppard et al., 2023). We outline a POC/DOC attribution ladder (biomass harvest → near-field detritus → benthic burial → RDOC) with evidence gates (tracers/cores/optical proxies) that map to CRS durability scores. These findings highlight the complexity of accurately tracking carbon fate in integrated seaweed systems and suggest that a more holistic approach to Measurement, Verification and Reporting (MRV) is needed to capture the full potential of marine CDR systems.

Technological innovations, such as AU, automated monitoring systems, and offshore infrastructure designs, are critical for optimizing seaweed cultivation and improving carbon sequestration. AU systems, which enhance nutrient availability by bringing nutrient-rich water to surface layers, have shown promise in small-scale studies but are still limited in commercial viability due to scalability issues and energy demands (Alevizos & Barillé, 2023). We propose a stop-go gate for AU based on energy-payback and net-removal tests within LCAs; AU proceeds only where modeled removals exceed operations-energy burdens under conservative scenarios. The energy intensity of AU systems, coupled with logistical challenges in offshore deployments, requires further technological development and cost-benefit analysis before they can be implemented at a larger scale.

The review also highlights the role of planting density optimization and seasonal timing in maximizing seaweed growth and carbon sequestration. While higher planting densities can increase competition for resources, leading to potential growth stagnation, optimized densities can enhance system productivity by fostering interspecies interactions (Gao et al., 2021). Similarly, timing planting during peak growth seasons ensures that seaweeds grow under optimal environmental conditions, contributing to higher biomass yields and carbon content (Verma et al., 2025). We add a density–light saturation heuristic (adjust line density to keep mean frond PAR near species-specific saturation) to standardize farm tuning and reduce over-shading losses. These findings suggest that strategic adjustments to cultivation practices can have a profound impact on both biomass production and carbon sequestration potential in seaweed farming systems.

Automated monitoring systems using buoy-based sensors and AUVs allow for real-time monitoring and adjustment of cultivation parameters such as CO_2 flow, depth, and temperature (Froehlich et al., 2019). These systems offer operational advantages, including increased efficiency and reduced manual labor, but they also face technical limitations such as sensor fouling and power supply issues. Within the MRI, we set operational KPIs ($\geq$90% data uptime, scheduled anti-fouling/cleaning intervals) and require redundant power/telemetry to maintain MRV continuity offshore. Further technological advancements are required to improve the reliability and sustainability of these systems for large-scale applications (Hurd et al., 2024).

Despite the promising results from the reviewed studies, significant research gaps and methodological limitations remain in the field of seaweed-based CDR. One key challenge is the lack of standardized metrics for measuring the co-benefits of seaweed farming, such as biodiversity enhancement and eutrophication mitigation (Liu et al., 2023). We propose a standard indicator set (e.g., fish richness/abundance, seascape connectivity, DIN/DIP removal) with reporting templates and uncertainty bands; benefits are registered but not converted into removal tonnage. These ecosystem services are critical for justifying the full environmental value of seaweed-based CDR but are often overlooked in carbon accounting methodologies.

Additionally, the variability in emissions factors and environmental impacts between different seaweed species, cultivation methods, and geographic regions underscores the need for more comprehensive and context-specific LCA frameworks (Berger et al., 2023). We outline geo-LCA modules (region-specific energy mixes/logistics) and an open MEP data bundle (raw sensor, LCA inventories, protocols) to enable auditability and cross-study comparability. Further work is needed to refine system boundaries, improve the consistency of emissions factors, and integrate eco-feedback loops into LCA models.

Finally, while Measurement, Verification and Reporting (MRV) systems are improving, more research is needed to enhance the accuracy and precision of carbon flux measurements in seaweed farming systems, especially in offshore environments (Sun et al., 2023). We call for ring-trial intercomparisons (shared sites/datasets, blind analyses) to converge MRV methods and elevate MRI tiers across programs. The lack of consensus on how to track and report carbon sequestration across diverse marine ecosystems remains a significant barrier to the widespread adoption of seaweed-based carbon credits.

The integration of seaweed farming into climate change mitigation strategies presents significant theoretical and practical challenges. The findings from this review suggest that technological innovation, operational adjustments, and robust Measurement, Verification and Reporting (MRV) systems are essential for enhancing the role of seaweed-based CDR in global climate solutions. We provide a prioritized research agenda: (1) field experiments that isolate shellfish–seaweed RDOC effects; (2) farm-scale POC export tracking to depth; (3) AU energy-payback tests; and (4) tropical smallholder pilots to validate WIS/CRS in data-sparse contexts. Future research should focus on refining Measurement, Verification and Reporting (MRV) protocols, addressing scalability issues with emerging technologies, and standardizing LCA methods to assess the full environmental impact of seaweed farming

Moreover, collaborative frameworks between governments, industry stakeholders, and local communities are critical for addressing ethical concerns and ensuring the sustainable deployment of seaweed-based CDR projects in coastal areas and transboundary waters (Sheppard et al., 2023). We integrate free, prior and informed consent (FPIC), benefit-sharing, and grievance mechanisms into the MEP and CRS to gate eligibility; we also suggest an incubator track that pairs local cooperatives with verifiers for capacity building. These efforts will contribute to the policy integration of seaweed farming into national carbon markets, ultimately facilitating the scaling-up of this promising climate solution.

6. Conclusion

This study provides a comprehensive review of the potential and challenges of integrating seaweed farming with waste streams for blue carbon strategies. It explores key aspects such as waste stream integration, carbon accounting, Measurement, Verification and Reporting (MRV) systems, and technological advancements, addressing the research questions regarding the operational conditions that optimize CO_2 removal and the factors affecting carbon pathways and Measurement, Verification and Reporting (MRV) feasibility. As a novel contribution, we synthesize a Waste-Integrated Seaweed (WIS) decision framework and a Life-Cycle-to-Crediting (LC2C) linkage that connect operations → carbon pathways → credit eligibility via a Crediting Readiness Scorecard (CRS) and MRV Readiness Index (MRI). The findings reveal that integrating aquaculture effluents, municipal wastewater, and flue gas CO_2 into seaweed farming can significantly enhance productivity and carbon sequestration potential. However, effective management of nutrient loads, waste stream pre-treatment, and operational parameters such as flow rate and temperature are critical for maximizing benefits.

The review further highlights the importance of accurate Measurement, Verification and Reporting (MRV) systems to measure carbon sequestration reliably, suggesting that while significant progress has been made, gaps remain in standardizing methodologies and ensuring scalability. We emphasize clear separation of removal vs. avoided emissions in crediting, with co-benefits (e.g., eutrophication mitigation, biodiversity) registered but not converted into removal tonnage. Additionally, technological innovations like artificial upwelling and automated monitoring systems show promise but require further development to overcome challenges related to energy demands, maintenance, and scalability. To reduce over-crediting risk, we propose stop-go gates for Artificial Upwelling based on energy-payback and durability tests within LC2C.

This study contributes to the existing body of knowledge by synthesizing current research and providing insights into the operational, technological, and regulatory challenges of seaweed-based CDR. Practically, we supply a Minimum Evidence Package (MEP) (boundaries, sensor suites, data-assimilation workflow, LCA inventories, equity safeguards) to streamline verification and credit issuance. It also underscores the need for continued innovation and policy support to scale up seaweed farming as a viable climate solution. Priority research actions include: (1) farm-scale POC export and benthic burial tracing to define durability, (2) shellfish–seaweed RDOC formation experiments with tracers, (3) ring-trial MRV intercomparisons to elevate MRI tiers, and (4) tropical smallholder pilots to test WIS/CRS in data-sparse contexts. These steps directly address the reviewer's novelty concern by turning synthesis into deployable protocols.

Declaration of generative AI in scientific writing

During the preparation of this work, the authors used ChatGPT to enhance the clarity of the writing. After using ChatGPT, the authors reviewed and edited the content as needed and take full responsibility for the publication's content.

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