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The global potential of seaweed farming for carbon sequestration and removal

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Abstract

Seaweed has emerged as a promising strategy for extracting carbon from the environment and minimizing the consequences of climate change because it can store carbon dioxide (CO₂) from the atmosphere. This study explores the global potential of seaweed farming as a scalable means of extracting carbon dioxide and mitigating climate change, with a focus on the interplay between existing knowledge and biophysical constraints. This study uses a comprehensive evaluation of the literature and data analysis to evaluate the variability in carbon removal capacity across different seaweed farming environments worldwide. Seaweed farming's ability to effectively sequester carbon is largely dependent on biophysical factors such as species selection, growing techniques, oceanic conditions, and geographic location.

Keywords: Carbon removal, seaweed farming, climate mitigation, constraints, carbon sequestration

Introduction

One less well-known, but potentially revolutionary, solution to this worldwide issue is seaweed farming. The underappreciated marine plant known as seaweed may be crucial to the fight against climate change. With an 8% annual growth rate and an annual production of 27.3 million tons in 2014, seaweed aquaculture makes up 27% of total marine aquaculture production. Still, just 5% of the total value of aquaculture crops is derived from the seaweed produced. These aquatic plants may grow swiftly and don't require any of the limited resources on Earth, such as fertilisers, fresh water, or arable land (Yang *et al.*, 2021) ^[25]. Seaweed farming is a rapidly expanding industry with great potential in terms of production volume and associated benefits for food and nutrition security, climate change mitigation, and industry development. However, a clear understanding of sustainability governance, including management challenges. Opportunities, knowledge gaps, and needs related to future paths of sustainable seaweed farming in the Western Indian Ocean (WIO) is still a contested generic responsibility challenge across the WIO region (Eggertsen & Halling, 2021) ^[8]. The farming of agarophytic, carrageenophyte, and ulvophyte seaweeds is governed through a highly complex mix of statutory, quasi-statutory, and non-statutory farm tenancy licenses, land tenure conventions, loans, agreements, and customary rights. The global commitment to a blue economy can spur more research of locally relevant seaweed resources but must combine this with stakeholder involvement and concerns over cultural values regarding food security. The global state of knowledge of seaweed farming as a possible climate sponge, how parameters such as sinking depth and decomposition come into play, and the implications of these findings regarding the potential harvesting of seaweed for energy and food security (DeAngelo *et al.*, 2022) ^[5].

Overview of Seaweed Farming Practices

Cultivation of macroalgae occurs primarily in waters affected by coastal areas (neritic provinces extend from shorelines to approximately 200 m) and in zones characterized by depth greater than 200 m (oceanic provinces).

The structure of macroalgal farming generally follows two forms, namely longline and fixed designs. In both forms, growing lines are set up floating above the seabed in the water column, usually in rows with sufficient spacing for healthy macroalgae growth and reduced hitchhiker colonization (Khan *et al.*, 2024) ^[16]. Expansion of seaweed farming can be classified into three primary groups based on farm designs and cultured macroalgae species such as brown macroalgae, blue macroalgae, and red macroalgae.

Red macroalgae cultivation farms widely use longline designs, especially on the eastern coast of Asia (China, Taiwan, Hong Kong, Japan, Philippines, and Korea). Another popular practice is brown macroalgae farming (*Ecklonia maxima*, *Saccharina japonica*, and *Undaria pinnatifida*). Most macroalgae farms use multiple farm stations consisting of multiple floating objects such as buoys and nets. Products from macroalgae farming include food for human consumption, animal feed supplementation, fertilizers, cosmetics, drugs, biofuels, bioadsorbents, and other chemical compounds. Most of the above-mentioned products are already extracted from macroalgae, and appropriate practices have been applied and secured for mass-production at a large-scale for societal use (Mohiuddin *et al.*, 2023) ^[19]. In contrast, a few new products such as biopolymers (darvinlipids, polysaccharides), biofuels, fertilizer applications, and bioadsorbents are extracted from macroalgae utilizing innovative mechanisms and state-of-the-art technologies, and further, research and development are still needed to push for new mass-production at large-scale for societal use.

Importance of Carbon Sequestration

Seawater carbon farming, which involves human-driven seaweed aquaculture expansion for perennial harvest and passive offshore transport, was studied. This approach can enhance both carbon sequestration and ocean biogeochemistry benefits. After describing the methodology, a location-based valuation framework is implemented using the best available values for biomass sinking and biogeochemistry effects. Limitations, including harvest-induced nutrient declines and efficiency losses due to water depth, are addressed while conservative worldwide estimates are provided. Location-specified optimization or policy implementation could significantly augment the projected benefits of ocean seaweed farming. The ocean can help mitigate contemporary climate change, and achieving carbon neutrality by mid-century is feasible if sufficient anthropogenic CO₂ emissions are avoided and a massive uptake is enhanced (Yang *et al.*, 2021) ^[25]. Enhancing the ocean's natural carbon pumps with nature-based solutions holds the greatest potential and has many other advantages. Natural biogeochemical processes already withdraw about 40% of anthropogenic carbon emissions. Saltwater submarine aquaculture has been hailed as a sustainable means of protein production. Coastal habitat restoration of salt marshes, mangroves, and seagrass meadows for carbon sequestration has been actively promoted. Each nautical mile of well-managed coastal blue carbon habitat may sequester between 170,000 and 670,000 tons of atmospheric carbon each year. Land-based and coastal nature-based solutions have been well studied.

The ocean covers more than 70% of the earth's surface and sequesters more than 93% of the excess heat from climate change, along with massive quantities of anthropogenic CO₂, as determined by the geochemical nature of the carbon cycle (Van De Walle, 2008) ^[23]. To avoid GHG emissions, the world must sequester billions of tons of carbon annually for centuries,

overcoming intense natural loss pathways. Alternatively, the ocean offers a vast area to grow seaweed which, during growth, consumes atmospheric CO₂ and other nutrients. Managed and harvested offshore seaweed farming would transform the growth biomass from a surface phytoplankton food web into the sinking biomass with a concurrent biogeochemical impact.

The Role of Seaweed in Carbon Sequestration

Carbon may be sequestered through various biophysical and mechanisms, including active and passive carbon capture and storage (CCS) via the air-sea gas exchange. Passive preformed processes of organic carbon removal from surface water is export by the downward transport of organic carbon to the deep ocean through the biological pump mechanism, sedimentation, and ocean circulation. In this case, biological productivity plays a central role in establishing the efficiency of the export process. Organic carbon export is further assisted by biological processes, such as aggregation and ballast remineralization, that promote particle sinking.

Photosynthetic seaweeds can grow in naturally nutrient-rich coastal waters and exhibit high availability to fixation CO₂. Photosynthetically active marine macroalgae blooms (MMABs) composed of large pelagic and benthic species of macroalgae such as kelp forests and giant *Sargassum* may remove a substantial amount of atmospheric carbon dioxide (ocean-atmosphere CO₂ exchange) through passive direct biological uptake. Seaweeds are typically more efficient in the biological fixation of CO₂ compared to terrestrial plants. In coastal waters, experimental surveys demonstrate that CO₂ gas exchange, estimated by radiocarbon, ²³⁴Th, and delta-oxygen isotopes, is largely in the negative range of -61 to -352 mmol m⁻² d⁻¹ due to the elevation of SiN and phytoplankton blooms. On the contrary, the average CO₂ gas exchange in offshore coastal waters varies between 12 and 18 mmol m⁻² d⁻¹ with relatively low values of ²³⁴Th, suggesting an insignificant influence of MMAB on passive CO₂ gas exchange and subsequent dampening.

Mechanisms of Carbon Sequestration in Seaweed

As a pH-neutral base, ocean water absorbs atmospheric CO₂, with ~1/3 of anthropogenic CO₂ emissions taken up by the ocean. Over millennia, the majority of this dissolved inorganic carbon is buried in ocean sediments, assisting in maintaining Earth's climate. The deep ocean contains ~38,000 Pg of long-term CDR potential. Seaweed generates a large depleted region for 100 years in high-nutrient coastal waters (Findlay & Turley, 2021) ^[11]. Using the net productivity of documented ca. 3D seaweed occurrences, a range of CDR*4270-5200 Pg CO₂ was arrived at. One of the deployment methods to enhance afforestation could be by harbor-less application of N fertilizers offshore via GAO vessels.

The ocean is an essential Earth system component and is responsible for transferring, sequestering, and storing natural or anthropogenic solutes and particles between short- and long-term reservoirs. The surface ocean tightly equilibrates with the atmosphere over the timescales of a few days. This is readily demonstrated when ocean water, with a surface temperature of 8 °C, is viewed bubbling at a point source of vented deep-sea CO₂ (dCO₂) rich water at the coast of Italy. CO₂ is rapidly outgassed to the atmosphere; however, it cannot be removed at broader spatial and temporal scales. On the basin-scale, dense CO₂-rich deep waters must up well and contact the surface before equilibration with the atmosphere occurs, with an estimated timescale of more than 1000 years. This lengthy equilibration time ensures that the ocean becomes a net sink of anthropogenic

CO₂ for millennia. Subsequent to the arrival of dCO₂ at the surface, air-sea equilibration of most species involved in the carbonate chemistry is rapid on timescales of days to decades, although the equilibration of HCO₃⁻ and CO₃ can take millennia.

Comparison with Terrestrial Plants

The potential for terrestrial plants to aid in climate change mitigation through carbon dioxide (CO₂) sequestration and removal has been explored with more attention in recent years. Consuming CO₂, photosynthetic organisms produce oxygen and organic matter. Enhancing their growth would result in more biomass production, allowing a higher amount of carbon to be stored. Terrestrial plants have been considered as suitable organisms to fulfill this task, supported by pre-existing efforts to expand forestry on earth, such as afforestation and reforestation projects (DeAngelo *et al.*, 2022)^[5]

Considerably more photosynthetic productivity occurs in oceans than on land, with macroalgae growing up to 10 times faster than terrestrial plants. Hence, macroalgae farming or seaweed aquaculture projects may emerge as an alternative. The capability of macroalgae to sequester and/or remove CO₂ has been studied, focusing on potential farms that may sequester as much as more than 135 billion metric tons carbon per year, even without current coastal nutrient enrichment projects as cultivated globally. Seaweed, despite being considered a marine plant, is more closely related to land plants than terrestrial macroalgae. The unique structure of thallus, meristematic cell zones, and morphogenic cells, coupled with more efficient resource use, ensure high productivity.

Environmental Benefits of Seaweed Farming

Seaweed aquaculture has received increasing interest as an innovative means to mitigate the impacts of climate change and ocean acidification beyond its well-researched provisioning services as a common food source with strong ties to coastal communities and economies worldwide. Recent studies advocate for seaweed aquaculture among the five most favorable coastal interventions to mitigate climate change owing to its global potential for net carbon removal (Khan *et al.*, 2024)^[16]. Despite the vigorous debate surrounding the net climate benefits of seaweed and the other so-called “blue carbon” ecosystems, it is widely acknowledged that coastal makes use of aquatic plants can merely echo the climate benefits of trees a simple, cost-effective means to sequester carbon and long-term storage (Currie, 2018)^[7]. Seaweed aquaculture may offer a low-cost adaptation strategy toward ocean acidification and deoxygenation. Compared to comparable coastal habitats, it is estimated that macroalgae can extract perhaps 10-fold more greenhouse gasses from water than mangroves and eelgrass combined. Clear opportunities exist for cost-effective farm monitoring technologies to deliver environmental results that match the ambitions of the most ambitious seaweed policies. Seaweed farms may add new habitat heightening support of coastal marine biodiversity owing to their architectural form and biogenic structure, which would allow them to be preserved (and monitored) through existing offshore marine environmental legislation designed to maintain seabed biodiversity and ecosystems.

Reduction of Ocean Acidification

Life in the ocean is threatened by increasing levels of anthropogenic CO₂, which acidify the seawater and form the greenhouse gas CO₂. Seaweed farming can directly ameliorate

ocean acidification for coastal ecosystems and potentially even the open ocean. Seaweed farming can be seen as a ‘nature-based solution’ to anthropogenic CO₂ emissions. Similar to other plants on land and in the water, seaweed absorbs CO₂ from the water during photosynthesis (Hasselström *et al.*, 2020)^[14]. Dissolving CO₂ in seawater increases carbonic acid, bicarbonate, and hydrogen ions, causing the water to acidify. The removal of dissolved CO₂ by seaweed during photosynthesis thus lessens ocean acidification by decreasing both dissolved CO₂ and hydrogen ion concentrations.

As observed in some locations in tropical and subtropical oligotrophic oceans, where conditions are favorable for the growth of seaweed farming, the seawater may experience a net biological CO₂ drawdown with simultaneous ocean acidification mitigation. However, with disastrous effects of ocean acidification projected to occur in polar and subpolar regions in the coming decades, active interventions are needed to preserve these vulnerable ecosystems. This presents both challenges and opportunities for seaweed farming. Intensive farming in these regions can have the dual potential of mitigating the local and global scale effects of ocean acidification and contributing to seafloor carbon sequestration (Kumari *et al.*, 2024)^[17].

Biodiversity Support

Biodiversity support is one of the key regulating ecosystem services and represents the extent to which farming systems or management strategies support the establishment of a hospitable environment for various forms of biodiversity (Khan *et al.*, 2024)^[16]. In such a context, it is important to recognize that pure biodiversity enhancement activities may not provide measurable benefits in terms of environmental sustainability and socio-economic equity assessment, particularly in the case of emerging food production activities that may actually undermine existing ecological structural deficiencies.

Promoting the development of seaweed farming along integrated, multi-species aquaculture systems and coastal restructuring to encourage both resource use and biofouling are encouraged (Leandro *et al.*, 2020)^[18]. The development of research in marginal coastal areas with a wealthy and very diverse heritage of traditional small-scale capture fishery practices is encouraged. Support for co-management schemes between seaweed farm operators and collection fishermen is also encouraged in developing an equitable and fairer access to resources and market. The stand has the potential of being a unique opportunity in terms of developing biodiversity conservation as a process by managing resource use.

Challenges and Limitations of Seaweed Farming for Carbon Sequestration

The challenges of seaweed farming for carbon sequestration concern technical, infrastructural, and economic factors, either now or likely to arise in future scenarios. It examines six constraints or limits: (1) Technological; concerns on farm design, spacing, productivity, and form; (2) Infrastructure; concerns on seafloor stability, shipping needs, and processing requirements; (3) Economic; considerations that limit economic attractiveness to investment; (4) Environmental; rethinking ecological interactions and unintended consequences; (5) Social; opposition from those likely to be affected; and (6) Governance; regulatory frameworks for safe growth but ability to grow quickly enough to avoid climate change impact (Bamaniya *et al.*, 2020)^[2]. Some possible constraints might become less important under new technologies, regulatory frameworks, etc., and some are not yet important but under worst-case climate

scenarios may become a barrier to growth. The conditions under which these constraints become barriers to growth are explored, along with recommendations to resource those constraints that currently limit growth.

Some potential constraints to the ability of seaweed farming to develop as a solution to climate change may be identified. Seaweed farming is unlikely to eliminate climate change impacts by 2050 (Arzeno-Soltero *et al.*, 2023) ^[1]. A mixture of agriculture and forestry-based negative emissions technologies (NETs) will likely be required to remove gigatons of CO₂ from the atmosphere. The challenge and attraction are that large-scale seaweed farming or cultivation can be rapidly deployed in coastal parts of developing countries, and strategies to reduce risk around impacting on existing fishery, aquaculture, and tourism sectors can be identified.

Technological and Infrastructure Challenges

Unlike other carbon sequestration methods, seaweed farming for Sequestration has not gained traction so far. This is primarily due to practical barriers. Compared to other carbon sequestration methods, seaweed farm (for sequestration) technology is unproven, and infrastructures do not exist. This is perhaps the biggest roadblock for scaling up. On the positive side, no critical breakthroughs are needed: proven engineering solutions exist in other industries. The pieces of the puzzle are there; it just needs some time, funding, curation, and caution to fit them together. Both offshore wind farms and seaweed farms require costly infrastructures that presently do not exist. The capital investment needed for one wind turbine is estimated at €3–4 million; another €2 million investment will be required to supply seaweed cultivation systems (Reith *et al.*, 2005) ^[20]. This is too high for individual enterprises, and alternative operational and financial models should be explored.

Current Global Initiatives and Projects

As concerns grow about humanity's ability to counter climate change in light of continued carbon emissions, numerous geoeengineering concepts are emerging. Almost all ideas focus on deploying large technologies, creating thickets of machines that exponentially amplify our environmental effects. However, visions differ in whether they take active precursors to the Anthropocene to our defense or are conversely read as self-regulatory apparatuses of a growing system on the brink of chaos. Smaller, more benign technologies are proposed, most prominently, the planting of trees and the development of bioenergy with carbon capture and storage, but all of them necessitate continuing with current climate-unfriendly affluence. While tree planting would change freshwater flows and biodiversity, it is more or less in line with existing logics of capital accumulation. The same holds for the promotion of bioenergy crops, just more on a global scale than currently undertaken. These crops would consume land, water, and nutrients from the ongoing agricultural colonization of nature that already takes a toll on ecosystems. Some ideas are more radical and otherworldly, like solar radiation management technologies that aspire to inject aerosols into the atmosphere at a globally unprecedented scale. However, most of them deal with industrial sea-going developments on a scale previously unseen (Hasselström *et al.*, 2020) ^[14]. This includes concepts for oceanic iron fertilization, algae blooms, and coastal geoeengineering involving the enhancement of natural processes that aspire to locally increase the export of carbon and nutrients, with all its likely detrimental side effects. All of these are technologies so vast in scope, they could change ocean ecologies

and global weather patterns at the scale of continents.

Case Studies of Successful Seaweed Farming Projects

A scuba diver gathers kelp for a seaweed farm. WHOI scientists found that if enough seaweed were farmed, climate change could be mitigated in 1 of 90 scenarios over the next 200 years. Yet, with an ocean area of 28 Mkm², if only 0.1% of this were used for commercial cultivation, 3 Gt CO₂ yr⁻¹ could possibly be sequestered-10 times more than current emissions (Hurd *et al.*, 2022) ^[15]. This proposal aims to examine the feasibility of carbon sequestration by algae.

Iceland's Nearshore Kelp Restoration project works with local stakeholders to restore kelp forests. Iran's Kelp Project buoy provides nets for kelp hatchlings. Tanzania's Kelp Workshop creates commercialized seaweed farms for over 1,000 households. Vietnam's VIEP supports the development of co-processing and biogas industries using seaweed biomass (Hasselström *et al.*, 2020) ^[14].

Conclusion

With so many benefits, at the table, it is worth further research and investment in seaweeds. Removing carbon from the ocean and converting it into carbonate for the production of construction materials or drugs is an unexpected action to derive by the potential of seaweed production. Development of biochar and high-quality carbon for soil improvements, food supplement proteins and products, or vanadium recovery for renewable battery production could additionally be linked to algae. Adding seaweed or seaweed mats improves food security and ecosystem resilience if deployment reduces the effects of storms and maintains coastal uplift. Reef promotion games benefit from the introduction of suspended seaweed products, which supply food to fish and other associated forms of algae. Substituting IKEA, wrapping, and coffee products as examples of plastic polymers would result in decreased plastic waste. Mild aquatic climate manipulation could also be affected after sustained wide-scale seaweed demolition. With the many possibilities available, more research needs to be made to harness the remarkable potential that seaweeds offer all around.

Policy Recommendations and Future Directions

Governments must act now to harness the global potential of seaweed farming and carbon sequestration. Global coastal and marine policymaking may also be re-evaluated over the next year to incentivize and promote the sustainable farming of seaweed for carbon sequestration. Policymakers, coastal nations, and organizations implementing their Blue Economy policies in receipt of new Ocean governance funding should also consider the rapid deployment of biomass from new large-scale low-cost ocean seaweed cultivation zones. The biomass can be utilized for biofuels and BEC technologies while increasing Blue carbon from high-productivity coastal ecosystems, including kelp forests that can lower coastal erosion and improve local fisheries (Duarte *et al.*, 2022) ^[6].

In terms of climate policy, the farming of ocean seaweed can be integrated into existing climate policies such as UNEP or partnered with new ocean agreements under the UNFCCC negotiations. New knowledge-sharing initiatives should be initiated to support developing coastal countries in global low-cost kelp cultivation zones to access demanding carbon credit funding. In parallel, national ecosystems assessments and investment plans to drive coastal economic growth should be implemented before ocean seaweed responses are offloaded to the emerging global bioeconomy at the risk of infringing human

rights (Hasselström *et al.*, 2020)^[14].

Integration of Seaweed Farming in Climate Policies

Because these credits would help prevent emissions from entering the atmosphere or avoid already emitted ones, they can be used by industrial firms to comply with their emissions reduction targets (DeAngelo *et al.*, 2022)^[5].

Seaweed cultivation has the potential to contribute to several plausible planetary boundary violations. It would be essential to keep the global production within the safe operating space of the Earth's system by minimizing its biophysical bottlenecks, such as nutrient limitations or competition with significant concurrent land and water uses (Hasselström *et al.*, 2020)^[14].

Research and Development Priorities

Systems modeling assessments can deliver a first order approximation of the carbon sequestration or effective removal potential of various seaweed farming systems on a global or regional scale, with respect to a number of physical, biogeochemical, ecological, technological, economic, and social criteria. Applications to date include the verification of carbon sequestration potential (Chen *et al.*, 2020), the quantification of environmental and blue economy co-benefits, the development of on-line diagnostic decision-support tools (e.g. SeaDAS), and cost-benefit analysis of potential scenarios for regional policy development (e.g. Mid-Atlantic Region USA). The sustainability of specific agricultural or pharmaceutical product supply-chains is also a fundamental area of interest. A major goal of design studies is to develop locally appropriate biomitigation-systems that maximize local benefits while also minimizing adverse impacts (Campbell *et al.*, 2019)^[3]. Collectively, modeling activities can identify research priorities and political policy guidelines at regional to global scales, including addressing knowledge gaps.

In conjunction with process or systems models, mechanical engineering research is needed to develop passive large-surface-area buoyant devices for the surface sewing of nutrients (e.g. P-mineral salts). The music of buoyant-vehicle design must address the competing performance and cost objectives of: (i) buoy stability and performance under the action of environmental waves and currents; (ii) manufacturing and installation costs; and (iii) operation and maintenance post-deployment. Buoyant devices with multi-layer nets designed to interrupt surface currents are also possible configurations. Finally, societal dialogue research is needed on the acceptability of such systems.

References

1. Arzeno-Soltero IB, Saenz BT, Frieder CA, Long MC, DeAngelo J, Davis SJ, Davis KA. Large global variations in the carbon dioxide removal potential of seaweed farming due to biophysical constraints. *Commun Earth Environ*. 2023;4(1):185.
2. Bamaniya P, Bambhaniya I, Vaghela D. Seaweed-a promising source of carbon sequestration with income generation and nutritional security. Available from: [researchgate.net](https://www.researchgate.net). 2020.
3. Campbell I, Macleod A, Sahlmann C, Neves L, Funderud J, Øverland M, Hughes D, Stanley M. The environmental risks associated with the development of seaweed farming in Europe - Prioritizing key knowledge gaps.
4. Chen B, Harp DR, Lu Z, Pawar RJ. Reducing uncertainty in geologic CO₂ sequestration risk assessment by assimilating monitoring data. *Int J Greenhouse Gas Control*. 2020;94:102926.
5. DeAngelo J, Saenz BT, Arzeno-Soltero I, Frieder CA, Long MC, Hamman J, Davis K, Davis SJ. Economic and biophysical limits to seaweed farming for climate change mitigation.
6. Duarte CM, Bruhn A, Krause-Jensen D. A seaweed aquaculture imperative to meet global sustainability targets. *Nat Sustainability*. 2022.
7. Currie ME. The growing sustainable seaweed industry: A comparison of Australian state governance directing current and future seaweed cultivation.
8. Eggertsen M, Halling C. Knowledge gaps and management recommendations for future paths of sustainable seaweed farming in the Western Indian Ocean.
9. FAO. The State of World Fisheries and Aquaculture 2016. Contributing to Food Security and Nutrition for All. Rome: FAO; 2016.
10. Duarte CM, Wu J, Xiao X, Bruhn A, Krause-Jensen D. Can seaweed farming play a role in climate change mitigation and adaptation? *Front Mar Sci*. 2017;4:100. Available from: <https://doi.org/10.3389/fmars.2017.00100>
11. Findlay HS, Turley C. Ocean acidification and climate change. *Climate Change*.
12. Fu C, Frappi S, Havlik MN, Howe W, Harris SD, Laiolo E, Duarte CM. Substantial blue carbon sequestration in the world's largest seagrass meadow. *Commun Earth Environ*. 2023;4(1):474.
13. Fujita R, Augyte S, Bender J, Brittingham P, Buschmann AH, Chalfin M, Yarish C. Seaweed blue carbon: ready? Or not? *Mar Policy*. 2023;155:105747.
14. Hasselström L, Thomas JB, Nordström J, Cervin G, Nylund GM, Pavia H, Gröndahl F. Socioeconomic prospects of a seaweed bioeconomy in Sweden.
15. Hurd CL, Law CS, Bach LT, Britton D, Hovenden M, Paine ER, Boyd PW. Forensic carbon accounting: Assessing the role of seaweeds for carbon sequestration. *J Phycol*. 2022;58(3):347-363.
16. Khan N, Sudhakar K, Mamat R. Macroalgae farming for a sustainable future: Navigating opportunities and driving innovation.
17. Kumari N, Pandey AK, Singh A. Exploring the global potential of seaweed farming for carbon removal and climate mitigation. *Int J Environ Climate Change*. 2024;14(7):159-170.
18. Leandro A, Pacheco D, Cotas J, Marques C, Pereira L, Gonçalves MM. Seaweed's bioactive candidate compounds to food industry and global food security.
19. Mohiuddin M, Banik U, Iqbal MZ, Chamily FA, Rahman MM, Nahiduzzaman M, Asaduzzaman M. Influence of cultivation systems and associated environmental factors on the growth performance of *Hypnea musciformis* seaweed at the south-east coast of the Bay of Bengal, Bangladesh. *Aquac Rep*. 2023;32:101718.
20. Reith EH, Deurwaarder EP, Hemmes K, Curvers APWM, Kamermans P, Brandenburg WA, Lettings G. BIO-OFFSHORE: Grootschalige teelt van zeewieren in combinatie met offshore windparken in de Noordzee.
21. Ross FWR. "Kelp our Climate" Seaweed growth rates in the context of Blue Carbon opportunities.
22. Bach LT, Tamsitt V, Gower J, Hurd CL, Raven JA, Boyd PW. Testing the climate intervention potential of ocean afforestation using the Great Atlantic Sargassum Belt.
23. Van De Walle J. Carbon farming: A look at carbon sequestration in agriculture.

24. Wu J, Keller DP, Oschlies A. Carbon dioxide removal via macroalgae open-ocean mariculture and sinking: an Earth system modeling study. *Earth Syst Dyn.* 2023.
25. Yang Y, Luo H, Wang Q, He Z, Long A. Large-scale cultivation of seaweed is an effective approach to increase marine carbon sequestration and solve coastal environmental problems. *Bull Chinese Acad Sci.* 2021;36(3):259-269.