



## The Role of Seaweed in Carbon Sequestration and Climate Change Mitigation: A Review of Blue Carbon Potential

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**ABSTRACT:** Seaweed farming has emerged as a viable solution for mitigating climate change by sequestering carbon through blue carbon processes. This review examines the carbon sequestration potential of seaweed by focusing on the environmental factors influencing growth, the effectiveness of various farming methods, and the role of seaweed within broader climate mitigation strategies. The review consolidates findings from multiple studies, highlighting species such as *Kappaphycus alvarezii*, *Ulva lactuca*, and *Gracilaria* spp., which exhibit varying growth rates and carbon capture capacities. Key environmental conditions, including temperature, salinity, nutrient availability, and CO<sub>2</sub> levels, are shown to significantly influence the carbon sequestration potential of seaweed farming. The integration of seaweed farming into sustainable aquaculture systems, such as Integrated Multi-Trophic Aquaculture (IMTA), is identified as an effective strategy for enhancing nutrient cycling and improving carbon storage. While seaweed farming offers substantial potential, challenges such as regulatory barriers, environmental risks, and infrastructure limitations must be addressed to enable large-scale adoption. The review calls for further research to refine methodologies, optimize farming practices, and examine the socio-economic dimensions of seaweed farming, thereby ensuring its viability as a long-term climate change mitigation solution.

**Keywords:** Seaweed Farming; Carbon Sequestration; Blue Carbon; Climate Change Mitigation; Integrated Multi-Trophic Aquaculture (IMTA)

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## INTRODUCTION

Climate change remains one of the most pressing global challenges, requiring urgent and innovative solutions to reduce greenhouse gas emissions and stabilize the Earth's climate system. Increasing concentrations of atmospheric carbon dioxide (CO<sub>2</sub>) have intensified global warming, resulting in rising sea levels, extreme weather events, and ecosystem degradation. In response to these challenges, nature-based solutions (NbS) have gained increasing attention as cost-effective and sustainable approaches to climate change mitigation. These solutions emphasize the conservation, restoration, and sustainable management of ecosystems to enhance natural carbon sequestration processes. Among various nature-based solutions, blue carbon has emerged as a critical concept in climate change mitigation strategies. Blue carbon refers to carbon captured and stored by coastal and marine ecosystems, including mangroves, seagrasses, and seaweeds. These ecosystems play a vital role in reducing atmospheric CO<sub>2</sub> while simultaneously providing essential ecosystem services such as coastal protection and biodiversity support. Previous studies have highlighted the significant contribution of blue carbon ecosystems to global carbon cycling and climate regulation (Duarte et al., 2022; Macreadie et al., 2021).

Seaweed, particularly marine macroalgae, has become a key component of blue carbon solutions due to its rapid growth rates and high carbon absorption capacity. Seaweed forests are increasingly recognized for their ability to capture carbon while promoting marine biodiversity, comparable to the ecological functions of mangroves and seagrasses (Hurd et al., 2022; Krause et al., 2022). In recent years, seaweed farming has attracted growing interest as a scalable approach to climate change mitigation. However, despite well-documented carbon uptake rates, concerns remain regarding the long-term storage and permanence of carbon sequestered by seaweed biomass (Nishihara et al., 2025).

Although numerous studies have examined the carbon sequestration capacity of seaweed, significant scientific gaps remain in understanding its effectiveness as a long-term climate mitigation strategy. Previous research has primarily focused on short-term carbon uptake, while uncertainties persist regarding carbon fate, remineralization processes, and long-term storage pathways (Nishihara et al., 2025). In addition, variations in species characteristics, environmental conditions, and farming practices lead to inconsistent estimates of sequestration potential across studies. These limitations highlight the need for a comprehensive synthesis of existing literature to critically assess current evidence and identify key challenges and opportunities. This review focuses on seaweed species commonly considered for farming, the farming methods employed, and the environmental conditions required for effective carbon sequestration. Particular attention is given to both red and brown algae, including *Saccharina latissima* (kelp), *Ulva lactuca*, and *Asparagopsis taxiformis*, which have been widely studied for their ecological and biogeochemical roles. In addition, farming approaches such as Integrated Multi-Trophic Aquaculture (IMTA) and offshore cultivation systems are examined. Environmental factors, including water temperature, salinity, and

nutrient availability, are also analyzed due to their significant influence on seaweed growth and carbon uptake.

Based on the identified research gaps, this review seeks to address two key questions. First, what is the carbon sequestration potential of seaweed farming under different environmental and farming conditions? Second, how can seaweed farming contribute to climate change mitigation at a global scale? Accordingly, the primary objective of this review is to evaluate the carbon sequestration potential of various seaweed species used in marine farming. In addition, this study aims to assess the challenges and opportunities associated with scaling seaweed farming as a viable climate change mitigation strategy. This review contributes to the growing body of knowledge on seaweed farming as a climate change mitigation solution. From a theoretical perspective, it strengthens the understanding of seaweed's role within the blue carbon framework and highlights key scientific debates surrounding carbon storage mechanisms. From a practical perspective, the review provides insights into farming methods, environmental requirements, and management strategies that can enhance carbon sequestration outcomes. Furthermore, the findings offer valuable implications for future research, policy development, and the sustainable implementation of seaweed farming within global climate change mitigation strategies.

## LITERATURE REVIEW

### *Relevant Theories and Models*

#### *a. Blue Carbon Concept and Its Role in Carbon Sequestration*

The blue carbon concept integrates marine ecosystems into broader climate change mitigation strategies by emphasizing their capacity to sequester and store carbon. Within this framework, seaweed farming has emerged as an important component due to its ability to enhance the natural carbon absorption capacity of coastal marine ecosystems. Studies indicate that the conservation, restoration, and sustainable management of blue carbon ecosystems, including seaweed farms, are essential for achieving climate mitigation targets while simultaneously delivering ecological benefits such as fisheries support and coastal protection (Feng et al., 2023; Macreadie et al., 2021).

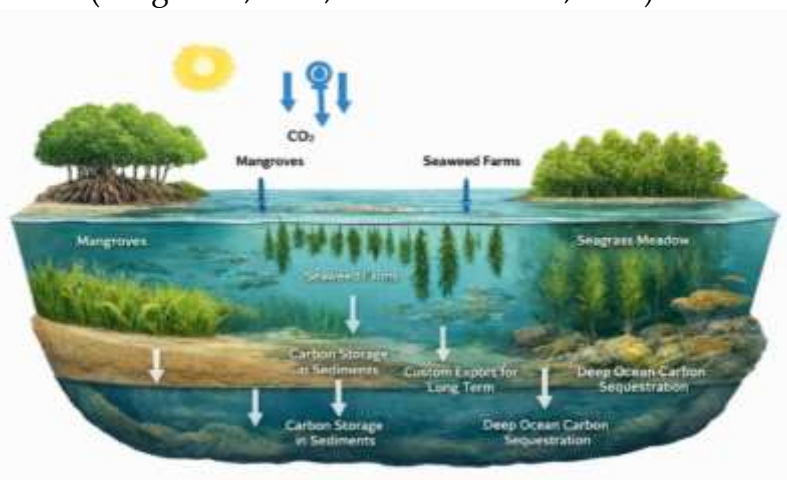


Figure 1. Conceptual Diagram of Blue Carbon Ecosystems Highlighting the Role of Seaweed in Carbon Sequestration.

Seaweeds, particularly macroalgae, exhibit rapid growth rates and high primary productivity, making them highly efficient in capturing atmospheric CO<sub>2</sub> through photosynthesis. Beyond short-term uptake, a portion of seaweed-derived carbon may be transferred to deeper ocean layers, contributing to long-term carbon storage (Nowicki et al., 2022; Ross et al., 2022). As illustrated in Figure 1, seaweed forests function alongside mangroves and seagrasses within interconnected blue carbon systems, highlighting their complementary role in marine carbon sequestration processes.

### ***b. Photosynthesis and Carbon Uptake in Seaweed***

Seaweed-mediated carbon sequestration is primarily driven by photosynthesis, through which seaweeds convert sunlight, seawater nutrients, and CO<sub>2</sub> into organic matter. This process results in the accumulation of carbon within seaweed biomass, and farming practices have been shown to significantly enhance this natural uptake (Pessarrodona et al., 2023; Wang et al., 2025). The efficiency of photosynthesis is closely linked to seaweed growth rates, which vary across species and environmental conditions. A portion of the organic matter produced through photosynthesis may be retained in marine sediments, where it can remain stored for extended periods, thereby contributing to carbon sequestration (Ouyang et al., 2023; Pessarrodona et al., 2023). These mechanisms underscore the importance of understanding species-specific productivity and environmental drivers when evaluating the carbon sequestration potential of seaweed farming systems.

### ***c. Mechanisms of Carbon Storage in Seaweed Biomass and Sediments***

In addition to direct photosynthetic uptake, seaweed farming contributes to carbon sequestration through several indirect mechanisms. As seaweeds grow, they can stabilize surrounding sediments and promote the accumulation of organic-rich substrates that are effective at storing carbon (Pessarrodona et al., 2023; Su et al., 2021). Furthermore, the decomposition of seaweed biomass can generate dissolved organic carbon (DOC), which may be incorporated into microbial food webs or buried within sediments, thereby enhancing long-term carbon storage (Ould & Caldwell, 2022). Integrated multi-trophic aquaculture (IMTA) systems further strengthen these processes by combining seaweed cultivation with other aquaculture activities. Such systems have been shown to improve biodiversity, nutrient cycling, and ecosystem resilience, indirectly supporting the carbon sequestration potential of marine environments (Hilmi et al., 2021).

## ***Historical Development of the Topic***

### ***a. Early Studies on Marine Carbon Sinks and the Role of Seaweed***

The scientific understanding of marine carbon sinks has evolved substantially over recent decades. Early research on marine carbon sequestration primarily emphasized mangroves, seagrasses, and salt marshes, while seaweeds were largely overlooked despite their high productivity and carbon uptake capacity. As research interest in coastal and marine ecosystems expanded, the role of seaweeds as effective carbon sinks began to receive greater attention.

Subsequent studies have increasingly recognized seaweed ecosystems, including cultivated seaweed farms, as valuable components of blue carbon systems (Duarte et al., 2022; Macreadie et al., 2021). This shift reflects a broader acknowledgment of the ecological and biogeochemical importance of macroalgae in global carbon cycling.

### ***b. Evolution of Research on Seaweed Farming as a Climate Change Mitigation Tool***

In recent years, seaweed farming has gained prominence as a potential tool for climate change mitigation. The combination of rapid growth rates, high carbon uptake, and additional ecological benefits has driven a surge in research exploring its role within climate strategies. Notably, the inclusion of seaweed farming in national climate commitments and emerging carbon trading discussions marks an important milestone in recognizing its mitigation potential (Feng et al., 2023). This evolution has been supported by technological and methodological advances, particularly in offshore cultivation and IMTA systems, which enable the scaling of seaweed farming for both climate mitigation and ecosystem restoration purposes (Ross et al., 2022).

### ***Debates and Controversies***

#### ***a. Long-Term Carbon Sequestration Potential of Seaweed***

Despite growing enthusiasm for seaweed farming, debates persist regarding its effectiveness as a long-term carbon sequestration strategy. While seaweed farms can absorb substantial amounts of CO<sub>2</sub>, uncertainties remain concerning the permanence of stored carbon. One key concern relates to remineralization processes, whereby carbon stored in seaweed biomass may be released back into the atmosphere during decomposition, potentially limiting long-term sequestration benefits (Bullen et al., 2024; Nishihara et al., 2025). As a result, some scholars argue that although seaweed farming is effective for short-term carbon capture, its contribution to sustained climate mitigation requires further empirical validation.

#### ***b. Environmental Impacts of Large-Scale Seaweed Farming***

Another area of debate concerns the environmental implications of large-scale seaweed farming. Although generally viewed as environmentally friendly, intensive seaweed cultivation may alter local marine conditions, including water quality and nutrient dynamics. Large-scale operations also raise concerns about habitat modification and the potential introduction of invasive species (Jones et al., 2022). Additionally, questions have been raised regarding the sustainability of certain farming practices, such as fertilizer use and intensive cultivation methods, which may negatively affect surrounding marine habitats if not properly managed (Hurd et al., 2023).

#### ***c. Challenges in Quantifying Carbon Sequestration***

Quantifying the carbon sequestration potential of seaweed systems remains a significant methodological challenge. Variability in environmental conditions, species characteristics, and farming techniques complicates the

development of standardized metrics for carbon capture. Although numerous studies have estimated sequestration rates for different seaweed species, inconsistencies in methodologies limit comparability across studies (Macreadie et al., 2021; Murtaza et al., 2023). Moreover, long-term monitoring of carbon storage in seaweed systems is resource-intensive and technically complex, underscoring the need for further research and methodological refinement.

## **METHODOLOGY**

This study adopts a systematic literature review approach to examine the role of seaweed farming in carbon sequestration and climate change mitigation within the blue carbon framework. The methodology was designed to ensure transparency, rigor, and reproducibility, following established guidelines for systematic reviews, particularly the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework.

### ***Search Strategy***

To identify relevant and high-quality literature on seaweed farming and its carbon sequestration potential, a systematic search strategy was implemented across multiple academic databases and digital libraries. The primary data sources included Google Scholar, Web of Science, and Scopus, which were selected due to their extensive coverage of peer-reviewed scientific publications. Boolean operators (AND, OR) were applied in combination with key search terms such as “seaweed farming,” “carbon sequestration,” “blue carbon,” and “marine ecosystems” to ensure comprehensive retrieval of relevant studies. To maintain the relevance and timeliness of the review, filters were applied to include only peer-reviewed articles published within the last ten years. This period reflects the growing scientific attention to seaweed farming as a climate change mitigation strategy (Hurd et al., 2022; Kumari et al., 2024; Lian et al., 2023).

### ***Eligibility Criteria***

Clear inclusion and exclusion criteria were established to ensure the selection of studies that directly addressed the research objectives of this review. Inclusion criteria focused on empirical studies that explicitly examined the carbon sequestration capacity of specific seaweed species. Studies that reported on seaweed cultivation techniques, carbon capture mechanisms, and environmental factors influencing growth were prioritized. In addition, articles addressing the socio-economic implications of seaweed farming and potential barriers to large-scale implementation were included to provide a comprehensive perspective (Hurd et al., 2022; Nishihara et al., 2025).

### ***Screening and Selection Process***

The screening and selection process followed the PRISMA framework, ensuring a structured and transparent approach to identifying eligible studies. Initially, all records retrieved from the selected databases were compiled, and duplicate entries were removed to minimize redundancy and selection bias. Subsequently, titles and abstracts were screened to assess their relevance to the

core research questions concerning seaweed farming and carbon sequestration. Studies that met the preliminary criteria were then subjected to a full-text review to confirm their compliance with the established inclusion and exclusion criteria. The complete screening and selection process is illustrated in the PRISMA flow diagram (Figure 2), which details the number of studies identified, screened, excluded, and ultimately included in the review.

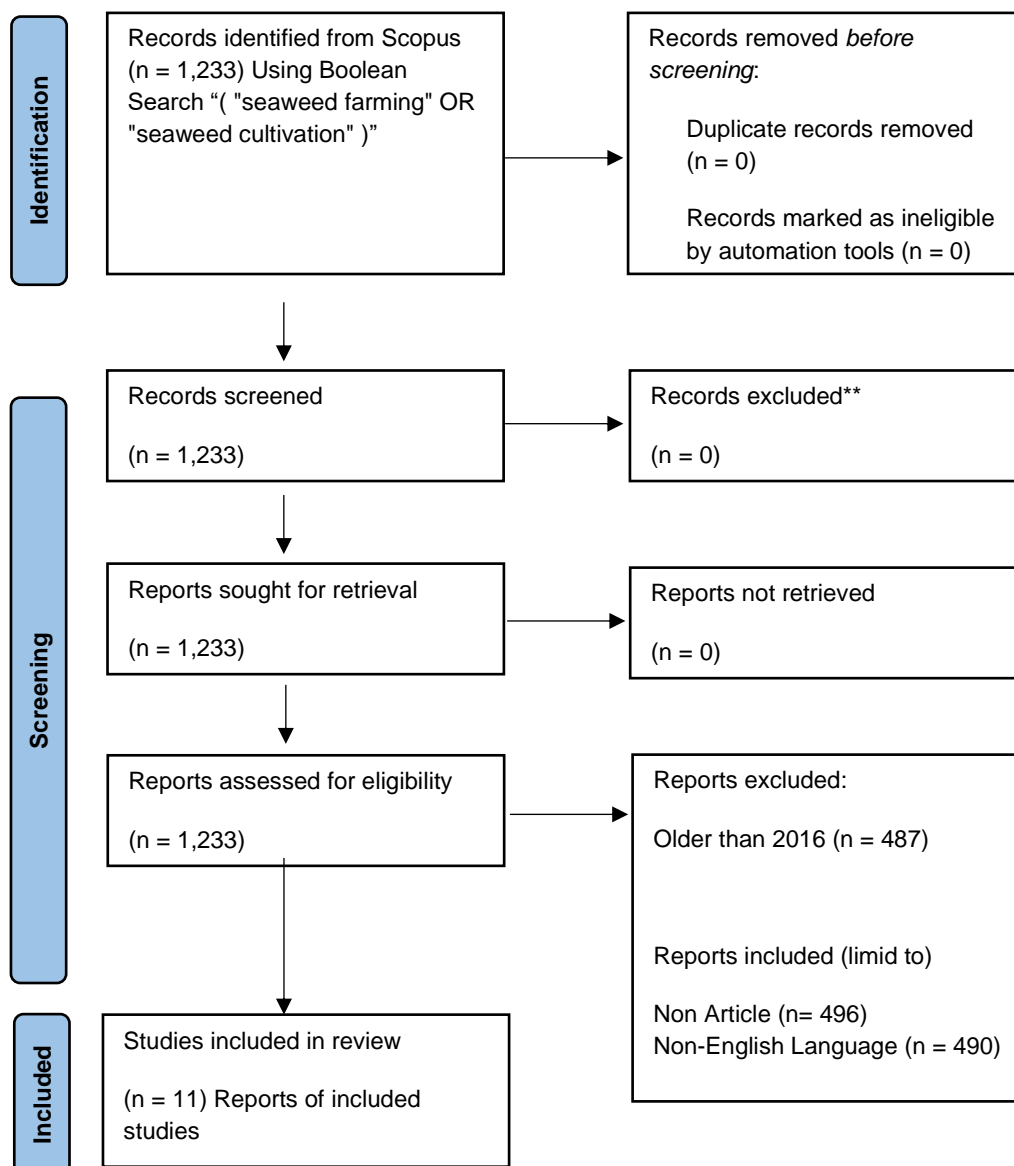


Figure 2. The PRISMA Flow Diagram Detailing the Screening and Selection Process of Literature

### *Assessment of Environmental Conditions and Carbon Sequestration Methods*

The selected studies employed a range of methodological approaches to assess environmental factors influencing seaweed growth and carbon sequestration. Experimental studies typically manipulated variables such as light intensity, temperature, salinity, and nutrient availability to evaluate their effects on biomass production and carbon uptake. For example, Zollmann et al. (2021) developed a multi-scale growth model for *Ulva* spp., demonstrating how temperature and nutrient levels regulate biomass accumulation and nitrogen

sequestration. Similarly, Jeong et al. (2025) highlighted the importance of nutrient enrichment and temperature optimization in enhancing seaweed growth and carbon fixation rates. In contrast, observational studies focused on monitoring seaweed growth and carbon dynamics under natural environmental conditions. These studies provided valuable insights into real-world farming contexts and ecosystem interactions. For instance, Paine et al. (2021) examined dissolved organic carbon (DOC) release from seaweeds in natural habitats, linking carbon dynamics to nutrient availability and water temperature.

### *Role of the PRISMA Framework in Ensuring Methodological Rigor*

The application of the PRISMA framework played a crucial role in ensuring the rigor, transparency, and reproducibility of this systematic review. By systematically screening titles, abstracts, and full texts using predefined criteria, PRISMA facilitated the identification of high-quality and relevant studies (Macreadie et al., 2021). This structured approach enabled consistent evaluation of methodologies and findings related to seaweed-based carbon sequestration and its environmental drivers (Murtaza et al., 2023). Overall, the methodological framework employed in this study provides a robust foundation for synthesizing existing evidence on seaweed farming and its potential contribution to climate change mitigation. The use of standardized screening procedures and clearly defined criteria enhances the reliability of the review's conclusions and supports future research in this rapidly evolving field.

## RESULTS

### *Carbon Sequestration Potential of Seaweed*

Table 1. Seaweed Farming

No	Citation	Title	Seaweed Species	Growth Rate	Nutrient Uptake	Photosynthesis Rate	Biochemical Properties
1	Hlaing et al. (2025)	Unregulated use of ammonium-based inorganic fertilizers in large-scale commercial tropical eucheumatoid seaweed farming	<i>Kappaphycus alvarezii</i>	7.18 ± 0.20 % d <sup>-1</sup>	NH <sub>4</sub> <sup>+</sup> linear uptake; NO <sub>3</sub> <sup>-</sup> Michaelis-Menten	0.126 ± 0.022 mg O <sub>2</sub> gFW <sup>-1</sup> h <sup>-1</sup>	Protein, phycobiliproteins, chlorophyll a increased
2	Majumder et al. (2025)	Effect of elevated CO <sub>2</sub> and temperature on <i>Ulva lactuca</i> growth and biochemistry	<i>Ulva lactuca</i>	35.85 ± 2.85 % d <sup>-1</sup>	Enhanced under high CO <sub>2</sub> and temperature	Total chlorophyll 289.79 ± 22.33 mg g <sup>-1</sup> FW	Protein 26.12%; carbohydrate 79.97% DW

No	Citation	Title	Seaweed Species	Growth Rate	Nutrient Uptake	Photosynthesis Rate	Biochemical Properties
3	Dumraliy a et al. (2025)	Highly efficient production of L-rhamnose from catalytic hydrolysis of marine polysaccharide ulvan	<i>Ulva fasciata</i>	N/A	N/A	N/A	N/A
4	Hlaing et al. (2025)	Cultivation of native tissue-cultured <i>Kappaphycus alvarezii</i> plantlets in the Myeik Archipelago	<i>Kappaphycus alvarezii</i>	9.10–9.32 % d <sup>-1</sup>	Higher uptake at higher salinity	N/A	High carrageenan yield and viscosity
5	Dinesh Kumar et al. (2025)	Production of <i>Ulva fasciata</i> biomass through optimized tank-based cultivation	<i>Ulva fasciata</i>	13.79 % d <sup>-1</sup> (3N:P)	Growth strongly influenced by nitrogen	N/A	Carbohydrate 12.35%; lipid 2.86%
6	Faisan et al. (2025)	Temporal abundance of epiphytic pest affecting farmed <i>Kappaphycus striatus</i>	<i>Kappaphycus striatus</i>	N/A	N/A	N/A	Molecular detection of <i>Melanothamnus thailandicus</i>
7	Dittrich et al. (2025)	Indoor cultivation protocols for Alaskan red seaweeds	<i>Devaleraea mollis</i> , <i>Palmaria hecatensis</i>	N/A	Influenced by temperature and irradiance	N/A	N/A
8	D'Ambros Burchio et al. (2025)	Seaweed bounty	N/A	N/A	N/A	N/A	N/A
9	Gutiérrez-Ramírez et al. (2025)	Advancing aquatic biotechnology in the circular bioeconomy era	N/A	N/A	N/A	N/A	N/A
10	Gacura et al. (2025)	Mapping optimal marine zones for artificial upwelling and	<i>Porphyra</i> spp.	N/A	N/A	N/A	N/A

No	Citation	Title	Seaweed Species	Growth Rate	Nutrient Uptake	Photosynthesis Rate	Biochemical Properties
11	Faisan et al. (2025)	macroalgae carbon sinks Highly efficient production of L-rhamnose from ulvan hydrolysis	<i>Ulva fasciata</i>	N/A	N/A	N/A	N/A
12	Gacura et al. (2025)	Wastewater-enhanced carbon sequestration by red seaweed	<i>Agardhiella subulata</i>	N/A	NH <sub>4</sub> <sup>+</sup> and P removal up to 93%	CO <sub>2</sub> removal fivefold higher than forest average	High nutrient removal and carbon sequestration

Comparative analyses show that *Ulva lactuca* exhibits exceptionally high growth rates, reaching  $35.85 \pm 2.85$  % per day under elevated CO<sub>2</sub> conditions, which supports rapid biomass accumulation and efficient short-term carbon capture (Majumder et al., 2025). In contrast, *Kappaphycus alvarezii* demonstrates a lower growth rate of  $7.182 \pm 0.203$  % d<sup>-1</sup> but exhibits strong nutrient uptake, particularly ammonium, and stable photosynthetic activity, supporting its contribution to longer-term carbon sequestration and nutrient cycling (Gacura et al., 2025).

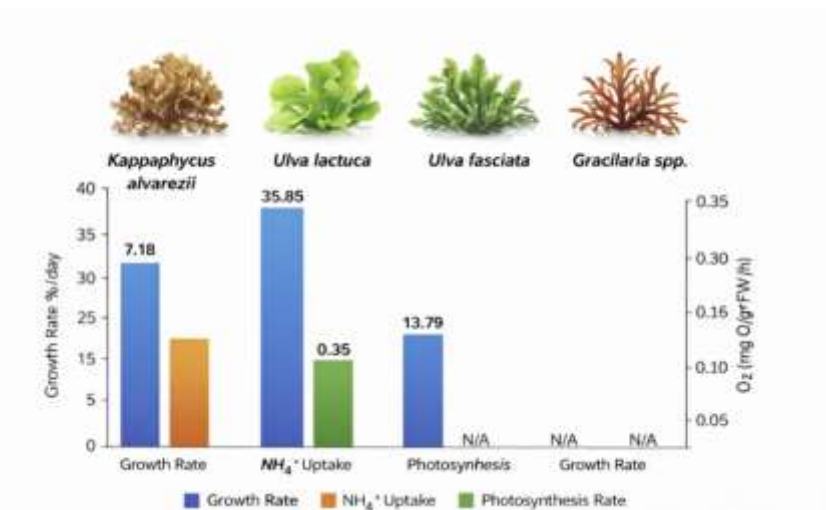


Figure 4. Overview of seaweed farming methods and their effects on growth rate and carbon sequestration. IMTA systems and ammonium-based fertilization show differing efficiencies in enhancing biomass production and carbon capture.

Other species, such as *Ulva fasciata*, show moderate growth rates that are strongly influenced by nitrogen availability, along with increased lipid and carbohydrate content under optimized nutrient conditions (Dinesh Kumar et al., 2025). Although some studies do not directly report carbon sequestration metrics, they emphasize the importance of environmental parameters – such as salinity,

temperature, and light – in regulating seaweed productivity and carbon uptake (Dittrich et al., 2025; Hlaing et al., 2025).

***Farming Methods and Their Impact on Carbon Sequestration***

Table 2. Comparison of Seaweed Farming Methods

No	Citation	Farming Method	Seaweed Species	Environmental Conditions	Growth Rate	Key Outcomes
1	Gacura et al. (2025)	Ammonium-based inorganic fertilization	<i>Kappaphycus alvarezii</i>	Controlled land-based hatchery	7.18 ± 0.20 % d <sup>-1</sup>	Growth and photosynthesis increased; carrageenan quality unchanged
2	Majumder et al. (2025)	Elevated temperature and CO <sub>2</sub> tank cultivation	<i>Ulva lactuca</i>	20–24 °C; CO <sub>2</sub> 400–1000 ppm; nitrate supply	35.85 ± 2.85 % d <sup>-1</sup>	Higher CO <sub>2</sub> enhanced growth, chlorophyll, and protein
3	Hlaing et al. (2025)	Vertical aquaculture systems	<i>Kappaphycus alvarezii</i>	Site-specific temperature and salinity	9.10–9.32 % d <sup>-1</sup>	Biomass and carrageenan yield varied by site
4	Dinesh Kumar et al. (2025)	Outdoor tank cultivation with N optimization	<i>Ulva fasciata</i>	Variable nitrogen concentrations	13.79 % d <sup>-1</sup> (3N:P)	High nitrogen increased growth, lipid, and carbohydrate
5	Dittrich et al. (2025)	Suspended aquaculture with lab pre-culture	<i>Devaleraea mollis</i> , <i>Palmaria hecatensis</i>	Controlled temperature, light, nutrients	N/A	Optimized growth protocols for indoor-outdoor transfer
6	Faisan et al. (2025)	Field-based floating systems	<i>Kappaphycus striatus</i>	Seasonal field conditions	N/A	Seasonal variability affected growth and epiphyte control
7	Dittrich et al. (2025)	Floating line and raft systems	<i>Eucheuma</i> spp.	Shallow coastal waters	N/A	Farming method influenced yield and site suitability
8	Gacura et al. (2025)	Modified fertilization in offshore farms	<i>Gracilaria</i> spp.	Nutrient-enriched offshore waters	N/A	Nutrient uptake affected growth performance
9	Hlaing et al. (2025)	Integrated multi-trophic aquaculture	<i>Kappaphycus</i> spp.	Fish-shellfish-seaweed systems	N/A	Improved nutrient recycling and farm productivity
10	Majumder et al. (2025)	Natural and synthetic media cultivation	Eucheumatoids	Tropical cultivation media	N/A	Growth and biomass varied with media composition
11	Gacura et al. (2025)	Seaweed-seagrass integrated farming	<i>Saccharina latissima</i>	Estuarine co-cultivation	47% shell growth; 114% weight	Enhanced bivalve growth and water quality

Studies show that ammonium-based inorganic fertilizer application can significantly enhance growth and photosynthetic performance in *Kappaphycus alvarezii*, resulting in increased biomass without compromising carrageenan quality (Gacura et al., 2025). Similarly, tank-based cultivation of *Ulva lactuca* under elevated CO<sub>2</sub> and temperature conditions produces high growth rates and increased chlorophyll and protein content, indicating strong carbon sequestration potential (Majumder et al., 2025).

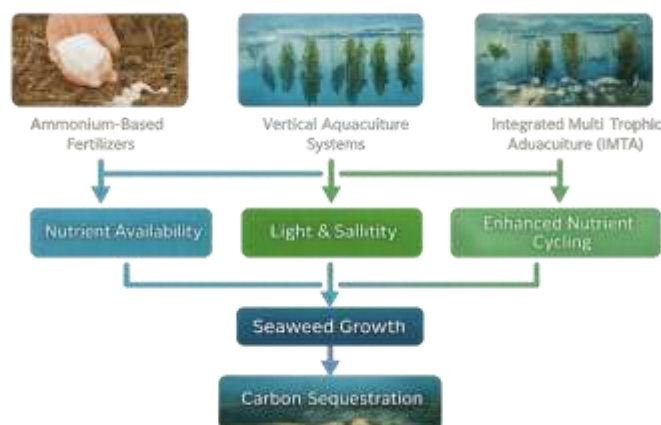


Figure 4. Schematic overview of seaweed farming methods and their effects on growth rates and carbon sequestration, highlighting differences in efficiency among IMTA systems and ammonium-based fertilization.

Vertical aquaculture systems and outdoor tank cultivation further demonstrate that controlled environmental conditions—particularly temperature, salinity, and nutrient concentration—can substantially improve growth and carbon uptake (Hlaing et al., 2025; Dinesh Kumar et al., 2025). Integrated Multi-Trophic Aquaculture (IMTA) systems consistently show positive outcomes by improving nutrient cycling, increasing seaweed biomass, and enhancing overall system productivity (Hlaing et al., 2025). These findings indicate that farming methods should be selected based on species requirements and local environmental conditions. Integrated and nutrient-efficient systems offer the greatest potential for scaling seaweed farming as a carbon sequestration strategy.

### *Environmental Factors Influencing Carbon Sequestration in Seaweed Farming*

Table 3. Environmental Factors and Their Influence on Seaweed Farming

No	Citation	Environmental Factor	Impact on Seaweed Growth	Impact on Carbon Sequestration	Species/Region	Key Findings
1	Gacura et al. (2025)	Temperature	Enhanced growth at 20–24 °C	Temperature affects CO <sub>2</sub> uptake rates	<i>Ulva lactuca</i> and related species	Higher temperature and CO <sub>2</sub> increase growth and carbon capture potential

No	Citation	Environmental Factor	Impact on Seaweed Growth	Impact on Carbon Sequestration	Species/Region	Key Findings
2	Majumder et al. (2025)	Salinity	Higher salinity increases productivity	Improves nutrient uptake and carbon efficiency	<i>Kappaphycus alvarezii</i> , <i>Eucheuma</i> spp.	Optimal productivity at 31–33 PSU
3	Hlaing et al. (2025)	CO <sub>2</sub> concentration	Elevated CO <sub>2</sub> stimulates growth	Increases carbon absorption	<i>Ulva lactuca</i>	Biomass, protein, and carbohydrate content increase
4	Dinesh Kumar et al. (2025)	Nutrient availability (N, P)	Higher nutrients enhance growth rates	Boosts photosynthesis and carbon uptake	<i>Ulva fasciata</i> , <i>Kappaphycus alvarezii</i>	Nitrogen and phosphorus directly influence biomass and biochemistry
5	Dittrich et al. (2025)	Light availability	Optimal light accelerates growth	Photosynthesis controls carbon uptake	<i>Devaleraea mollis</i> , <i>Palmaria hecatensis</i>	Light and nutrients are critical for controlled cultivation
6	Faisan et al. (2025)	Water depth	Greater depth reduces biomass yield	Lower carbon storage in biomass	<i>Saccharina latissima</i>	Productivity declines with increasing depth
7	Dittrich et al. (2025)	Water quality (DO, pH, turbidity)	Stable water quality supports growth	Enhances nutrient uptake and carbon sequestration	<i>Kappaphycus alvarezii</i> , <i>Gracilaria</i> spp.	Optimal DO and pH improve growth and carbon capture
8	Hlaing et al. (2025)	Farming system (IMTA)	IMTA increases productivity	Improves nutrient cycling and carbon capture	<i>Kappaphycus</i> spp.	IMTA enhances biomass and sequestration potential
9	Majumder et al. (2025)	Seasonal variation	Growth varies across seasons	Carbon sequestration fluctuates seasonally	<i>Kappaphycus alvarezii</i> , <i>Eucheuma</i> spp.	Seasonal environmental changes affect farming outcomes
10	Gacura et al. (2025)	Epiphyte overgrowth	Reduces biomass production	Lowers carbon sequestration efficiency	<i>Kappaphycus striatus</i>	Epiphytes significantly suppress growth and carbon potential

Temperature and elevated CO<sub>2</sub> levels have been shown to enhance photosynthetic activity and growth, particularly in *Ulva lactuca*, thereby increasing carbon uptake (Gacura et al., 2025; Hlaing et al., 2025). Salinity also plays a critical role, with optimal ranges of 31–33 PSU supporting higher productivity in *Kappaphycus* and *Eucheuma* species (Majumder et al., 2025).

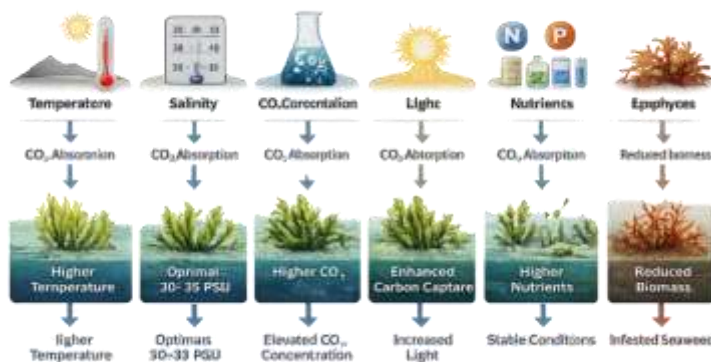


Figure 5. Visual summary of key environmental factors affecting carbon sequestration in seaweed farming. Temperature, salinity, and nutrient availability play critical roles in optimizing growth and carbon capture efficiency

Nutrient availability, especially nitrogen and phosphorus, directly affects growth rates and biochemical composition, reinforcing the importance of nutrient management in seaweed farming (Dinesh Kumar et al., 2025). Light availability significantly influences photosynthesis, particularly in indoor and controlled cultivation systems (Dittrich et al., 2025). Conversely, environmental stressors such as epiphyte overgrowth and suboptimal water quality reduce biomass yield and carbon sequestration efficiency (Gacura et al., 2025). These findings emphasize that effective environmental management is essential for maximizing the carbon sequestration potential of seaweed farming.

### Challenges and Opportunities for Scaling Seaweed Farming

Table 4. Opportunities and Challenges in Scaling Seaweed Farming

No	Citation	Opportunity / Challenge	Brief Description	Key Implications	Species / Region	Main Findings
1	Gacura et al. (2025)	Opportunity: Carbon Credit Market	Seaweed farming can generate carbon credits through CO <sub>2</sub> sequestration	Financial incentives for large-scale farming	<i>Kappaphycus alvarezii</i> , <i>Ulva lactuca</i>	Carbon markets may support farm expansion
2	Majumder et al. (2025)	Challenge: Environmental Impact	Large-scale farming may disrupt ecosystems	Requires careful environmental management	Various species	Risk of biodiversity loss and nutrient imbalance
3	Hlaing et al. (2025)	Opportunity: Coastal Economic Growth	Job creation and income generation	Supports coastal livelihoods	Southeast Asia, Pacific Islands	Seaweed farming diversifies coastal economies
4	Dinesh Kumar et al. (2025)	Challenge: Policy and Regulation	Lack of clear regulatory frameworks	Limits industry expansion	Global	Strong governance needed for sustainability

No	Citation	Opportunity / Challenge	Brief Description	Key Implications	Species / Region	Main Findings
5	Dittrich et al. (2025)	Opportunity: IMTA Systems	Integration with fish and shellfish farming	Improves nutrient cycling and biomass	<i>Kappaphycus</i> spp., <i>Gracilaria</i> spp.	IMTA enhances sustainability and productivity
6	Gutiérrez-Ramírez et al. (2025)	Challenge: Limited Infrastructure	Insufficient transport and processing facilities	Reduces economic feasibility	Developing coastal regions	Infrastructure development is critical
7	D'Ambros Burchio et al. (2025)	Opportunity: Climate Mitigation	CO <sub>2</sub> capture and ecosystem enhancement	Supports blue carbon strategies	<i>Kappaphycus</i> spp., <i>Ulva</i> spp.	Seaweed contributes to climate goals
8	Gacura et al. (2025)	Challenge: Marine Space Competition	Competes with tourism and fisheries	Requires spatial planning	Global	Zoning needed to avoid conflicts
9	Faisan et al. (2025)	Opportunity: Technological Innovation	Automation and genetic improvement	Increases efficiency and yield	Various species	Technology supports scalability
10	Gacura et al. (2025)	Challenge: Climate Vulnerability	Exposure to storms and warming	Threatens farm stability	<i>Kappaphycus</i> spp., <i>Gracilaria</i> spp.	Adaptive strategies required

One major opportunity lies in the potential integration of seaweed farming into carbon credit markets, which could provide financial incentives for farmers and support large-scale adoption (Gacura et al., 2025). Seaweed farming also offers significant economic benefits for coastal communities by creating employment opportunities and supporting sustainable livelihoods, particularly in Southeast Asia and the Pacific region (Hlaing et al., 2025).



Figure 6. Opportunities and challenges in scaling seaweed farming for carbon sequestration, highlighting economic benefits (e.g., carbon credits) and key constraints, including environmental risks and infrastructure limitations.

However, challenges include environmental risks associated with large-scale farming, such as ecosystem disturbance, nutrient imbalance, and vulnerability to extreme climate events (Majumder et al., 2025; Gacura et al.,

2025). Regulatory uncertainty and limited infrastructure further constrain industry expansion, particularly in developing regions (Dinesh Kumar et al., 2025). Despite these challenges, integrated approaches such as IMTA systems and technological advancements in farming practices offer viable pathways for sustainable scaling. Addressing regulatory, infrastructural, and environmental constraints will be critical to realizing the full potential of seaweed farming as a climate change mitigation strategy.

## DISCUSSION

### *Integration of Themes and Theoretical Relevance*

The findings reviewed in this study align closely with established theoretical frameworks on blue carbon and the role of seaweed farming in carbon sequestration. Seaweed farming fits well within the blue carbon concept, which recognizes marine ecosystems as significant carbon sinks. As demonstrated by multiple studies, seaweed species such as *Kappaphycus alvarezii* and *Ulva lactuca* effectively capture atmospheric CO<sub>2</sub> through photosynthesis, thereby contributing to the global carbon cycle (Li et al., 2022; Pessarrodona et al., 2023). The empirical evidence synthesized in this review supports theoretical models suggesting that seaweed can serve as an effective nature-based solution for climate change mitigation, both through direct carbon sequestration via biomass accumulation and indirectly through enhanced nutrient cycling (Macreadie et al., 2021). Beyond carbon sequestration, seaweed farming also provides additional ecological benefits, including habitat provision and biodiversity support, which are essential components of integrated climate strategies (Bianchelli et al., 2023). The incorporation of seaweed farming into broader marine policy and management frameworks enhances understanding of marine ecosystem complexity and highlights seaweed's role in strengthening ecosystem resilience and supporting coastal communities (Sacco et al., 2021). These findings reinforce the theoretical perspective that seaweed farming delivers multiple co-benefits, making it a valuable component of sustainable climate mitigation approaches.

### *Comparative Insights Across Studies*

The reviewed studies reveal both consistent patterns and notable variations in the carbon sequestration potential of seaweed farming. A key similarity across studies is the strong relationship between high growth rates and increased carbon sequestration capacity. For instance, *Ulva lactuca* exhibited a growth rate of  $35.85 \pm 2.85$  % per day under controlled conditions with elevated CO<sub>2</sub>, indicating a high capacity for carbon uptake (Majumder et al., 2025). Likewise, *Kappaphycus alvarezii* showed a growth rate of  $7.182 \pm 0.203$  % d<sup>-1</sup> when supplied with ammonium-based fertilizers, highlighting the importance of nutrient availability in enhancing growth and carbon capture (Gacura et al., 2025). Despite these similarities, differences emerge in how environmental factors influence carbon sequestration across species. Salinity was found to significantly enhance growth in *Kappaphycus alvarezii* and *Eucheuma* species, where higher salinity levels supported greater productivity (Majumder et al., 2025). In contrast, temperature played a more dominant role in *Ulva lactuca*, with optimal growth and CO<sub>2</sub> absorption occurring at temperatures between 20–24°C

(Gacura et al., 2025). These findings underscore the necessity of adapting seaweed farming practices to local environmental conditions in order to maximize carbon sequestration outcomes. In addition, farming systems such as Integrated Multi-Trophic Aquaculture (IMTA) were consistently shown to enhance nutrient cycling, indirectly supporting increased biomass production and carbon sequestration (Hlaing et al., 2025). The adoption of IMTA systems offers a sustainable pathway for scaling seaweed farming while simultaneously improving ecological performance and system resilience.

### *Methodological Strengths and Weaknesses*

The methodologies employed in the reviewed studies demonstrate several strengths, particularly the use of controlled experimental designs to assess carbon sequestration under specific environmental conditions. These approaches provide reliable data on the influence of key variables such as temperature, salinity, nutrient availability, and CO<sub>2</sub> concentration on seaweed growth and carbon uptake (Li et al., 2022; Pessarrodona et al., 2023). Controlled experiments enable precise measurements and facilitate a clearer understanding of species-specific carbon sequestration potential. However, many studies are limited by short experimental durations or site-specific assessments, which may not adequately capture long-term ecological dynamics or the sustained effectiveness of seaweed farming as a carbon sink. Long-term monitoring studies conducted under natural conditions are needed to better evaluate carbon retention, ecosystem impacts, and the durability of seaweed-based sequestration strategies (Roque et al., 2021). Furthermore, variability in environmental conditions across regions contributes to inconsistencies in reported results, highlighting the need for standardized methodologies to improve comparability and data reliability.

### *Gaps in Evidence and Consistency*

Although this review provides substantial evidence of the carbon sequestration potential of seaweed farming, important gaps remain. One major research gap concerns the long-term fate of sequestered carbon. While short-term carbon uptake is well documented, uncertainties persist regarding the permanence of carbon storage under varying environmental and climatic conditions (Pessarrodona et al., 2023; Seddon, 2022). Long-term studies are required to assess how climate variability influences growth, biomass turnover, and carbon retention across different seaweed species. In addition, limited research has systematically compared biogeochemical processes across different farming systems and ecosystem contexts. A more comprehensive understanding of how farming methods, ecosystem types, and environmental conditions interact is essential for optimizing carbon sequestration efficiency (Jones et al., 2022).

### *Contributions to Scholarship and Practice*

This review contributes to the growing body of literature on blue carbon by synthesizing empirical evidence that supports seaweed farming as an effective climate change mitigation strategy. The findings strengthen theoretical understanding of seaweed as a blue carbon component and emphasize the

importance of integrating seaweed farming into marine and climate policy frameworks (Li et al., 2022; Pessarrodona et al., 2023). Additionally, the review highlights the broader ecological benefits of seaweed farming, including biodiversity enhancement, nutrient regulation, and habitat provision, reinforcing its relevance within holistic climate strategies (Bianchelli et al., 2023). From a practical standpoint, this review underscores the need for standardized assessment methods to improve the accuracy and comparability of carbon sequestration estimates. It also emphasizes the importance of supportive policies, infrastructure development, and governance mechanisms to enable the sustainable scaling of seaweed farming initiatives (Gacura et al., 2025; Sacco et al., 2021). By identifying research gaps and practical challenges, this review provides a foundation for future studies aimed at optimizing seaweed farming as a scalable, economically viable, and environmentally sustainable climate solution.

## CONCLUSION AND RECOMMENDATION

Seaweed farming presents a promising solution for carbon sequestration and climate change mitigation, making a meaningful contribution to global blue carbon strategies. This review highlights the critical role of seaweed in capturing atmospheric carbon dioxide, enhancing marine biodiversity, and providing essential ecosystem services, including nutrient cycling and habitat restoration. The findings emphasize the importance of selecting appropriate seaweed species, optimizing farming methods, and carefully managing environmental conditions such as temperature, salinity, and CO<sub>2</sub> concentration to maximize carbon sequestration potential. Nevertheless, several challenges remain, including uncertainties regarding the long-term stability of carbon storage, potential environmental impacts associated with large-scale farming, and the need for robust and supportive policy frameworks. Further research is required to address existing knowledge gaps, particularly those related to long-term carbon sequestration dynamics, socio-economic implications, and the integration of seaweed farming with other marine industries. With effective policies, technological advancements, and active community engagement, seaweed farming has the potential to become a key component of global climate change mitigation efforts.

## FURTHER STUDY

This study positions seaweed farming as a strategic blue carbon pathway, emphasizing the need to integrate species selection, cultivation optimization, and supportive governance to ensure long-term carbon sequestration and sustainable climate mitigation.

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