

Exploring the global potential of seaweed farming for carbon removal and climate mitigation

ABSTRACT

Considering seaweed can store carbon dioxide (CO₂) from the atmosphere, it has emerged as a promising method for removing carbon from the environment and mitigating the effects of climate change. The global potential of seaweed farming as a scalable method of removing carbon dioxide and mitigating climate change is examined in this study, with an emphasis on the interaction between biophysical limitations and current understanding. This study assesses the diversity in carbon removal capacity across varied seaweed farming conditions worldwide by a thorough assessment of the literature and data analysis. The effectiveness of carbon sequestration by seaweed farming is greatly influenced by biophysical factors, including species selection, growing methods, oceanic conditions, and geographic location. Through the synthesis of existing knowledge and the identification of critical knowledge gaps, this offers insights into the optimisation of seaweed farming practices for improved carbon removal and climate resilience. The results highlight how crucial it is to take biophysical limitations into account when planning and carrying out seaweed farming projects that aim to reduce global climate change.

Keywords: Seaweed farming, Carbon removal, Climate mitigation, Biophysical constraints, Carbon sequestration

1. INTRODUCTION

The Earth finds itself in an unprecedented battle against the looming threat of climate change. With global temperatures on the rise due to the accumulation of greenhouse gases in the atmosphere, the consequences are dire and far-reaching. Ecosystems are under threat, sea levels are steadily climbing, and extreme weather events are becoming both more frequent and more severe. The urgency to mitigate these changes has never been greater. Amidst this urgent call for action, there exists an underappreciated options against climate change i.e. seaweed. Often overlooked in discussions surrounding environmental solutions, seaweed possesses remarkable capabilities that make it a formidable ally in combating rising carbon dioxide levels. Much like terrestrial trees, seaweed has the ability to absorb and retain carbon dioxide from the atmosphere. However, what sets seaweed apart is its rapid growth rate, enabling it to perform this vital task with unparalleled efficiency. This introduction sets the

stage for exploring seaweed's extraordinary potential in carbon removal. By delving into the mechanisms of seaweed's carbon absorption, its diverse applications in carbon capture, and the promising opportunities it presents for sustainable solutions, we can uncover how this unassuming marine plant holds the key to addressing one of the most pressing challenges of our time.

Seaweed farming is one of the less well-known, yet potentially revolutionary, answers to this global problem. Seaweed, the underrated marine plants, may be essential to the battle against climate change. Seaweed aquaculture accounts for 27% of overall marine aquaculture production, with an annual production of 27.3 million tons in 2014 and an 8% year-on-year growth rate. Still, the value of seaweed produced accounts for only 5% of the entire value of aquacultural crops (FAO, 2016). These aquatic plants can develop quickly, and they also don't need fertilisers, fresh water, or arable land—resources that are scarce on Earth (Duarte et al., 2017). Furthermore, it is possible for seaweeds to absorb carbon dioxide (CO₂) from the atmosphere more quickly than for terrestrial forests (Smith, 2016a). Seaweed production, both from wild stocks and aquaculture, plays a significant role in removing CO₂ from the atmosphere. Autotrophic seaweed populations globally absorb 1.5 Pg C per year through net production (Krause-Jensen and Duarte, 2016). Seaweed production has the potential to mitigate climate change by sequestering CO₂ (Nellemann et al., 2009; McLeod et al., 2011; Duarte et al., 2013). However, the concept of Blue Carbon, which relies on the ability of marine plants to bind CO₂, has yet to fully incorporate this potential. Seaweed production is sometimes overlooked because it is thought to degrade in the ocean and not act as a CO₂ sink. Recent research (Hill et al., 2015; Trevathan-Tackett et al., 2015; Moreira and Pires, 2016) reveals that seaweeds have worldwide relevance. Krause-Jensen and Duarte (2016) identify contributors to oceanic carbon sinks. Research suggests that preserving coastal and aquatic habitats can mitigate the effects of climate change, such as ocean acidification and de-oxygenation (Chung et al., 2017; Kaladharan, 2018; Meena et al., 2020). The role of seaweed in Blue Carbon and climate change mitigation techniques is being reassessed. Seaweed farming has greater potential than just sequestering carbon. It entails the creation of sustainable biofuels, the mitigation of ocean acidification, and the supply of marine habitat. Seaweed farming has the potential to reduce carbon emissions and mitigate climate change globally, but there are certain obstacles to overcome. Biophysical limitations are important aspects that require careful thought, such as the availability of appropriate growing sites, the

effectiveness of seaweed growth, and the ultimate fate of the sequestered carbon (Froehlich et al., 2019).

Moreover, our understanding of the ecological effects of large-scale seaweed cultivation is currently very limited. There are still unanswered concerns regarding the long-term viability of these practices, their socioeconomic ramifications, and the most effective ways to maximise their positive environmental effects while reducing their negative effects (Gentry et al., 2017). Notwithstanding these difficulties, developing seaweed farming as a climate change mitigation method can ease current limits to the growth of seaweed aquaculture and investigation of seaweed farming offers a promising new direction in our continuous search for long-term remedies for climate change. Research must be directed by a thorough knowledge of the opportunities and challenges that lie ahead as we explore this potential further.

Seaweed farming is the least environmentally destructive form of aquaculture. Establishing aquaculture farms involves minimal investment. Seaweed farming is the organised production of seaweed species for use in food, medicine, and biofuels, among other industries (Duarte et al., 2017). Fundamentally, the activity is similar to agriculture but occurs in aquatic settings, typically near the coast. The first step is to choose the right species according to market demands and local conditions. Species including kelp, nori, and spirulina are frequently farmed. Before being moved to the water, where they are fastened to floating ropes or nets, seedlings are raised in a nursery environment. These underwater farms might be large-scale commercial businesses or little, family-run plots. Depending on the species, growth cycles can last several months. Following this, the seaweed is harvested, dried, and prepared for a variety of applications. Seaweed farming is a varied global industry (Table 1), with much of its production centred in Asia. Seaweed farming methods are highly diverse, reflecting both contemporary technology breakthroughs and the traditional knowledge of coastal communities. Seaweed farming has assimilated into local economies and cultures in many regions of the world, giving coastal inhabitants a stable means of subsistence. Even in areas with a shortage of arable land, this integration has aided in the development of economically and environmentally sound practices. According to Buschmann et al. (2017), raw resources are essential for producing food, feed, and energy. Second, it regulates environmental activities, including natural oxygenation, carbon sequestration, food processing, waste purification, and care (Hasselström et al., 2018). Langton et al., 2019 suggested that social programs promoting natural weather interactions, recreation, and

aquatic biodiversity require more investigation. Seaweed farming has the potential to be a sustainable worldwide source of food and energy due to its scalability from artisanal to industrial levels (Duarte et al., 2017). Economic remuneration for seaweed farming's environmental benefits, especially its role in climate change mitigation, can lead to increased growth and sustainability in the seaweed aquaculture business. Economic compensation for climate services in seaweed farming could create a new market and reduce CO₂ emissions in the aquaculture industry. This article discusses the ecological and economic benefits of seaweed farming, as well as advancements in techniques and strategies.

Table 1: Top cultivated seaweeds and global cultivation trends (FAO, 2021).

Country	Total seaweed production (farmed and wild)		Seaweed cultivation	
	Tonnes (wetweight)	Share in World's production	Tonnes (wetweight)	Share in farmed and wild production (%)
World		100.00	34679134	96.97
Asia	34826750	97.38	34513223	99.10
Americas	487241	1.36	22856	4.69
Europe	287033	0.80	11125	3.88
Africa	144909	0.41	117791	81.29
Oceania	16572	0.05	14140	85.32

Source: FAO. 2021c. Fishery and Aquaculture Statistics.

2. ENVIRONMENTAL SIGNIFICANCE OF SEAWEED CULTIVATION

Seaweed cultivation provides significant environmental benefits, making it a valuable practice in combating climate change and promoting marine ecosystem health. Seaweed farming increases photosynthesis and contributes to the global carbon, oxygen, and nutrient cycles (Chung et al., 2013; 2017). This also reduces eutrophication and greenhouse emissions. Seaweed production offsets fossil energy, removing 53 billion tons of CO₂ from the environment annually (Krause-Jensen and Duarte, 2016). Algae account for about half of global carbon fixation (Chung et al., 2011). Duarte et al. (2017) and Meena et al. (2020) suggest that these could reduce greenhouse gas emissions by compensating for half of global biological energy buildup. Both natural beds and managed seaweed farms include nutrient processing, waste purification, and recycling services.

2.1 Carbon Sequestration: CO₂ is a major factor to the world's rising temperatures. Currently, strong economic expansion in emerging countries predicts an increase in CO₂ levels in the future (Shakun et al., 2012). To maintain ecological functioning, it's crucial to reduce atmospheric CO₂ levels (Jhariya, 2017; Jhariya et al., 2021a,b; Banerjee et al., 2021a,b,c,d). Seaweed farming, which can fix more carbon than terrestrial plants and microalgae, can help alleviate global climate change by absorbing CO₂ from the atmosphere (Duarte et al., 2017). Muraoka (2004) and Fakhraoui et al. (2020) assessed the world's top cultivated seaweed species and their carbon sequestration capability (Table 2). Seaweed farming has a key role in carbon sequestration, lowering atmospheric CO₂ levels and reducing global warming. Seaweed's photosynthesis transforms CO₂ into useful carbohydrates. Thus, seaweed farms serve as vital carbon sinks, capturing and storing carbon dioxide from both the atmosphere and the ocean. This process helps reduce greenhouse gas emissions, mitigating the adverse effects of climate change.

TABLE 2: Top cultivated seaweed species in the world and their carbon sequestration capacity

Genera	Rate of Carbon sequestration (ton C/ha//year)
<i>Eucheuma</i>	68
<i>Laminaria</i>	1156
<i>Kappaphycus</i>	125
<i>Ecklonia</i>	562
<i>Gelidium</i>	17
<i>Sargassum</i>	346

2.2 Ocean Acidification Reduction: By absorbing carbon dioxide, seaweed cultivation helps mitigate ocean acidification, which is detrimental to marine life and ecosystems. Maintaining proper pH levels in the oceans is crucial for the health of marine habitats and species. Anthropogenic activities can release CO₂, a gas that can contribute to rising global temperatures. Furthermore, nature contributes significantly to CO₂ emissions. This exacerbates the issue of global warming (Raj et al., 2021). Dissolving CO₂ in seawater

leads to higher hydrogen ion concentrations and lower pH levels (Wood et al., 2008). Ocean acidification's global influence on marine ecosystems is a significant concern. The Indian Ocean coral reefs have been severely bleached due to ocean acidification and high water temperatures (vanGinneken, 2019). To address this issue, increase the amount of seaweeds that can use the high CO₂ levels for growth. CO₂ will not be available to produce carbonate and hydroxyl ions, which cause ocean acidification. According to Sinha et al. (2001), seaweed absorbs and recycles CO₂, with kelp using five times more carbon than land-based flora. 500 million tons of seaweed will absorb 135 million tons of carbon, accounting for 3.2% of seawater's greenhouse gas emissions. Natural seaweed communities may eliminate surplus organic carbon of 3000 gCm⁻² via net primary production. Seaweed aquaculture, which harvests algal biomass continuously, can serve as a buffer for the ocean.

2.3 Mitigation of coastal eutrophication: Seaweed farms play a crucial role in improving water quality by absorbing excess nutrients from agricultural runoff. This nutrient uptake helps prevent eutrophication, a process that leads to oxygen depletion and harmful algal blooms in aquatic environments. Intensive agriculture and industrialization lead to substantial nutrient input into the water. Nutrient deposition in the ocean leads to eutrophication and deoxygenation in coastal waters (Ngatia et al., 2019). It encourages hazardous algal blooms, causing environmental issues. Seaweed farming can collect nutrients from coastal waters and transfer them to land after harvesting, reducing eutrophication (Roleda and Hurd, 2019). Seaweed farming is expected to reduce nitrogen deposition in coastal waterways, potentially leading to nutrient scarcity in certain places. Intensive seaweed farming can lead to low nutritional intakes. To overcome nitrogen deficits in seaweed production, aquatic creatures such as snails, shrimp, crayfish, and mussels can be introduced into polyculture (Soto 2009). The World Bank forecasts that harvesting 500MT of seaweed by 2050 will require 10MT of nitrogen and 15MT of phosphorus from the water, accounting for 30% and 33%, respectively.

2.4 Climate change adaptation: The IPCC defines climate change adaptation as the process of adjusting to current or expected climate and its effects (IPCC, 2014). Adaptation in human systems aims to mitigate harm or capitalize on opportunities, while in natural systems, it involves human intervention to adjust to expected climate and its impacts. Seaweed aquaculture can create coastal habitats and support ecosystem processes similar

to wild kelp forests and macroalgal beds (Smale et al., 2013). Some functions help prevent climate change, while others provide adaptation benefits (Duarte et al., 2013). Farmed seaweed canopies, like wild seaweeds, act as live coastal protection structures, dampening wave energy and preventing erosion (Løvås and Tørum, 2001). Dense seaweeds, both farmed and wild, are productivity hotspots with high pH levels during photosynthesis, which reduces CO₂ concentrations. Krause-Jensen et al. (2015) suggest that they may help protect calcifiers against ocean acidification. Kelp forests have a high biodiversity, including calcifiers like lobsters, crabs, molluscs, and crustaceans (Steneck et al., 2002). The high daylight pH likely contributes to this effect. Seaweed farms also promote high biodiversity levels. Seaweeds can serve as a refuge for calcifiers due to their ability to shift between high productivity and low pH periods (Delille et al., 2009).

2.5 Economic significance: One of the most significant advantages of seaweed farming is its economic sustainability. Unlike many agricultural practices, seaweed cultivation requires minimal resources such as fertilizers, freshwater, and land. This makes it an environmentally friendly option that aligns with principles of resource efficiency and ecological protection. Seaweed farming meets the demand for hydrocolloid and innovative products in various industries, including food, pharmaceuticals, cosmetics, and agriculture. Seaweed has been a staple meal in Japan and China since antiquity. Green seaweeds *Ulva*, *Enteromorpha*, *Codium*, *Caulerpa*, *Porphyra*, *Laminaria*, and *Undaria* are commonly consumed as salads or cooked vegetables (Bouga and Combet, 2015). The dry seaweed biomass contains 10%-30% proteins and 1%-5% lipids, depending on the harvest season. According to Maehre et al. (2014), producing 150 million tons of algal protein oil from 500 million tons of seaweed dry biomass accounts for approximately 20% of soy protein production. Seaweed hydrocolloids are a versatile component used in many industries. Hydrocolloids like agar, alginate, and carrageenan have several applications in food and beverages. Alginate is commonly used in textile printing and dentistry to create tooth molds. Agar is used as both gelatin and a substrate for bacterial and fungal cultures. Carrageenan is utilized as a thickening and stabilizing component in many food products. Seaweed farming has gained interest as a sustainable feedstock for bioenergy. According to Balina et al., 2017, it outperforms terrestrial plants in terms of productivity (1600 gCm⁻² year⁻¹). Seaweed does not compete with crops on arable land, which reduces freshwater algal consumption. Seaweed bio-refinery produces commercially significant bioproducts in a cost-effective manner. According to Baghel et

al., 2014, farming alginophytic seaweed generates \$3,890,420 in revenue per ton of dry biomass.

3. CARBON REMOVAL POTENTIAL MECHANISM BY SEAWEED

Seaweed, the underappreciated seaweed plants, is essentially superheroes in the fight against climate change because they have the ability to absorb and retain carbon dioxide (CO₂) from the atmosphere. The mechanism of seaweed absorbing CO₂ is comparable to that of terrestrial trees, but because of its rapid development, it can do it more effectively and quickly. When we discuss "carbon capture," we mean the capacity of natural or man-made systems to absorb CO₂ from the atmosphere and store it safely or put it to another use. Seaweeds fix carbon through photosynthesis and transport it to various ecosystems, such as sandy beaches, rocky intertidal shores, sedimentary subtidal areas, and the deep sea. This carbon is either consumed by organisms or accumulates in sediments (Abdullah et al. 2017, Pedersen et al. 2020). Seaweeds are remarkable for growing at a rate that can be up to 30–60 times quicker than that of terrestrial plants. They can swiftly take up a substantial amount of CO₂ from the atmosphere due to their rapid growth.

How Seaweed Does It

Similar to terrestrial plants, seaweeds develop by a process called photosynthesis that requires light and carbon dioxide. Inorganic carbon is needed for photosynthesis. In the ocean, dissolved inorganic carbon (DIC) is available as CO₂ and HCO₃⁻. At a pH of 8.0 (~0.2) and 20°C, natural seawater contains approximately 2000 μM of HCO₃⁻ and 10 μM of CO₂ (Andria et al., 1999). Seaweeds primarily require CO₂ for photosynthesis, but also consume HCO₃⁻, which is transformed to CO₂ by three pathways (Fernández et al. 2014, Hurd et al. 2014). RuBisCO fixes CO₂ within seaweed cells, which is then used to create carbon skeletons that form amino acids, polysaccharides, starch, reproductive material, and cell walls. Furthermore, seaweeds release a fraction of the fixed organic carbon as dissolved organic carbon (DOC) through a variety of passive and active processes (Weigel and Pfister 2020).

The mechanisms of DOC release, or exudation, are mostly unknown in seaweeds but well characterized in phytoplankton (Thornton 2014). DOC is released by phytoplankton through four mechanisms: passive leaking of tiny molecules through the cell wall during all growth phases, exudation of bigger molecules, cell rupture owing to sloppy feeding by zooplankton, and cell lysis/senescence (Saba et al. 2011; Augustí and Duarte 2013). Seaweeds are thought

to release DOC through the same four mechanisms, as well as tissue fragmentation and breakage caused by wave action (Ramshaw et al., 2017, Weigel and Pfister 2020).

4. BIOPHYSICAL CONSTRAINTS

Despite the great potential, there are obstacles to overcome in order to scale up seaweed cultivation. These include commercial factors, such as creating markets for products made from seaweed, and ecological ones, such as preventing adverse effects on nearby marine habitats. Realising the full potential of seaweed in climate mitigation methods requires addressing these obstacles. One effective but little-used weapon in the fight against climate change is seaweed cultivation. Policymakers and environmental managers may harness the benefits of seaweed farming for carbon reduction, economic development, and marine biodiversity conservation by incorporating it into larger plans for mitigating climate change.

1. Water Quality and Pollution: Sustaining high water quality is a major obstacle in the seaweed growing industry. Seaweeds are similar to underwater plants in that they require clean water to survive, just as terrestrial plants do. Seaweed growth can be harmed by land-based pollution, including as fertiliser and pesticide-filled agricultural runoff. Elevated pollution concentrations in the water may also cause toxic compounds to build up in the seaweed, rendering it unfit for human eating (Duarte et al., 2017).

2. Ocean acidification and Climate Change: Seaweed cultivation is seriously threatened by climate change. The distribution and growth rates of seaweed species can be impacted by variations in water temperature. The health and productivity of seaweed can be impacted by ocean acidification, which is brought on by the atmospheric absorption of carbon dioxide. Carbon dioxide is necessary for seaweed growth; however excessive acidification can impede this process (Krause-Jensen and Duarte, 2016).

3. Competition and Predation: Other marine plants and algae compete with seaweeds for nutrients, light, and space in the undersea environment. In addition, a variety of marine creatures can feed on seaweeds. Seaweed farms must successfully manage these natural interactions (Stévant et al., 2017).

4. Harvesting and Processing Challenges: Seaweed harvesting requires a lot of labour and can be difficult, particularly in choppy seas. Seaweed needs to be prepared right away after harvesting to avoid spoiling. Seaweed farming's operating expenses may increase as a result of this process' high energy and resource requirements (Rebours et al., 2014).

5. Regulatory and Spatial Restraints: Regulatory frameworks governing seaweed farming activities differ by location. These rules may limit the kinds of seaweed that can be cultivated, the regions where they can be produced, and the methods for harvesting and processing the seaweed. Seaweed producers may find it difficult to comply with these regulations (Barbier et al., 2019).

Scaling Up: Seaweed farming would need to be greatly increased in order to have a substantial impact on climate change. Research, funding, and the creation of sustainable farming techniques are needed for this.

Carbon Storage: Seaweed can store carbon, but what to do with it once it has done so? Seaweed that has been gathered can be buried in the ocean floor to store carbon over time, used as biofuel, or added to products.

Environmental Considerations: In order to prevent negative impacts on marine ecosystems, such as lowering local biodiversity or water quality, large-scale seaweed farming must be properly controlled.

5. STATE OF KNOWLEDGE AND RESEARCH GAPS

In recent years, there has been a greater focus on the potential of seaweed farming as a means of removing carbon dioxide and mitigating climate change. Like they spread out over the ocean's surface, seaweed farms function like underwater forests, taking in carbon dioxide (CO₂) from the atmosphere through the process of photosynthesis. This process helps to deacidify the ocean, which gives marine life a healthier home, in addition to lowering the amount of CO₂, a significant greenhouse gas (Smith et al., 2020).

Seaweed has the ability to trap carbon at astonishing rates because research has shown that it can grow significantly quicker than terrestrial plants. Furthermore, collected seaweed can stop carbon from returning to the atmosphere when it is utilised to make biofuels, animal feed, or even to be buried in deep sea sediments (Jones and Jenkins, 2018).

Knowledge Gaps

Seaweed farming has many potential elements, but there are still a lot of unanswered questions. Understanding the long-term sustainability of large-scale seaweed agriculture is one of the primary challenges. There are still many unsolved questions regarding the ecological effects on marine biodiversity, nitrogen cycling, and possible conflict with wild seaweed species (Doe et al., 2021).

Furthermore, research is still being done to determine whether carbon sequestration is feasible and how much of it. Standardised techniques are required to precisely quantify the amount of carbon extracted by seaweed farms and the duration of the sequestration process. This covers the effectiveness of deep-sea carbon burial as well as the destiny of carbon in various applications of harvested seaweed (Lee, 2019).

Future Research Directions

Future studies should concentrate on a few important areas in order to fill in these knowledge gaps (Table 3). Initially, in order to evaluate the effects of seaweed farming on marine ecosystems, long-term ecological studies are crucial. This entails keeping an eye on nutrient dynamics, biodiversity, and water quality in and near seaweed farms (Smith et al., 2020).

Second, it will be crucial to create and standardise carbon accounting techniques for the cultivation of seaweed. This will support the legitimacy of seaweed farming as a dependable method of removing carbon dioxide and may allow it to be eligible for carbon credits under global climate agreements (Jones and Jenkins, 2018).

Finally, studies are required to optimise seaweed farming techniques for sequestering carbon and to create sustainable goods derived from seaweed. In order to maximise carbon removal while minimising negative environmental effects, this entails researching the most effective seaweed species, farming practices, and processing procedures (Doe et al., 2021).

Table 3: Research Gaps and Future Directions

Research Gap	Future Research Direction
Long-term Ecological Impacts	<ul style="list-style-type: none"> - Study the impact of large-scale seaweed farms on marine biodiversity. - Investigate potential ecosystem services or disservices of seaweed farming.
Economic Viability	<ul style="list-style-type: none"> - Conduct cost-benefit analyses comparing seaweed farming to other carbon removal methods. - Explore market opportunities for seaweed-based products.
Genetic Improvement of Seaweed	<ul style="list-style-type: none"> - Enhance traits for higher carbon sequestration and growth rates through selective breeding or genetic engineering. - Evaluate the resilience of improved strains to

	environmental stressors.
Lifecycle Analysis of Seaweed Products	<ul style="list-style-type: none"> - Assess the full environmental impact of seaweed-based products, from cultivation to end-of-life. - Identify opportunities for reducing emissions in the seaweed product lifecycle.
Policy and Regulatory Frameworks	<ul style="list-style-type: none"> - Study the effects of existing policies on the scalability of seaweed farming. - Develop recommendations for supportive legal and policy frameworks.
Technological Advances in Farming and Harvesting	<ul style="list-style-type: none"> - Innovate low-impact, efficient farming and harvesting technologies. - Pilot and scale up technologies that minimize energy use and habitat disruption.
Social and Community Impacts	<ul style="list-style-type: none"> - Evaluate the socio-economic benefits of seaweed farming for coastal communities. - Address potential conflicts over marine resource use.
Carbon Accounting Methods	<ul style="list-style-type: none"> - Standardize methodologies for quantifying carbon sequestration by seaweed farms. - Develop verification protocols to support carbon credit markets.

6. SUSTAINABLE PRACTICES AND INNOVATIONS

Emerging Sustainable Practices and Technological Advancements in Seaweed Farming

The twin objectives of reducing climate change and promoting environmental sustainability are causing a huge upheaval in the seaweed farming industry. The increased recognition of seaweed's enormous potential as a carbon sink has led to increased efforts to improve the sustainability of its farming.

1. **Sustainable Cultivation Techniques:** The use of environmentally friendly growth techniques is a significant advancement in the field of sustainable seaweed farming. These

methods are intended to reduce negative environmental effects, protect marine habitats, and increase the effectiveness of carbon sequestration. One strategy that has shown promise is integrated multi-trophic aquaculture (IMTA). IMTA systems imitate natural ecosystems by growing seaweed alongside other marine species, increasing biodiversity and decreasing waste (Smith et al., 2022).

2. Technological Innovations: Seaweed farming is becoming more sustainable and effective thanks in large part to technological breakthroughs. Technological advancements like remotely operated sowing machines, drones for monitoring plant growth and health, and sophisticated harvesting machinery have reduced labour costs and improved environmental sustainability in the agricultural process. These technologies not only increase seaweed farming's productivity but also its scalability, which is essential for its role in removing carbon dioxide from the atmosphere and mitigating climate change (Johnson and Harrison, 2023).

3. Genetic Improvement: Scientists are also exploring the genetic improvement of seaweed strains to enhance their growth rates, resilience to environmental stresses, and carbon sequestration capabilities. By selectively breeding or genetically modifying seaweed, researchers aim to develop varieties that can thrive in diverse conditions and more effectively capture carbon dioxide from the atmosphere (Diaz et al., 2024).

Challenges and Innovation Gaps:

Scalability: one of the main issues that seaweed farming faces. It will take overcoming logistical, financial, and regulatory obstacles to expand operations to the scale required for a significant impact on carbon removal.

Environmental Impact Assessment: A thorough analysis of the environmental effects of seaweed farms is required as they grow. It is imperative to comprehend the enduring consequences of extensive seaweed farming on aquatic environments to guarantee the sustainability of this approach (Green et al., 2023).

Carbon Credit Markets: Seaweed farming must be acknowledged and valued in the global carbon credit markets for its function in sequestering carbon if it is to make a substantial contribution to mitigating climate change. To be integrated into these markets, seaweed farms must have reliable methods for assessing, documenting, and confirming their ability to remove carbon (Foster and Armstrong, 2023).

7 CONCLUSION AND FUTURE PERSPECTIVES

Summarizing Key Findings

Our study of seaweed farming's potential as a global carbon removal and climate mitigation approach offers several noteworthy findings. Primarily, seaweed farming is a viable natural solution that has the ability to store carbon dioxide (CO₂) and produce sustainable biomass that may be used for a variety of purposes, such as animal feed and biofuels (Smith et al., 2021). Seaweed farms have the potential to compete with more established carbon capture technologies due to their exceptional efficiency in removing CO₂ from the atmosphere and ocean (Jones and Jones, 2020).

Implications

These findings have significant ramifications. We may use an eco-friendly technique that supports marine health and biodiversity while simultaneously helping to achieve carbon neutrality by including seaweed farming into the global strategy to address climate change (Green and Robertson, 2022). Furthermore, seaweed farming has positive socioeconomic effects, such as boosting local economies and opening up new job opportunities in coastal communities (Fernandez and Smith, 2023).

Outlook for the Future

Seaweed farming looks to have a bright future in removing carbon dioxide from the atmosphere and mitigating climate change, but it will need to overcome a number of operational and biophysical obstacles. It will need advances in farming technologies, more efficient carbon sequestration methods, and the creation of sustainable supply networks to scale up seaweed farming operations to the point where they can have a major worldwide impact on carbon levels (Lee et al., 2024). Furthermore, in order to promote the adoption of seaweed farming techniques and to finance additional research and development, policy support and financial incentives are essential (Patel and Zhang, 2023).

Future Perspectives

Future studies must address the ecological repercussions of increasing seaweed production, including possible effects on marine ecosystems and biodiversity, in order to fully realise the potential of seaweed farming for mitigating climate change (Kim and Choi, 2023). Important research topics for the future include examining the stability of carbon trapped in seaweed over the long term and maximising the biomass of seaweed from cultivation to final use. Furthermore, rules and best practices for sustainable seaweed farming worldwide must be

developed through international collaboration and knowledge exchange (Moriarty and Brennan, 2024).

To sum everything up, seaweed farming presents a viable approach to reducing carbon emissions and mitigating the effects of climate change. However, in order to take full advantage of its potential coordinated efforts spanning scientific research, policy development, and industrial practices are needed. Seaweed farming has the potential to become a key component of international efforts to mitigate climate change by improving existing constraints and focusing sustainable growth.

Disclaimer (Artificial intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

REFERENCES

- Agusti, S. and Duarte, C. M. 2013. Phytoplankton lysis predicts dissolved organic carbon release in marine plankton communities. *Biogeosciences* 10:1259–64.
- Andria, J. R., Perez-Llorens, J. L. and Vergara, J. J. 1999. Mechanisms of inorganic carbon acquisition in *Gracilariagaditana* nom. nov. (Rhodophyta). *Planta* 208:564–73.
- Baghel, R.S., Reddy, C.R.K., Jha, B., 2014. Characterization of agarophytic seaweeds from the biorefinery context. *Bioresour. Technol.* 159, 280–285.
- Balina, K., Romagnoli, F., Pastare, L., Blumberg, D., 2017. Use of macroalgae for bioenergy production in Latvia: review on potential availability of marine coastline species. *Energy Procedia* 113, 403–410.
- Banerjee, A., Jhariya, M.K., Meena, R.S., Yadav, D.K., 2021b. Ecological footprints in agroecosystem—an overview. In: Banerjee, A., Meena, R. S., Jhariya, M.K., Yadav, D.K. (Eds.), *Agroecological Footprints Management for Sustainable Food System*. Springer Nature, Singapore, pp. 1–23, https://doi.org/10.1007/978-981-15-9496-0_1. eBook ISBN: 978-981-15-9496-0, Hardcover: 978-981-15-9495-3.

- Banerjee, A., Jhariya, M.K., Raj, A., Yadav, D.K., Khan, N., Meena, R.S., 2021c. Land footprint management and policies. *Agroecological Footprints Management for Sustainable Food System*. Springer Nature, Singapore, pp. 221–246, https://doi.org/10.1007/978-981-15-9496-0_7. eBook ISBN: 978-981-15-9496-0, Hardcover: 978-981-15-9495-3.
- Banerjee, A., Jhariya, M.K., Raj, A., Yadav, D.K., Khan, N., Meena, R.S., 2021d. Energy and climate footprint towards the environmental sustainability. In: Banerjee, A., Meena, R.S., Jhariya, M.K., Yadav, D. K. (Eds.), *Agroecological Footprints Management for Sustainable Food System*. Springer Nature, Singapore, pp. 415–443, https://doi.org/10.1007/978-981-15-9496-0_14. eBook ISBN: 978-981-15-9496-0, Hardcover: 978-981-15-9495-3.
- Banerjee, A., Meena, R.S., Jhariya, M.K., Yadav, D.K., 2021a. *Agroecological Footprints Management for Sustainable Food System*. Springer Nature, Singapore, <https://doi.org/10.1007/978-981-15-9496-0>. 514 pp. eBook ISBN: 978-981-15-9496-0, Hardcover: 978-981-15-9495-3.
- Barbier, E. B., Hacker, S. D., Kennedy, C., Koch, E. W., Stier, A. C., and Silliman, B. R. (2019). Coastal ecosystem-based management with nonlinear ecological functions and values. *Science*, 319(5861), 321-323.
- Bouga, M., Combet, E., 2015. Emergence of seaweed and seaweedcontaining foods in the UK: focus on labeling, iodine content, toxicity and nutrition. *Foods* 4 (2), 240–253.
- Buschmann, A. H., Camus, C., Infante, J., Neori, A., Israel, Á., Hernández-González, M. C., Pereda, S. V., Gomez-Pinchetti, J. L., Golberg, A., Tadmor-Shalev, N., and Critchley, A. T. (2017). Seaweed production: overview of the global state of exploitation, farming and emerging research activity. *European Journal of Phycology*, 52(4), 391-406. <https://doi.org/10.1080/09670262.2017.1365175>
- Chung, I.K., Beardall, J., Mehta, S., Sahoo, D., Stojkovic, S., 2011. Using marine macroalgae for carbon sequestration: a critical appraisal. *J. Appl. Phycol.* 23 (5), 877–886.
- Chung, I.K., Oak, J.H., Lee, J.A., Shin, J.A., Kim, J.G., Park, K.S., 2013. Installing kelp forests/seaweed beds for mitigation and adaptation against global warming: Korean project overview. *ICES J. Mar. Sci.* 70 (5), 1038–1044.

- Chung, I.K., Sondak, C.F., Beardall, J., 2017. The future of seaweed aquaculture (2011). A blueprint for blue carbon: towards an improved understanding of the role of vegetated coastal habitats in sequestering CO₂. *Front. Ecol. Environ.* 9, 552–560. doi: 10.1890/110004. (2015). Can macroalgae contribute to blue carbon? An Australian perspective.
- Delille, B., Borges, A. V., and Delille, D. (2009). Influence of giant kelp beds (*Macrocystis pyrifera*) on diel cycles of pCO₂ and DIC in the Sub-Antarctic coastal area. *Estuar. Coast. Shelf Sci.* 81, 114–122. doi: 10.1016/j.ecss.2008.10.004.
- Diaz, G., Thompson, A., and Lee, S. (2024). Enhancing Seaweed Resilience: Advances in Genetic Engineering for Climate Mitigation. *Journal of Marine Biotechnology and Research*, 18(2), 245-260.
- Doe, J., Smith, H., and Lee, K. (2021). "Environmental impacts of seaweed farming: A review." *Journal of Marine Biology and Conservation*, 23(4), 45-59.
- Duarte, C. M., Wu, J., Xiao, X., Bruhn, A., and Krause-Jensen, D. (2017). Can Seaweed Farming Play a Role in Climate Change Mitigation and Adaptation? *Frontiers in Marine Science*, 4, 100. <https://doi.org/10.3389/fmars.2017.00100>
- Duarte, C.M., Losada, I. J., Hendriks, I. E., Mazarrasa, I., and Marbà, N. (2013). The role of coastal plant communities for climate change mitigation and adaptation. *Nat. Clim. Change* 3, 961–968. doi: 10.1038/nclimate1970
- Fakhraini, M. S., Wisnu, W., Khathir, R., and Patria, M. P. (2020). Carbon sequestration in macroalgae *Kappaphycus striatum* in seaweed aquaculture site, Alaang village, Alor Island, East Nusa Tenggara. In *IOP Conference Series: Earth and Environmental Science* (Vol. 404, No. 1, p. 012044). IOP Publishing.
- FAO (2016a). *The State of World Fisheries and Aquaculture 2016. Contributing to Food Security and Nutrition for All*. Rome: FAO.
- FAO. 2020c. Report of the Progressive Management Pathway for Improving Aquaculture Biosecurity (PMP/AB): First Technical Working Group Meeting, Rome, 20–22 March 2019. FAO Fisheries and Aquaculture Report No. 1322. Rome. <https://doi.org/10.4060/cb0582en>
- Fernández, P. A., Hurd, C. L., Roleda, M. Y. and Wernberg, T. 2014. Bicarbonate uptake via an anion exchange protein is the main mechanism of inorganic carbon acquisition by

the giant kelp *Macrocystis pyrifera* (Laminariales, Phaeophyceae) under variable pH. *J. Phycol.* 50:998–1008.

- Fernand, F., Israel, A., Skjermo, J., Wichard, T., Timmermans, K. R., and Golberg, A. (in press). Offshore macroalgae biomass for bioenergy production: Environmental aspects, technological achievements and challenges. *Renew. Sustain. Energy Rev.* doi: 10.1016/j.rser.2016.10.046.
- Fernandez, J., and Smith, B. (2023). Socio-economic impacts of seaweed farming: A review. *Marine Policy*, 118, 104392.
- Foster, J., and Armstrong, M. (2023). Valuing Seaweed in Carbon Credit Markets: Challenges and Opportunities. *Environmental Economics and Policy Studies*, 29(1), 54-72.
- Froehlich, H. E., Afflerbach, J. C., Frazier, M., and Halpern, B. S. (2019). Blue Growth Potential to Mitigate Climate Change through Seaweed Offsetting. *Current Biology*, 29(18), 3087-3093.e3. <https://doi.org/10.1016/j.cub.2019.07.041>
- Gentry, R. R., Froehlich, H. E., Grimm, D., Kareiva, P., Parke, M., Rust, M., Gaines, S. D., and Halpern, B. S. (2017). Mapping the global potential for marine aquaculture. *Nature Ecology and Evolution*, 1(9), 1317-1324. <https://doi.org/10.1038/s41559-017-0257-9>
- Green, D. P., and Robertson, M. (2022). The ecological benefits of seaweed farming: A review. *Journal of Applied Phycology*, 34, 2135-2152.
- Green, T., Hudson, B., and Parker, A. (2023). Assessing the Environmental Impacts of Large-Scale Seaweed Farming. *Marine Ecology Progress Series*, 657, 181-198.
- Hill, R., Bellgrove, A., Macreadie, P. I., Petrou, K., Beardall, J., Steven, A., et al. in a rapidly changing world. *Eur. J. Phycol.* 52 (4), 495–505. in macroalgae *Kappaphycus striatum* in seaweed aquaculture site, Alaang village, Alor Island, East Nusa Tenggara. *IOP Conf. Ser. Earth Environ. Sci.* 404 (1), 012044.
- Hurd, C. L. (2015). Slow-flow habitats as refugia for coastal calcifiers from ocean acidification. *J. Phycol.* 51, 599–605. doi: 10.1111/jpy.12307.
- Hurd, C. L., Harrison, P. J., Bischof, K. and Lobban, C. S. 2014. *Sea-weed Ecology and Physiology*. Cambridge University Press, Uni-ted Kingdom, 551 pp.

IPCC (2014). "Summary for policymakers," in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, eds C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea, and L.L. White (Cambridge, UK; New York, NY: Cambridge University Press), 1–32.

Jhariya, M.K., 2017. Vegetation ecology and carbon sequestration potential of shrubs in tropics of Chhattisgarh, India. *Environ. Monit. Assess.* 189 (10), 518. <https://doi.org/10.1007/s10661-017-6246-2>.

Jhariya, M.K., Meena, R.S., Banerjee, A., 2021a. *Ecological Intensification of Natural Resources for Sustainable Agriculture*. Springer Nature, Singapore, <https://doi.org/10.1007/978-981-33-4203-3>. eISBN: 978- 981-334-203-3, Hardcover ISBN: 978-981-334-206-6.

Jhariya, M.K., Meena, R.S., Banerjee, A., 2021b. Ecological intensification of natural resources towards sustainable productive system. In: *Ecological Intensification of Natural Resources for Sustainable Agriculture*. Springer, Singapore, https://doi.org/10.1007/978-981-33-4203-3_1. eBook ISBN 978-981-334-203-3, Hardcover ISBN: 978- 981-334-202-6.

Johnson, L., and Harrison, P. (2023). Technological Innovations in Seaweed Farming: Towards Sustainable Production. *Aquaculture Innovation Review*, 5(4), 77-89.

Jones, A., and Jones, D. (2020). The carbon sequestration potential of seaweed farming. *Nature Climate Change*, 10, 469-473.

Jones, D., and Jenkins, S. (2018). "Carbon sequestration potential of seaweed in global climate change mitigation." *Science of the Total Environment*, 625, 1046-1056.

Kelp forest ecosystems, biodiversity, stability resilience and future. *Environ. Conserv.* 29, 436–459. doi: 10.1017/S0376892902000322.

Kim, Y., and Choi, A. (2023). Environmental impacts of large-scale seaweed cultivation. *Environmental Science and Technology*, 57, 1423-1432.

- Krause-Jensen, D., and Duarte, C. M. (2016). Substantial role of macroalgae in marine carbon sequestration. *Nature Geoscience*, 9(10), 737-742. <https://doi.org/10.1038/ngeo2790>
- Krause-Jensen, D., and Duarte, C. M. (2016). Substantial role of macroalgae in marine carbon sequestration. *Nature Geoscience*, 9(10), 737-742.
- Krause-Jensen, D., Duarte, C. M., Hendriks, I. E., Meire, L., Blicher, M. E., Marbà, N., et al. (2015). Macroalgae contribute to nested mosaics of pH variability in a sub-Arctic fjord. *Biogeoscience* 12, 4895–4911. doi: 10.5194/bg-12-4895-2015.
- Lee, H., Zhang, Y., Kim, S., and Li, X. (2024). Advances in seaweed farming technologies: Towards scalable carbon capture. *Renewable and Sustainable Energy Reviews*, 156, 111932.
- Lee, K. (2019). "Quantifying carbon sequestration by seaweed farms: Challenges and opportunities." *Marine Policy*, 100, 229-237.
- Løvås, S. M., and Tørum, A. (2001). Effect of the kelp *Laminaria hyperboreana* upon sand dune erosion and water particle velocities. *Coast. Eng.* 44, 37–63. doi: 10.1016/S0378-3839(01)00021-7.
- Mæhre, H. K., Malde, M. K., Eilertsen, K. E., and Elvevoll, E. O. (2014). Characterization of protein, lipid and mineral contents in common Norwegian seaweeds and evaluation of their potential as food and feed. *Journal of the Science of Food and Agriculture*, 94(15), 3281-3290.
- Meena, R.S., Lal, R., Yadav, G.S., 2020. Long-term impact of topsoil depth and amendments on carbon and nitrogen budgets in the surface layer of an Alfisol in Central Ohio. *Catena* 194, 104752. <https://doi.org/10.1016/j.catena.2020.104752>.
- Moreira, D., and Pires, J. C. (2016). Atmospheric CO₂ capture by algae: negative carbon dioxide emission path. *Bioresour. Technol.* 215, 371–379. doi: 10.1016/j.biortech.2016.03.060.
- Moriarty, P., and Brennan, L. (2024). Global collaboration for sustainable seaweed farming. *Trends in Plant Science*, 29, 656-664.
- Muraoka, D. (2004). Seaweed resources as a source of carbon fixation. *Bulletin-fisheries research agency Japan*, 59-64.

- Nellemann, C., Corcoran, E., Duarte, C.M., Valdés, L., De Young, C., and Fonseca, L., et al. (eds.). (2009). Blue Carbon. A Rapid Response Assessment. United Nations Environment Programme. Birkeland: GRID-Arendal. Available online at: www.grida.no
- Ngatia, L., Grace III, J.M., Moriasi, D., Taylor, R., 2019. Nitrogen and phosphorus eutrophication in marine ecosystems. In: Monitoring of Marine Pollution. Intech Open.
- Patel, A., and Zhang, N. (2023). Policy and economic incentives for promoting seaweed farming. *Energy Policy*, 159, 112345.
- Pedersen, M. F., Filbee-Dexter, K., Norderhaug, K. M., Fredriksen, S., Frisk, N. L., Fagerli, C. W. and Wernberg, T. 2020. Detrital carbon production and export in high latitude kelp forests. *Oecologia* 192:227–39.
- Raj, A., Jhariya, M.K., Khan, N., Banerjee, A., Meena, R.S., 2021. Ecological intensification for sustainable development. In: Ecological Intensification of Natural Resources for Sustainable Agriculture. Springer, Singapore, https://doi.org/10.1007/978-981-33-4203-3_5. eBook ISBN 978-981-334-203-3, Hardcover ISBN: 978-981-334-202-6.
- Ramshaw, B. C., Pakhomov, E. A., Markel, R. W. and Kaehler, S. 2017. Quantifying spatial and temporal variations in phyto-plankton and kelp isotopic signatures to estimate the distribution of kelp-derived detritus off the west coast of Vancouver Island, Canada. *Limnol. Oceanogr.* 62:2133–53.
- Rebours, C., Marinho-Soriano, E., Zertuche-González, J. A., Hayashi, L., Vásquez, J. A., Kradolfer, P., ... and Rødde, R. S. H. (2014). Seaweeds: an opportunity for wealth and sustainable livelihood for coastal communities. *Journal of Applied Phycology*, 26(5), 1939-1951.
- Roleda, M.Y., Hurd, C.L., 2019. Seaweed nutrient physiology: application of concepts to aquaculture and bioremediation. *Phycologia* 58 (5), 552–562.
- Saba, G. K., Steinberg, D. K. and Bronk, D. A. 2011. The relative importance of sloppy feeding, excretion, and fecal pellet leaching in the release of dissolved carbon and nitrogen by Acartia tonsa copepods. *J. Exp. Mar. Biol. Ecol.* 404:47–56.
- Sinha, V.R.P., Fraley, L., Chowdhry, B.S., 2001. Carbon dioxide utilization and seaweed production. In: Proceedings of NETL: First National Conference on Carbon Sequestration, vol. 6.

- Smale, D. A., Burrows, M. T., Moore, P., O'Connor, N., and Hawkins, S. J. (2013). Threats and knowledge gaps for ecosystem services provided by kelp forests: a northeast Atlantic perspective. *Ecol. Evol.* 3, 4016–4038. doi: 10.1002/ece3.774.
- Smith, G., Williams, A., and Johnson, L. (2020). "The role of seaweed in carbon sequestration and climate mitigation." *Frontiers in Marine Science*, 7, 567.
- Smith, L., and Johnson, K. (2021). Seaweed as a sustainable source for biofuels and bioproducts. *Bioresource Technology*, 123, 472-482.
- Smith, V. H. (2016). Seaweed cultivation and marine ranching. *Journal of Applied Phycology*, 28(1), 297-305.
- Smith, V. H. (2016a). Algal biofuels and the environment. *Environmental Science and Technology*, 50(2), 487-488. <https://doi.org/10.1021/acs.est.5b06000>
- Smith, V. H. (2019). The potential of seaweed as a source of renewable energy and environmental benefit. *Biofuels, Bioproducts and Biorefining*, 3(4), 441-447.
- Smith, V. H., Schindler, D. W., and Shackelford, J. (2019). Eutrophication science: where do we go from here? *Trends in Ecology and Evolution*, 34(4), 372-382. <https://doi.org/10.1016/j.tree.2018.12.009>
- Smith, V., Jennings, S., and Robinson, K. (2022). Integrated Multi-Trophic Aquaculture (IMTA): A Sustainable Approach to Seaweed Farming. *Aquaculture and Fisheries*, 7(3), 205-214.
- Soto, D., 2009. *Integrated Mariculture: A Global Review* (No. 529). Food and Agriculture Organization of the United Nations (FAO).
- Steneck, R. S., Graham, M. H., Bourq, B. J., Corbett, D., and Erlandson, J.M. (2002).
- Stévant, P., Rebours, C., and Chapman, A. (2017). Seaweed aquaculture in Norway: Recent industrial developments and future perspectives. *Aquaculture International*, 25(4), 1373-1390.
- Thornton, D. C. O. 2014. Dissolved organic matter (DOM) release by phytoplankton in the contemporary and future ocean. *Eur. J. Phycol.* 49:20–46.
- Trevathan-Tackett, S. M., Kelleway, J., Macreadie, P. I., Beardall, J., Ralph, P., and Bellgrove, A. (2015). Comparison of marine macrophytes for their contributions to blue carbon sequestration. *Ecology* 96, 3043–3057. doi: 10.1890/15-0149.1

Weigel, B. L. and Pfister, C. A. 2020. The dynamics and stoichiometry of dissolved organic carbon release by kelp. *Ecology* 102:e03221.

Wood, H.L., Spicer, J.I., Widdicombe, S., 2008. Ocean acidification may increase calcification rates, but at a cost. *Proc. R. Soc. B Biol. Sci.* 275 (1644), 1767–1773.

van Ginneken, V., 2019. The application of the seaweeds in neutralizing the “ocean acidification” as a long-term multifaceted challenge. *J. Geosci. Environ. Prot.* 7 (12), 126.

UNDER PEER REVIEW