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ECONOMIC FEASIBILITY ANALYSIS OF MACROALGAE FARMING-BASED CARBON DIOXIDE REMOVAL

ZULPIKAR FIRMAN[1]*, HANDAYANI TRI[1], RENYAAN JEVERSON[1], PRASETIA HAFIIZH[2], SAFAAT MUHAMMAD[2] AND PUTRI ARY MAULIVA HADA[2]

[1]*Research Center for Oceanography-National Research and Innovation Agency (BRIN), 10340 Jakarta, Indonesia.* [2]*Research Center for Chemistry-National Research and Innovation Agency (BRIN),10340 Jakarta, Indonesia.*

**Corresponding author: firman.zulpikar@brin.go.id*

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Abstract: Macroalgae farming has been proposed to remove carbon dioxide in climate mitigation programs. However, the success of this initiative will depend on economic feasibility. Two types of macroalgae farming, *Kappaphycus alvarezii* and *Gracilaria* sp. cultivated in Serang Banten were used to determine the economic feasibility of this concept in the future. Data on the farming cost and business profile were collected through interviews with macroalgae farmers. The results showed that the investment cost for *K. alvarezii* was 20,042,423 IDR/ha/year (eq. to 1,432 USD), while *Gracilaria* sp. is lower at about Rp. 13,598,831 IDR/ha/year (eq. to 971 USD), with macroalgae biomass production reaching 8.3 tonnes/ha/year and 6.0 tonnes/ha/year respectively. The potential for carbon dioxide absorption through the cultivation of *K. alvarezii* and *Gracilaria* sp. are estimated at 9.13 tonnes CO_2/ha/year and 6.60 tonnes CO_2/ha/year. The investment cost of reducing emissions by cultivating macroalgae ranges from 2,058,557-2,193,233 IDR/ton CO_2 (eq. to 147-157 USD). This value is not yet feasible economically, but relatively lower than the estimated average cost of reducing emissions using macroalgae in the region. Our study provides a preliminary estimate of the investment cost and capacity of macroalgae farming-based carbon removal that can be considered in future climate mitigation programs.

Keywords: Macroalgae farming, CDR, investment analysis, climate mitigation.

Introduction

The urgency of climate mitigation demands the use of every possible tool available, including marine resources for carbon sequestration. Recent and very ambitious initiatives propose to use large-scale macroalgae to remove carbon dioxide from the atmosphere (Krause-Jensen & Duarte, 2016; Duarte *et al*., 2017; Froehlich *et al*., 2019). Promoting macroalgae in climate mitigation provides several benefits; macroalgae have potential to capture 173 million metric tonnes of CO_2 per year globally (Krause-Jensen & Duarte, 2016), contribute to climate change adaptation by damping wave energy and protecting shorelines, as well as improving environmental conditions by elevating pH and supplying oxygen to the waters (Duarte *et al*., 2017). Moreover, macroalgae farming is a well-established industry worldwide. However, the feasibility of this approach is potentially limited by the large volume of cultivated macroalgae that would be required, competing human uses, and the constraints imposed by financial, regulatory, and political landscapes (Klinger, 2021). Some of these limitations are potentially addressed, especially in Indonesia where macroalgae farming is being carried out intensively.

Indonesia is a significant contributor to global macroalgae production, particularly the red macroalgae *Kappaphycus alvarezii* and *Gracilaria* sp. (Rimmer *et al*., 2021). Macroalgae production rises annually, with an average value rising of 11.80%. In 2013 macroalgae production was about 9.31 million tonnes, and it rose to approximately 11.3 million tonnes in 2015 (Sriwulandari *et al*., 2020). The increase was driven by domestic and international demand growth primarily for processed foods and cosmetic row materials. The recent identification of macroalgae for climate mitigation and adaptation purposes (Duarte *et al*., 2017), such as carbon dioxide removal has the potential to multiply macroalgae production. However, this is a relatively new idea with many unknowns in ecological and economic aspects.

Macroalgae Farming Based Carbon Dioxide Removal (MFB-CDR) is believed to offer an adequate solution particularly to achieve the goal of carbon neutrality in the aquaculture industry in line with blue growth (Gao *et al*., 2022). This approach not only promotes the sustainable management of marine resources but also could provide new economic growth (Zhang *et al*., 2017). Economic compensation for the environmental benefits brought by macroalgae farming, including its role in climate change mitigation, would allow for further growth and a more sustainable macroalgae aquaculture industry. In particular, economic compensation for climate services associated with macroalgae farming would help generate a new market for macroalgae production while also creating incentives to reduce further the life-cycle CO_2 emissions of aquaculture (Duarte *et al*., 2017).

Given that current macroalgae have been widely used for commercial purposes, the success of large-scale CO_2 emission reduction based on macroalgae farming will depend on whether it is economically feasible compared to the existing purposes. Using macroalgae farming to remove carbon dioxide requires a modification of economic analysis from commercial use. The economic feasibility analysis should consider the amount of CO_2 uptake reflected in carbon content analysis and the amount of macroalgae carbon stored in the marine environment. Conversely, harvesting macroalgae biomass for commercial purposes is considered to contribute to carbon release, which could impact the feasibility of this approach. However, the information on the economic feasibility of macroalgae production for this purpose, especially in tropical areas that are canters of macroalgae cultivation worldwide, is limited. This study aims to assess the economic feasibility of macroalgae farming for future carbon sequestration programs using the farming cost approach. We use the analysis of the production costs of macroalgae for commercial purposes as a benchmark to determine how far the opportunities for future implementation of climate mitigation strategies can be attractive for farmers and companies.

Materials and Methods

Study Area

This research was conducted in Lontar Village and Tengkurak Village. Both villages are centres of macroalgae farming in Serang Regency, Indonesia (Figure 1). The dominant type of macroalgae cultivated is *Kappaphycus alvarezii,* cultivated along marine waters with the long line technique and *Gacilaria* sp. cultivated in the pond area. The total area used for macroalgae farming is about 107 ha. The number of people who work as cultivators is approximately 250 people, the majority of them cultivate the *K. alvarezii*.

Data Collection

Data was collected through interviews with macroalgae farmers and secondary data analysis. The number of farmers involved in this study were 50 people consisting of two groups of farmers *K. alvarezii* and *Gracilaria* sp. each of which was 25 people. The sample size for the *Gracilaria* sp. farmers includes the entire population in the study area, while the sample size for *K. alvarezii* farmers was determined proportionally using quota sampling. Critical questions in the questionnaire include respondent profile, area managed, biomass production, and business profile. The value of carbon content in the biomass of the two types macroalgae was calculated using the conversion approach to the average value of carbon content of 30% of dry weight (Sondak *et al*., 2017). To convert the sequestration of 1 kg of carbon to the associated removal of CO_2 from the atmosphere, the amount of carbon is multiplied by 12/44, resulting in 3.67 kg of CO_2 (Pendleton *et al*., 2012; Froehlich *et al*., 2019).

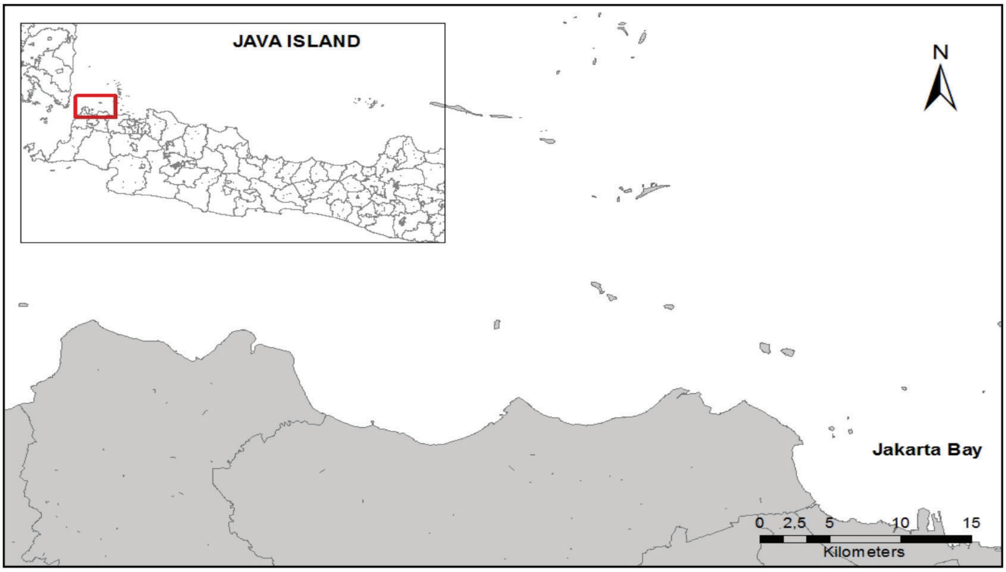


Figure 1: Map of Serang Regency

Data Analysis

The data were subjected to statistical analysis and business feasibility analysis. The statistical analysis was conducted using t-test to determine whether there were significant differences between *K. alvarezii* and *Gracilaria* sp. Business feasibility analysis was examined using the Revenue/Cost ratio (R/C) and Payback Period (PP) to determine whether the carbon macroalgae farming-based carbon removal is feasible or not to be developed. Revenue/Cost Ratio was used to calculate the comparison between the ratio and cost of the feasibility analysis of macroalgae farming (Tawakal *et al.*, 2019), with the following formula:

$$R/C = \frac{Total\ Revenue}{Total\ Cost}$$

The business is feasible to run if R/C ratio > 1, and the business is not feasible to run if R/C ratio < 1 (Soekartawi, 2003).

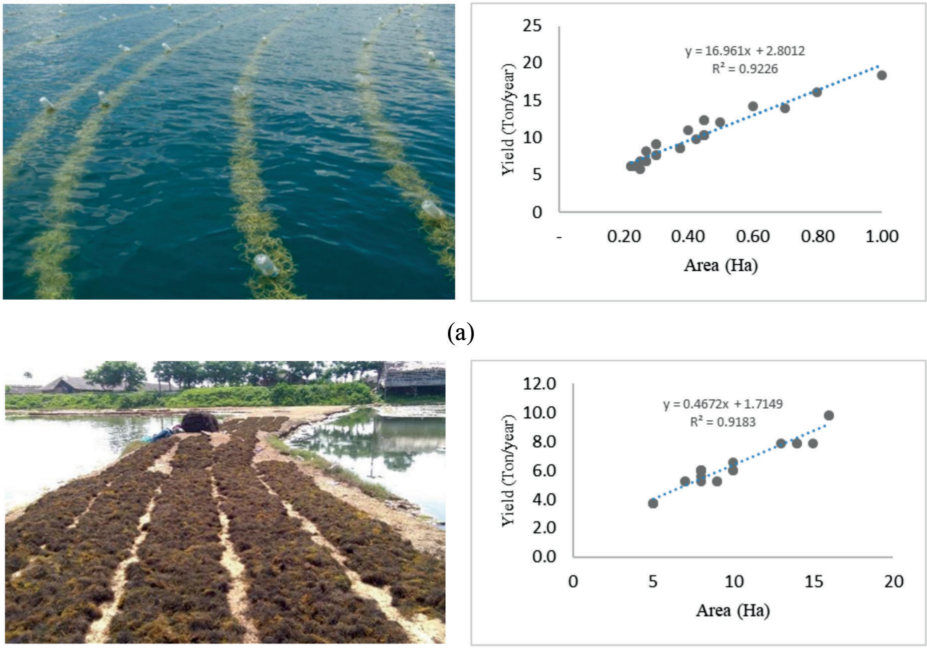
The Payback Period is the time it takes for a project's benefits to cover all previous project investments, usually within an annual timeframe (Kreckhoff & Ngangi, 2018; Naufal *et al.,* 2022) with the following formula:

$$PP = \frac{Initial\ investment}{Cash\ flow}\ x\ 1$$

The capital return is fast if < 3 years, moderate if 3-5 years, and slow if the capital return > 3 years (Riyanto, 2010).

Results and Discussion

The production of macroalgae species *K. alvarezii* and *Gracilaria* sp. in Serang Regency, Banten, reaches an average of 500-700 tonnes/year. The total area of *K. alvarezii* farming used is 57 ha, while the pond area used for *Gracilaria* sp. farming is about 50 ha. Although *K. alvarezii* cultivated in marine areas, the average area used by each farmer is relatively small, only 0.25 ha/farmer. On the other hand, *Gracilaria* sp. which is cultivated in ponds, have a much larger area of cultivation, which is an average of 2 ha/farmer. Despite having a small cultivation area, the farmers of *K. arverezii* were able to produce a much larger harvested biomass of 8.3 tonnes/ha/year, while the farmers of *Gracilaria* sp. only produce of biomass around 6.0 tonnes/ha/year. This amount is an accumulation of 5-7 harvest cycles per year with an average cultivation period of 45 days.



(a)

(b)

Figure 2: Comparison of farming practice and productivity (a) *K. alvarezii* (b) *Gracilaria* sp.

The availability of capital cost is an important factor in determining the type of macroalgae, and the scale of cultivation. *K. alvarezii* cultivated with the long line technique requires a higher capital cost than *Gracilaria* sp. The main capital cost components include the provision of seeds and materials such as nylon rope, floats, and others, as shown in Table 1. The capital costs that must be prepared for the cultivation of *K. alvarezii* and *Gracilaria* sp. are 6,710,423 IDR/ha/year and 5,838,031 IDR/ha/year. Our calculations for the capital cost of *Gracilaria* sp. do not include costs for opening new ponds because the area is mostly already available. However, rent cost were calculated in this study in case the farmers do not have their ponds.

Apart from the capital costs, macroalgae farming also requires a high enough operating cost every year. The largest operating cost component for *K. alvarezii* comes from labour wages, which reach 51%. Another cost component which are pretty significant is planting cost which reached 23% (Table 2). Meanwhile, maintenance cost is the highest operating cost component for *Gracilaria* sp. Similar to the capital cost, the cultivation of *K. alvarezii* costs more to operate than the cultivation of *Gracilaria* sp.

The percentage of operating cost of *K. alvarezii* farming is higher than *Gracilaria* sp. while the percentage of capital cost of *Gracilaria* sp. is higher than *K. alvarezii* as shown in Figure 3. In general, *K. alvarezii* requires more investment costs than *Gracilaria* sp. The total investment cost for *K. alvarezii* was 20,042,423 IDR/ha/year, while *Gracilaria* sp. is lower at about 13,598,831 IDR/ha/year. The investment cost is directly proportional to the productivity of the macroalgae produced and the economic benefits obtained by each farmer. The price of dry biomass in the market for the two types of macroalgae ranges from 8,000-10,000 IDR.

Macroalgae productivity is critical in achieving carbon neutrality in the aquaculture sector. *K. alvarezii* had higher productivity than *Gracilaria* sp. However, the productivity of

Tabel 1: The comparison of capital cost for *K. alvarezii* and *Gracilaria* sp.

K. alvarezii		
Items	**Useful Life (Years)**	**Percentage (%)**
6 mm strap	5	13
4 mm strap	5	22
2 mm strap	2	10
Floats	0.5	4
Knife	0.5	1
Bamboo	3	6
Seed	5	30
Sack	0,3	4
Tarp	2	1
Boat	5	2
Engine boat	10	6
Total percentage (%)		100
Total capital cost (IDR/ha/year)		6,710,423

***Gracilaria* sp.**		
Items	**Useful Life (Years)**	**Percentage (%)**
Rental pond and maintenance	1	43
Fiber boat	5	4
Raft boat:		
a. Ropes	5	0.17
b. Foam	3	1
c. Bamboo	3	0.44
Seed	5	34
Sack	0.2	4
Tarp	2	3
Netting mat	2	10
Total percentage (%)		100
Total capital cost (IDR/ha/year)		5,838,031

Tabel 2: The comparison of operating cost for *K. alvarezii* and *Gracilaria* sp.

K. alvarezii		
Items	**Cost (IDR/ha/year)**	**Percentage (%)**
Labor wages	6,734,000	51
Fuel	598,000	4
Planting Cost	3,000,000	23
Harvesting cost	1,500,000	11
Miscellaneous	1,500,000	11
Operational Cost (IDR/Ha/year)	13,332,000	100

***Gracilaria* sp.**		
Items	**Cost (IDR/ha/year)**	**Percentage (%)**
Planting Cost	1,250,000	16
Fertilizer	280,800	4
Maintenance cost	1,620,000	21
Harvesting cost	4,000,000	52
Miscellaneous	610,000	8
Operational Cost (IDR/Ha/year)	7,760,800	100

these two types of macroalgae is relatively low when compared to the same species in other countries, such as China, where *Gracilaria* sp. can produce a biomass of 9.5 tonnes/ha/year (Gao *et al*., 2022). Macroalgae productivity undoubtedly will affect the total amount of carbon dioxide absorbed through macroalgae farming. The value of total carbon dioxide uptake by *K. arvarezii* and *Gracilaria* sp. refers to the conversion of the average value of carbon content of 30% of the dry weight, namely 2.49 tonnes C/ha/year and 1.8 tonnes C/ha/year. The carbon dioxide absorption value obtained by multiplying the carbon value by a conversion factor of 3.67 is estimated to reach 9.13 tonnes CO_2/ha/year and 6.60 tonnes CO_2/ha/year, respectively. This productivity estimate does not calculate the amount of Particulate Organic

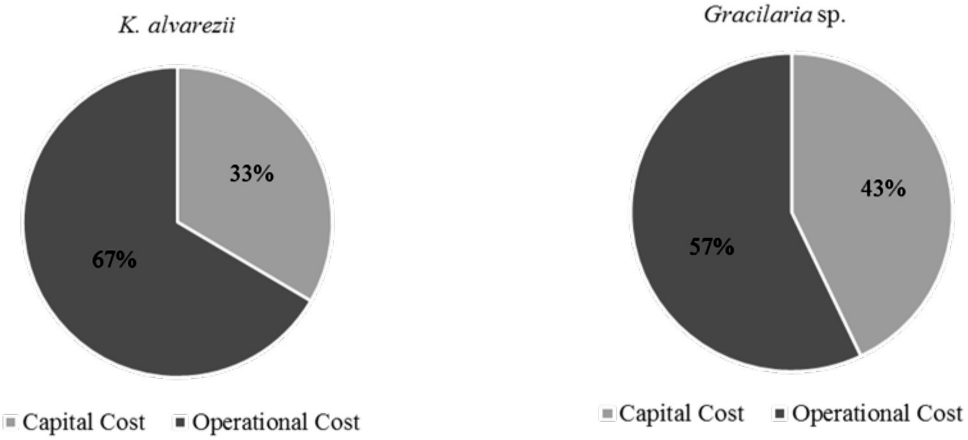


Figure 3: The comparison of investment costs for *K. alvarezii* and *Gracilaria* sp.

Table 3: The estimation of macroalgae farming cost and carbon price

Species	Yield (ton/ha/year)	Carbon (ton/ha/year)	CO$_2$ (ton/ha/year)	Farming Cost (IDR/ton)	Estimate Carbon price* (IDR/ton)
K. alvarezii	8.3	2.49	9.13	2,193,233	112,000-210,000
Gracilaria sp.	6.0	1.8	6.60	2,058,557	

*Price converted from USD with assumption 1 USD=14.000 IDR

Carbon (POC) and Dissolve Organic Carbon (DOC) donated during the cultivation process, whose value is estimated to reach 23-26% of the primary productivity (Krause-Jensen & Duarte, 2016).

Our study shows that the investment cost of CO$_2$ reducing emissions by cultivating macroalgae in Banten Province are around 2,190,000 IDR/ton CO$_2$ (equivalent to 157 USD) for *K. alvarezii*, and 2,058,557 IDR/ton CO$_2$ (equivalent to 147 USD) for *Gracilaria* sp. The investment cost of *K. alvarezii* is $10 higher than *Gracilaria* sp., however it can absorb carbon dioxide 27% higher than *Gracilaria* sp. The current carbon price in the carbon market ranges from $8-15, (Gao *et al*., 2022) equivalent to 112,000-210,000 IDR. Our assessment using the Revenue/Cost ratio and Payback Period indicates that carbon dioxide removal using these two types of macroalgae is not yet economically feasible (value 0.07) with a very long Payback Period of 38-72 years for *K. alvarezii* and 36-67 years for *Gracilaria* sp. However, this estimated cost is relatively lower than the average cost of macroalgae farming in Indonesia and other macroalgae-producing countries such as the Philippines, which averages about 543 USD (Froehlich *et al*., 2019) or equivalent to 7,600,000 IDR/ton CO$_2$, except in China where production costs only reach 85 USD/ton dry weight (Gao *et al*., 2022) or around 1,190,000 IDR.

The amount of the investment cost is not final and may change depending on the species grown, oceanographic conditions, and available technology (Froehlich *et al*., 2019). For instance, one of the fastest growing species in the world, *Macrocystis pyrifera* could contribute approximately 27% more production per hectare (Correa *et al*., 2016) than the average species, and maximising macroalgae carbon content could potentially reduce costs by 38% (Froehlich *et al*., 2019). Moreover, the demand for offset projects in the global carbon market is predicted to continue increasing, which has the potential to increase the selling price of this carbon. The selection of a location with high water productivity and more competitive labor wages is also a strategy that can be used to cut macroalgae production costs. Another solution that can be implemented to cut farming costs is by providing subsidies and selling the harvested parts of the macroalgae to cover the cultivation costs (Gao *et al*., 2022).

The investment cost of carbon removal using macroalgae appears more competitive when compared to many of the land-based strategies and technologies. For example, land-based carbon offsetting estimates of 31.84-383.62 USD/ton CO_2 (Froehlich *et al*., 2019) Emission reduction via technology applications such as biodiesel could reach 150-250 USD/ton CO_2, low carbon fuel standard estimates of 100–2.900 USD/ton CO_2 and solar photovoltaics subsidies about 140–2.100 USD/ton CO_2 (Gillingham & Stock, 2018). The efficiency in reducing emission costs can encourage the flow of carbon offset demand from other sectors that must cut their emissions but require higher costs.

Although reducing CO_2 emissions through macroalgae cultivation is not yet economically feasible, this approach could provide more benefits from a socio-ecological point of view while simultaneously supporting Blue Growth initiatives (Froehlich *et al*., 2019). The social benefits of this approach could improve the welfare of coastal communities by creating jobs and alternative income derived from compensation or climate incentive mechanisms (Duarte *et al.,* 2017). In the future, this scheme could become a community-based climate mitigation model, considering that macroalgae cultivation is a large-scale business activity. Furthermore, from an ecological perspective, this approach can improve the quality of the marine environment and support carbon-neutral programs in the aquaculture sector. New research is demonstrating the ability of macroalgae to buffer some of the other impacts of anthropogenic pollution, including ocean acidification (Duarte *et al*., 2017) and low-oxygen events (Alleway *et al*., 2019). The oxygen generated by macroalgae cultivation could increase dissolved oxygen in seawaters by 21% daily with gas exchange excluded, which could effectively counteract deoxygenation in seawaters (Gao *et al*., 2022). However, the use of macroalgae to reduce carbon emissions in the future does not only consider aspects of economic benefits but also needs to consider social acceptance and environmental sustainability.

Recommendation

Our economic feasibility analysis highlights the estimated costs for macroalgal farming-based carbon removal at the community scale in coastal areas. These calculations show that the climate mitigation strategy through macroalgae farming still faces challenges, especially cost restrictions. The high investment costs not commensurate with the amount of carbon absorbed can have implications for the low interest of the community, companies, or related institutions to choose this approach in future climate mitigation strategies. However, this approach still has an excellent opportunity to be developed if several challenges can be addressed.

Some recommendations to reduce investment costs while optimizing macroalgae productivity include:

i. Selecting the macroalgae species with high productivity. Several macroalgae species, such as *K. alvarezii* and *Sargassum* sp., have high productivity and carbon content.

ii. Choosing cultivation techniques that are cost-efficient and easy maintenance. Equipment installation is one of the most significant cost components in macroalgae farming. Therefore, effective and efficient cultivation systems should be designed to maximize the available growth area while minimizing installation costs.

iii. Determining suitable locations with good water quality and affordable labor wages. The main components of operational expenditure are labor wages, planting, and transportation costs. Ideally, the farming location is near the coast to reduce working hours and transportation costs, including boat rental and fuel.

As the macroalgae farming industry develops in Indonesia, currently, there is available economic and life cycle data that can be used by researchers or stakeholders as benchmarks to predict dan map the suitable locations, species, and techniques to achieve the feasibility economic level of this approach.

Conclusion

Carbon dioxide removal using macroalgae *K. alvarezii* cultivated in marine areas is more productive than *Gracilaria* sp. which cultivated in the pond. However, the investment costs for these two types of macroalgae are not yet feasible economically. Investment costs can be reduced significantly through a strategy for selecting the suitable type of macroalgae and farming location. The use of macroalgae farming, however, could be considered in the future climate mitigation portfolio because of offers more competitive costs than any other option. Moreover, macroalgae farming-based carbon dioxide removal provides ecological co-benefits, especially in making aquaculture more sustainable.

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