

Carbon Sequestration Potential of *Kappaphycus alvarezii* Seaweed Cultivation in Bondo Waters, Jepara Regency, Indonesia

Wiwien Mukti Andriyani¹, Ari Wibawa Nurma Saputra², Handoko Agung Prabowo², Cocon^{1*}, Nur Azizah², Noor Azharul Fuad², Mustagfirin², Imam Taukhid³, Rachman Syah³

¹Jepara Brackish Water Aquaculture Center, Ministry of Maritime Affairs and Fisheries
Cik Lanang Street IV, Bulu, Jepara Regency, Central Java Province

²PT. Bhumi Jati Power, Tanjung Jati Power Plant Unit 5 and 6

³Center of Fisheries Research, National Research and Innovation Agency

Correspondence:

utamabbpbapjpr@gmail.com

Received:

April 23th, 2026

Accepted:

May 11th, 2026

Published:

May 23th, 2026

Keywords:

Kappaphycus alvarezii,
Carbon Sequestration, Blue
Carbon, Seaweed
Cultivation, Climate Change
Mitigation

ABSTRACT

Global warming poses a critical challenge worldwide, driven by high levels of carbon emissions. This study aims to evaluate the carbon sequestration potential of *Kappaphycus alvarezii* seaweed cultivated using the longline system in Bondo waters, Mlonggo District, Jepara Regency. The research involves measuring carbon absorption, analyzing carbon content, estimating the total carbon sequestration potential of the cultivation area, and assessing the relationship between water quality parameters and carbon absorption levels. Samples were collected periodically on days 14, 28, 42, and 49 during a single cultivation cycle. Results reveal a total carbon absorption of 305.21 tons of C per cycle (1,831.27 tons of C per year) with the highest carbon content recorded at 43.68% on day 28. The total carbon sequestration potential across an effective cultivation area of 44.36 hectares is estimated at 40,617.79 tons of C annually. The study also identifies a positive correlation between carbon absorption, biomass growth, and water quality parameters such as brightness, salinity, and pH. These findings support the development of seaweed cultivation as a viable solution for mitigating carbon emissions through integration into carbon trading schemes and blue economy programs. This research makes a significant contribution toward Indonesia's net zero emissions target by 2060 while offering sustainable economic and social benefits for coastal communities. Further studies are recommended to explore the long-term effects of repeated cultivation cycles and the diversification of other seaweed species.

INTRODUCTION

Global warming continues to be one of the most urgent challenges of the present era, with significant impacts on environmental quality and the sustainability of aquatic resources.

Its direct effects have triggered a crisis in natural resources, including declining aquatic productivity that may threaten human survival (Sherman *et al.*, 2009; Niinemets *et al.*, 2017; Gaines *et al.*, 2018; Yanik & Aslan, 2018; Tseng *et al.*, 2021; Brosse *et al.*, 2022; Nimma *et al.*, 2025). According to Seneviratne (2023), the increase in greenhouse gas (GHG) concentrations due to human activities is the primary driver of rising global average temperatures since the mid-20th century. Additionally, global temperatures have increased by approximately 0.65°C in 2022 compared to long-term averages since 1880 (L'Ecuyer & Lang, 2011; Kumar & Pooja, 2020; Filonchyk *et al.*, 2024).

For Indonesia, a country characterized by high biodiversity and strong dependence on natural resources, climate change presents a serious challenge. The industrial sector contributes more than 80% of GHG emissions due to the dominant use of fossil fuels as energy sources (Hadi *et al.*, 2018; Meehan *et al.*, 2019; Respitawulan & Rahayu, 2019; Ardiyanto *et al.*, 2021; Harnowo *et al.*, 2021; Basuki *et al.*, 2022; Firmansyah *et al.*, 2023; Ayuningtias *et al.*, 2024; Sayuti, 2024; Syartinilia *et al.*, 2024; Vinata *et al.*, 2024; Handaja *et al.*, 2024; Nainggolan *et al.*, 2024).

As part of its commitment to the Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC), Indonesia has undertaken efforts to reduce carbon emissions, as stipulated in Law No. 16 of 2016. Through its Nationally Determined Contribution (NDC), Indonesia initially targeted a 29% reduction in GHG emissions independently and up to 41% with international support by 2030 (Winanti *et al.*, 2023; Ayuningtias *et al.*, 2024). This target was later revised through the Enhanced Nationally Determined Contribution (ENDC) in 2022, increasing the targets to 31.89% (unconditional) and 43.20% (conditional) (Oshiro *et al.*, 2017; Jeong *et al.*, 2022; Di Lallo *et al.*, 2024). Indonesia has also set a long-term goal of achieving net-zero emissions by 2060. In this context, aquatic ecosystems play a crucial role in carbon sequestration. Seaweed, in particular, has the ability to absorb and store carbon through photosynthesis, thereby reducing carbon dioxide (CO₂) levels in both the atmosphere and marine environments (Packer, 2009; Handayani *et al.*, 2022; Yong *et al.*, 2022; Lian *et al.*, 2023; Pessarrodona *et al.*, 2024; Hurd *et al.*, 2024).

The waters of Jepara, especially the Bondo area, have significant potential for seaweed cultivation. A feasibility study conducted by the Brackish Water Aquaculture Center (BBPBAP) Jepara in 2021 identified an effective cultivation area of 44.36 hectares (Effendi *et al.*, 2021; Ayuningtyas *et al.*, 2024; Naskar *et al.*, 2024; Tamrin *et al.*, 2024). This potential is particularly relevant due to the presence of the Tanjung Jati B coal-fired power plant (PLTU), which is one of the major sources of carbon emissions in the region, with an estimated emission potential of 6,762,690 tons C per year (PT. BJP, 2013). One of the most widely cultivated species is *Kappaphycus alvarezii*, known for its rapid growth rate and high photosynthetic efficiency (Hayashi *et al.*, 2007; de Góes & Reis, 2012; Reis *et al.*, 2015; Hurtado & Critchley, 2018; Solorzano-Chavez *et al.*, 2019; Rajaram & Rameshkumar, 2019; Shalvina *et al.*, 2022; Mantri *et al.*, 2024; Nunes *et al.*, 2024; Nursidi *et al.*, 2024; Bhowmik *et al.*, 2025). In addition to its economic importance, seaweed cultivation provides significant ecological benefits, particularly in carbon sequestration as a natural carbon sink (Mendonça *et al.*, 2017; Ould & Caldwell, 2022; Luo *et al.*, 2023; Chen *et al.*, 2024; Han *et al.*, 2025). Furthermore, seaweed cultivation can enhance coastal community livelihoods through increased production and diversification of seaweed-based products (Chung *et al.*, 2017; Steenbergen *et al.*, 2017; Henríquez-Antipa & Cárcamo, 2019; Mirera *et al.*, 2020; Jagtap & Meena, 2021; Guillén *et al.*, 2022; Sutrisno *et al.*, 2024).

The utilization of blue carbon through seaweed cultivation represents a strategic solution for carbon mitigation. Previous studies have shown that oceans can absorb up to 2 billion tons of CO₂ annually (Muraoka, 2004). In Japan, seaweed species such as *Sargassum*, *Ecklonia*, and *Laminaria* are capable of absorbing up to 2.7 million tons of CO₂ per year, including contributions from aquaculture activities. Despite these potentials, research on carbon sequestration by *Kappaphycus alvarezii* cultivated near coal-fired power plants remains limited. Therefore, this study is essential to explore the carbon sequestration potential of this species under such environmental conditions. This research is expected to provide a scientific basis for developing sustainable aquaculture strategies that contribute to climate change mitigation. Strategically, it also supports the integration of carbon sequestration data into sustainability policy frameworks, including potential applications in carbon trading schemes. Moreover, the findings are expected to open opportunities for further exploration, including species diversification and long-term studies on cultivation impacts on coastal ecosystems.

METHODS

Study Site and Time

The study was conducted in the waters of Bondo, Mlonggo District, Jepara Regency, Central Java Province. The research duration covered one seaweed cultivation cycle of 49 days, carried out from November to December 2024. The seaweed seedlings used in this study were *Kappaphycus alvarezii*, obtained from tissue culture produced by the Brackish Water Aquaculture Center (BBPBAP) Jepara. During the study, both seaweed and seawater samples were collected from the cultivation site on days 0, 14, 28, 42, and 49 after planting. Samples were taken from two randomly selected clumps as replicates. The selection of sampling intervals (days 14, 28, 42, and 49) was designed to capture the dynamics of biomass growth and carbon sequestration comprehensively throughout the cultivation cycle. These intervals reflect key biological growth phases of seaweed, including the initial growth phase (14 days), peak phase (28 days), and maintenance or stabilization phase (42–49 days). Day 28 was specifically selected to monitor peak carbon content, based on previous findings indicating that seaweed at this age typically exhibits maximum photosynthetic efficiency and biomass accumulation.

Additionally, the 49-day cultivation period represents the standard cultivation cycle in Bondo waters, where biomass quality tends to decline beyond this period due to physiological and environmental factors. To ensure data accuracy, measurements were conducted at each interval using strict standard procedures, including regular equipment calibration and repeated sampling. This approach provides a comprehensive understanding of carbon sequestration dynamics at each growth stage and ensures the applicability of results for optimizing future cultivation strategies within blue carbon management frameworks.

Cultivation Method

Seaweed cultivation was conducted using the longline method. The initial weight of the seedlings was approximately 50 g per planting point. The cultivation system consisted of one longline unit with two main ropes. The spacing between planting points was 20 cm (each rope contained 15 planting points), and the distance between ropes was 100 m. The cultivation period lasted one cycle of 49 days, following Indonesian National Standards (SNI, 2010), which also aligns with local farming practices in Bondo coastal waters.

Observed Parameters

Growth was measured by weighing the wet biomass of sampled seaweed from each planting point at days 0, 14, 28, 42, and 49. Measurements were conducted using a digital scale with 0.1 g precision. In situ water quality parameters were measured every two weeks, including: Temperature (thermometer), pH (pH meter pen-224), Salinity (Refractometer ATAGO S/Mill-E), Current velocity (current meter), Water transparency (Secchi disk), Water depth (weighted measuring rope), Laboratory analyses included: Nitrate (cadmium reduction method, spectrophotometer) Phosphate (ascorbic acid method, spectrophotometer), Seaweed samples (two replicates) were dried and analyzed for: Moisture content (gravimetric method, SNI 9091-1:2022) Ash content (gravimetric method, SNI 9091-2:2022), Volatile matter, Total carbon content using the Loss on Ignition (LOI%) method, referring to the Institute of Marine Organic Geochemistry, Ocean University of China (Meng *et al.*, 2014), Carbon sequestration was calculated based on Muraoka (2004), while daily growth rate and productivity followed Erlania *et al.* (2013).

Table 1. Measurement Method

Parameter	Measurement Method	Formula	Description	Reference
Growth rate (%)	Growth rate was calculated from the difference between initial and final biomass during the cultivation period	$DGR (\%) = [(Wt - Wo) / t] \times 100 \%$	Wt = final weight at time t; Wo = initial weight t = cultivation time (days)	Erliana <i>et al.</i> (2013)
Biomass (g/rope)	Seaweed biomass was measured by weighing the total fresh weight from each cultivation rope using a digital balance.	$Biomass (\%) = \frac{(a)}{b} \times 100\%$	a = Wet sample weigh; b = Sample weight after oven-drying at 90°C (g)	Erliana <i>et al.</i> (2013)
Standing stock (g/m ²)	Standing stock was determined by dividing total biomass by cultivation area	$Standing\ stock\ (\frac{g}{m^2}) = \frac{a}{b} \times 100\%$	a = Wet sample weigh; b = Sample plot area (m ²)	Erliana <i>et al.</i> (2013)
P-B ratio	Production-biomass ratio was calculated from production value divided by standing biomass	$Rasio\ P - B = \frac{a}{b}$	a = Wet sample weigh; b = Biomass sample weight (g)	Erliana <i>et al.</i> (2013)
Carbon content (%)	Carbon content was analyzed using laboratory carbon analysis methods on	$CC (\%) = 100\% - MC (\%) - VM (\%) - AC (\%)$	MC = Moisture content; VM = Volatile matter;	Meng <i>et al.</i> (2014)

Paremeter	Measurement Method	Formula	Description	Reference
	dried seaweed samples.		AC = Ash content	
Carbon sequestration (Ton C per Cultivation Cycle)	Carbon sequestration was estimated from biomass carbon accumulation during one cultivation cycle.	$C = A \times SS \times (P-B \text{ ratio}) \times CC$	A = cultivation area; SS = standing stock; P-B ratio = production-biomass ratio; CC = carbon content.	Muraoka (2004)

The study applied standing stock and P–B ratio (Production to Biomass ratio) as key indicators for assessing carbon sequestration. These indicators provide a quantitative representation of biomass accumulation and carbon uptake efficiency in *Kappaphycus alvarezii* cultivation. However, this method has limitations, particularly in not fully accounting for environmental variables such as photosynthetic efficiency and respiration rates. Therefore, future studies are recommended to incorporate additional parameters such as: Light intensity, Nutrient availability, Temperature dynamics, Net Ecosystem Production (NEP), Carbon isotope analysis. These improvements would enhance the robustness and validity of blue carbon assessments. The collected data were presented in tables and figures. Regression and correlation analyses were applied to evaluate the influence of water quality parameters on standing stock, P–B ratio, and carbon sequestration.

RESULTS

Seaweed Cultivation Performance and Carbon Content

The initial weight per clump was 50 g on day 0, which increased progressively to 158.32 ± 34.63 g on day 49 (Table 2). Growth rates varied over time, indicating distinct growth phases: Rapid growth phase (first 14 days) Slowing phase Acceleration phase toward the end (days 42–49).

Table 2. Growth and Biomass of *K. alvarezii*

Age (days)	Seaweed Weight (g/clump)	Growth Rate (g/day)	Biomass (g/rope)	Carbon Content (%)
0	50 ± 0	0	750 ± 0.0	-
14	80.13 ± 10.05	3.36 ± 0.60	1201.9 ± 100	58.98 ± 0.18
28	100.95 ± 17.32	1.68 ± 0.40	1514.3 ± 208.7	43.68 ± 0.07
42	123.77 ± 27.21	1.45 ± 0.04	1856.5 ± 268.2	37.55 ± 0.28
49	158.32 ± 34.63	1.75 ± 0.13	2374.9 ± 385.3	30.54 ± 0.09

The biomass weight calculated on a per longline unit also exhibited an increasing trend consistent with the weight per clump. The increase in biomass weight indicates the effectiveness of cultivation practices in enhancing large-scale seaweed production. The relatively high biomass accumulation at the end of the cultivation period suggests a recovery

phase in growth, possibly due to environmental adaptation or more favorable conditions during the final days of the study.

Total Carbon Sequestration

The carbon sequestration rate of *Kappaphycus alvarezii* during the cultivation period using a longline system in the Bondo waters, Jepara, is presented in Table 3.

Table 3. Total Carbon Sequestration and Carbon Content of the Seaweed Species *Kappaphycus alvarezii* in Longline Cultivation Systems in Bondo Waters, Jepara Regency

Age	Total Area (km ²)	Standing Stock (g/m ²)	P- B Ratio	Carbon Content (%)	Total carbon Sequestration (Ton C per Cultivation Cycle)
Days- 14	0.02	500.78 ± 41.68	23.63 ± 0.04	58.98 ± 0.18	139.60 ± 12.21
Days- 28	0.02	630.94 ± 86.97	30.99 ± 0.01	43.68 ± 0.07	170.80 ± 23.76
Days- 42	0.02	773.57 ± 111.72	39.83 ± 0.13	37.55 ± 0.28	231.27 ± 31.19
Days- 49	0.02	989.53 ± 160.56	50.50 ± 0.19	30.54 ± 0.09	305.21 ± 49.74

The Relationship between Growth and Carbon Sequestration

The regression model indicates a strong relationship between seaweed growth and carbon sequestration, with $R = 0.99$ and an F-value of 832.325 ($p < 0.00$). Biomass growth in seaweed, particularly *Kappaphycus alvarezii*, is closely associated with the rate of carbon sequestration (Table 4). The primary process underlying this relationship is photosynthesis, which serves as the fundamental mechanism for organic carbon accumulation in autotrophic organisms. During photosynthesis, seaweed converts dissolved carbon dioxide (CO₂) in seawater into organic compounds in the form of carbohydrates. These carbohydrates are subsequently stored within seaweed biomass tissues.

As biomass growth increases, the capacity for carbon sequestration also rises, as more carbon is assimilated and retained within the aquatic system. This finding highlights that higher biomass productivity directly enhances the role of seaweed cultivation in carbon sequestration and reinforces its potential as a nature-based solution for climate change mitigation.

Table 4. Regression Analysis of Growth on Carbon Sequestration

Variables	Coefficient (B)	T-statistic	Sig. (p-value)	Note
(X) Growth (g/day)	2.012	28.850	0.000	Significant
Constant (Intercept)	-18.931	-2.484	0.380	
R ²	0.990	-	-	
Adjusted R ²	0.898	-	-	
F-statistic	832.325	-	0.000	Model significant

The Relationship between Standing Stock and Carbon Sequestration

The model demonstrates a very strong relationship between standing stock and carbon sequestration, with $R = 0.99$, indicating that 99% of the variation in carbon sequestration is

explained by standing stock. The F-value of 787.006 further indicates a highly significant relationship ($p < 0.000$) (Table 5).

Standing stock reflects the total biomass available within the cultivation system, which directly contributes to carbon sequestration capacity (Mashoreng *et al.*, 2019; Gao *et al.*, 2022; Ould & Caldwell, 2022; Luo *et al.*, 2023). In *Kappaphycus alvarezii* cultivation, higher standing stock corresponds to a greater amount of carbon that can be sequestered and stored within seaweed biomass tissues.

This process has significant implications for climate change mitigation, as it contributes to reducing carbon dioxide concentrations in both marine environments and the atmosphere (Duarte *et al.*, 2017). Moreover, an increase in standing stock reflects the effectiveness of the cultivation system in utilizing environmental resources to enhance biomass production in a sustainable manner.

Table 5. Regression Analysis of Standing Stock on Carbon Sequestration

Variables	Coefficient (B)	T-statistic	Sig. (p-value)	Note
(X) Standing stock (g/m ²)	0.322	28.054	0.000**	Significant
Constant (Intercept)	-19.442	-2.475	0.380	
R ²	0.990	-	-	
Adjusted R ²	0.989	-	-	
F-statistic	787.006	-	0.000**	Model significant

The Relationship between P–B Ratio and Carbon Sequestration

The regression model demonstrates a highly significant relationship between the P–B ratio and carbon sequestration ($p < 0.001$). The Model Summary indicates a coefficient of determination ($R^2 = 0.916$), suggesting that 91.6% of the variation in carbon sequestration can be explained by the P–B ratio (Table 6).

Table 6. Regression Analysis of Standing Stock on Carbon Sequestration

Variables	Coefficient (B)	T-statistic	Sig. (p-value)	Note
(X) Rasio P-B	6.068	9.315	0.000**	Significant
Constant (Intercept)	-4.847	-0.219	0.832	
R ²	0.916	-	-	
Adjusted R ²	0.905	-	-	
F-statistic	86.767	-	0.000**	Model significant

Water Quality

Water quality is one of the most critical factors determining the success of aquaculture systems. To achieve optimal cultivation outcomes, it is essential to understand the specific water quality requirements for each type of aquaculture activity. In seaweed cultivation, environmental factors play a decisive role in both growth and survival. Key environmental parameters influencing seaweed growth include temperature, salinity, pH, nitrate, phosphate, dissolved oxygen (DO), light intensity, and other related factors (Martínez *et al.*, 2012; Jin *et*

al., 2016; Endo *et al.*, 2017; Chen, 2019; Roleda & Hurd, 2019; Kinnby *et al.*, 2021; Dudley *et al.*, 2022; Bao *et al.*, 2023).

Table 7. Range of Water Quality Parameters in Bondo Waters for Seaweed Cultivation during the Study Period

No	Parameter	Unit	Range of Measurement Result	Standard	Reference
1	Physic				
	- Current velocity	cm/s	15.00 – 21.40	20.00 – 40.00	Zainuddin & Rusdani (2018)
	- Transparency	meter	1.50 – 3.00	>5 optimum	Sindopong <i>et al.</i> (2022)
	- Temperature	°C	28.00 – 29.00	24.00 – 31.00	SNI (2010)
	- Depth	meter	2.00 – 6.00	>2	Sindopong <i>et al.</i> (2022)
	- Substrate	-	muddy sand, coral rubble	Sand	Sindopong <i>et al.</i> (2022)
2	Chemical				
	- pH	-	7.25 – 8.20	6.50 – 8.50	SNI (2010)
	- Salinity	ppt	29.00 – 32.00	28.00 – 33.00	SNI (2010)
	- Nitrate	mg/L	0.18 – 0.54	1.00 – 3.00	Atmanisa <i>et al.</i> (2020)
	- Phosphate	mg/L	0.029	1.00 – 3.00	Indriani & Sumiarsi (1991)

DISCUSSION

Seaweed Cultivation Performance

In the growth analysis of *Kappaphycus alvarezii* observed in this study, a distinct growth pattern was identified, characterized by different phases, beginning with a rapid growth phase during the first 14 days. This phase indicates that the seaweed adapted well to the initial cultivation environment. However, following this period, a decline in growth rate was observed, likely attributable to several factors, including nutrient competition in limited aquatic environments, acclimatization to environmental conditions such as temperature and salinity, as well as biofouling or competition with other organisms that may inhibit optimal seaweed growth.

Furthermore, environmental factors play a critical role in supporting seaweed growth rates. Water quality, particularly nitrogen and phosphorus concentrations, strongly influences photosynthesis and biomass accumulation in seaweed (Hayashi *et al.*, 2017; Du *et al.*, 2023; Munisamy *et al.*, 2023; Capacio *et al.*, 2024; Faisan *et al.*, 2024; Sethuraman *et al.*, 2024). Adequate light intensity, which is essential for photosynthesis, also affects the efficiency of carbon conversion during growth processes (Zuldin *et al.*, 2016). In addition, optimal current conditions and water depth influence nutrient distribution available to seaweed, thereby supporting stable and sustained growth (Ask & Azanza, 2002).

Based on this biological performance, *Kappaphycus alvarezii* demonstrates a dynamic growth pattern with variable growth rates throughout the cultivation cycle. The significant increase in biomass indicates a high potential for carbon sequestration, supporting the

concept of seaweed cultivation as a climate change mitigation strategy. Environmental factors and maintenance strategies play a crucial role in cultivation success and should be carefully considered to enhance sustainable production outcomes.

Carbon Content

From Table 2, it can be observed that the carbon content was 58.98% on day 12, 43.68% on day 28, 37.55% on day 42, and 30.54% at the end of the cultivation period (49 days). When analyzed based on the age of the seaweed, the results indicate that carbon content progressively decreases with increasing age, despite the standing stock weight continuing to increase. This finding is supported by the study conducted by Erlania (2013), which concluded that the capacity of cultivated *Kappaphycus alvarezii* and *Gracilaria gigas* to absorb carbon from the aquatic environment declines with increasing cultivation age. Consequently, the percentage of carbon stored in seaweed biomass also decreases. Variations in carbon content are attributed to differences in moisture content, volatile matter, and ash content among seaweed species (Syad *et al.*, 2013; Olsson *et al.*, 2020; Zahra Zarei Jeliani *et al.*, 2021; Xu *et al.*, 2025). When moisture, volatile matter, and ash contents are high, carbon content in seaweed tends to be low, and vice versa. Based on the results of this study, among the three parameters (moisture content, volatile matter, and ash), volatile matter and ash appear to exert a more pronounced influence.

Furthermore, according to Erlania & Radiarta (2015), the carbon concentration within seaweed tissues also affects total carbon uptake. The greater the mass and volume of seaweed tissue, the greater the amount of carbon stored. Therefore, larger and more abundant seaweed biomass can absorb and store more carbon than smaller biomass. Recent studies indicate that seaweed has substantial capacity to absorb carbon from the atmosphere and convert it into organic carbon stored within its tissues. For instance, a study by Mendonça *et al.* (2017) estimated that global seaweed ecosystems can sequester approximately 173 million tons of carbon annually, equivalent to around 10% of total global carbon emissions.

This study demonstrates that carbon content in *Kappaphycus alvarezii* decreases with increasing cultivation age. The highest carbon content was recorded on day 28 (43.68%), declining to 30.54% by the end of the cultivation cycle (day 49). This phenomenon can be explained from both physiological and environmental perspectives. Physiologically, the early growth phase of seaweed is characterized by intensive metabolic activity, including photosynthesis and biomolecule synthesis. During this stage, photosynthetic efficiency is high, enabling substantial carbon uptake to support new tissue formation. However, as the seaweed ages, metabolism shifts from a rapid growth phase to a maintenance phase, where energy is primarily allocated to sustaining existing tissues rather than producing new biomass. This shift leads to reduced efficiency in carbon accumulation.

From an environmental perspective, changes in water quality—such as nutrient availability, salinity, and pH—also influence carbon content in seaweed biomass. This study found that nutrient concentrations, particularly nitrate and phosphate in the Bondo waters, tended to fall below optimal levels, especially during the later stages of the cultivation cycle. Nutrient limitation may reduce photosynthetic performance, thereby affecting carbon accumulation. Additionally, increases in moisture content, ash, and volatile matter in seaweed tissues with age contribute to a reduction in the proportion of carbon within the biomass. Other environmental factors, such as light intensity and temperature fluctuations, may also influence photosynthetic rates and carbon storage efficiency during later growth stages. Understanding these dynamics provides an important scientific basis for optimizing cultivation strategies to enhance carbon sequestration efficiency in seaweed.

When compared with carbon content in other seaweed types—such as seagrass (30–40%), *Laminaria* (25–31%), *Sargassum* (33–37%), *Ecklonia* (32–34%), and *Gelidium* (36–40%)—as reported by Muraoka (2004) in Japan, the results are not significantly different, despite those species being approximately one year old. This condition is likely influenced by environmental characteristics and species-specific traits, such as the relatively low ratio of fresh weight production to dry biomass.

Total Carbon Sequestration

The analysis results indicate that the total carbon uptake of the seaweed species *Kappaphycus alvarezii* cultivated using the longline method in the Bondo waters during the cultivation period reached 305.21 tons C per cultivation cycle (Table 3), or 1,831.27 tons C per year assuming six cultivation cycles annually. A study by Akmal & Putra (2009) reported that carbon uptake of *Kappaphycus alvarezii* in the Galesong waters, Takalar Regency, reached 219.12 tons C per cultivation cycle. This indicates that carbon uptake from seaweed cultivation in the Bondo waters, Jepara, is comparatively higher. This condition is likely attributed to higher cultivation productivity in Bondo waters compared to Galesong waters. This finding is further supported by monitoring results from the Technical Team of BBPBAP Jepara during June–August 2024, which concluded that at peak optimal production, the ratio between initial seedlings and final harvest increased significantly to 1:10 (tenfold from the initial biomass), whereas in Galesong waters the increase was only 2–3 times the initial biomass.

Carbon uptake is influenced by standing stock; as the biomass of seaweed increases, the level of carbon uptake correspondingly rises. This occurs because carbon uptake is strongly affected by standing stock and the production-to-biomass (P/B) ratio. In addition, carbon uptake is also influenced by environmental parameters and the growth rate of seaweed (Ho *et al.*, 2021; Jiang & Fang, 2021; Labbé *et al.*, 2024; Han *et al.*, 2025). According to Erlania *et al.* (2013), the estimation of carbon uptake in seaweed is affected by several factors, including species type, population density, as well as the duration and intensity of cultivation.

The findings of this study demonstrate that the cultivation of *Kappaphycus alvarezii* in the Bondo waters is capable of sequestering 1,831.27 tons C per year. When compared to global studies, this value is relatively competitive. For example, research conducted in Japan by Muraoka (2004) reported carbon uptake of *Ecklonia* sp. at 8.71 tons C per hectare per year, while *Sargassum* sp. and *Gelidium* sp. absorbed 4.04- and 0.89-tons C per hectare per year, respectively.

Other studies in Southeast Asia, such as in the Philippines and Vietnam, indicate that seaweed cultivation can sequester approximately 10 to 12 tons C per hectare per year. These differences in carbon uptake values highlight that cultivation methods, seaweed species, and local ecosystem conditions significantly influence carbon sequestration efficiency.

Globally, the carbon uptake capacity of *Kappaphycus alvarezii* observed in Bondo is above the average of various cultivated seaweed species. This presents substantial potential for positioning this species as part of international climate change mitigation strategies, particularly in the context of carbon trading and coastal ecosystem sustainability efforts.

However, to provide a more comprehensive understanding, further studies are required to compare the carbon sequestration capacity of *Kappaphycus alvarezii* with other species on a global scale, taking into account environmental factors, cultivation methods, and seasonal variability.

Estimated Carbon Sequestration Potential of *Kappaphycus alvarezii* in Bondo Waters

The results of this study indicate that the cultivation of *Kappaphycus alvarezii* in the Bondo waters possesses significant carbon sequestration potential. Under the existing

cultivation system, carbon sequestration was recorded at 152.60 tons C ha⁻¹ per cultivation cycle, or equivalent to 915.64 tons C ha⁻¹ yr⁻¹ assuming six cultivation cycles annually. This value reflects the high efficiency of the applied cultivation method, which optimizes biomass growth and carbon sequestration capacity throughout the cultivation period. When compared to carbon sequestration results in other regions, such as Galesong, Takalar, which averages 219.12 tons C per cultivation cycle on a smaller spatial scale, the potential in Bondo demonstrates higher performance, both at the individual and area scales.

Based on a feasibility assessment conducted by the Research Team of the Balai Besar Perikanan Budidaya Air Payau Jepara (BBPBAP Jepara) in 2021, the optimal area suitable for cultivating *Kappaphycus alvarezii* in the Bondo waters reaches 44.36 hectares. With this area, the estimated total carbon sequestration potential is approximately 40,617.79 tons C per year. This figure indicates that the intensive development of seaweed cultivation in this area could contribute substantially to global carbon emission reduction through blue carbon resource management. Furthermore, this carbon sequestration value also provides opportunities to integrate seaweed cultivation into carbon trading schemes, both at national and international levels.

This substantial carbon sequestration potential offers strategic opportunities for the development of sustainable coastal economies. By optimizing the use of cultivation areas and improving cultivation techniques, the Bondo region could serve as a model for blue carbon management in Indonesia's coastal zones. In addition, integrating this cultivation activity into environmental policies—such as the Nationally Determined Contribution (NDC) and Indonesia's net-zero emissions target by 2060—could strengthen the role of the fisheries sector in climate change mitigation. Further research is required to map environmental dynamics and assess the potential for scaling up cultivation to maximize both economic and ecological benefits. Thus, the Bondo waters have the potential not only to become a center of blue carbon production but also to contribute to global sustainability efforts.

The Relationship between Growth, Standing Stock, and P–B Ratio of *Kappaphycus alvarezii* and Carbon Sequestration

The Relationship between Growth and Carbon Sequestration

During the process of photosynthesis, seaweed utilizes sunlight to generate the energy required for its growth. This energy is also used to convert CO₂ into organic compounds that become part of the biomass. Therefore, faster biomass growth reflects an increased conversion of carbon into organic forms. This process supports the accumulation of carbon within seaweed biomass, thereby enhancing the carbon sequestration potential of seaweed cultivation systems (Zuldin *et al.*, 2016; Sato *et al.*, 2022; Kim, 2024).

Photosynthesis in seaweed not only functions to reduce carbon dioxide concentrations in aquatic environments but also contributes to balancing carbon levels between the atmosphere and the ocean. High biomass growth enables seaweed to absorb greater amounts of CO₂ from the water column. This leads to a reduction in dissolved carbon dioxide concentrations and contributes to climate change mitigation by lowering atmospheric CO₂ levels, which are a major driver of global warming (Duarte *et al.*, 2017).

A rapid biomass growth rate also enhances the efficiency of the system in sequestering carbon from aquatic environments. High productivity, reflected in elevated biomass growth rates, allows greater carbon accumulation within seaweed tissues. Substantial biomass accumulation increases carbon sequestration capacity, thereby supporting the sustainability of marine ecosystems. This process further accelerates climate change mitigation by reducing atmospheric CO₂ concentrations that contribute to global warming. With increased

productivity, seaweed can function as an efficient carbon sink (Fakhraini *et al.*, 2019; Kwon *et al.*, 2022; Ye *et al.*, 2024).

Referring to the capacity of seaweed to efficiently sequester carbon, the cultivation of species such as *Kappaphycus alvarezii* has strong potential as a nature-based solution to climate change. Increased seaweed biomass production can enhance carbon sequestration capacity in marine environments. Consequently, more carbon is retained within seaweed biomass and prevented from being released back into the atmosphere, thereby contributing to the reduction of excessive atmospheric CO₂ concentrations and supporting climate regulation.

Overall, accelerated biomass growth directly contributes to increased carbon sequestration, carrying significant implications for climate change mitigation. Seaweed cultivation not only provides economic benefits as a valuable natural resource but also plays a critical role in global carbon management. By enhancing carbon sequestration capacity, seaweed farming can support global efforts to reduce greenhouse gas emissions and address climate change challenges in a sustainable manner.

The Relationship between Standing Stock and Carbon Sequestration

Standing stock refers to the total accumulation of biomass within an ecosystem and represents a key parameter in assessing carbon sequestration capacity in seaweed cultivation systems (Mashoreng *et al.*, 2019; Gao *et al.*, 2022; Ould & Caldwell, 2022; Luo *et al.*, 2023). Conceptually, standing stock describes the amount of biomass present at a given point in time, encompassing all autotrophic organisms, including plants and algae. In the context of seaweed cultivation, standing stock specifically refers to the total biomass of seaweed present in the culture system at the time of measurement. Higher standing stock corresponds to a greater capacity of the system to sequester carbon through photosynthesis, thereby enhancing overall carbon sequestration in marine ecosystems.

Greater seaweed biomass implies increased carbon accumulation within plant tissues, derived from the conversion of dissolved carbon dioxide (CO₂) into organic compounds. As standing stock increases, the amount of carbon that can be sequestered and stored within seaweed biomass also rises. Previous studies, such as Duarte *et al.* (2017), demonstrate that seaweed cultivation systems with higher standing stock exhibit greater capacity for carbon sequestration and storage.

The carbon accumulated within biomass can be retained over extended periods, depending on environmental conditions and decomposition rates. When biomass is not rapidly degraded, the carbon stored in seaweed tissues can function as a long-term carbon reservoir within marine ecosystems. Therefore, high standing stock not only reflects high productivity but also contributes to sustained carbon sequestration over time.

Cultivation systems characterized by high standing stock indicate that seaweed grows efficiently, converting solar energy and available nutrients into biomass. Through photosynthesis, seaweed absorbs CO₂ from seawater and converts it into glucose and oxygen, which are subsequently utilized for growth and biomass formation. As environmental conditions—such as nutrient availability, temperature, salinity, and light intensity—remain optimal, seaweed continues to grow and sequester increasing amounts of carbon (Jiang *et al.*, 2016; Sondak *et al.*, 2017; Chen *et al.*, 2024; Luo *et al.*, 2024; Rukminasari *et al.*, 2024).

In relation to climate change, increasing standing stock has significant implications for reducing atmospheric CO₂ concentrations. Carbon sequestration through seaweed biomass accumulation acts as a natural carbon sink, lowering the amount of CO₂ released into the

atmosphere and thereby mitigating global warming. In this context, standing stock serves as a form of carbon storage that contributes to regulating the global carbon balance.

Seaweed systems with high standing stock also contribute directly to reducing greenhouse gas (GHG) concentrations. Studies by Duarte *et al.* (2017) and Faisan *et al.* (2024) indicate that higher biomass systems are more effective in reducing atmospheric CO₂ levels. Stable biomass accumulation supports carbon balance in marine ecosystems, which in turn influences global carbon cycling and climate regulation.

However, effective management of standing stock is essential to ensure optimal carbon sequestration performance. Factors such as nutrient management, stocking density, planting distance, and cultivation depth must be carefully regulated to maintain high productivity. Proper management enables seaweed cultivation systems to function as ecosystem-based solutions for improving global carbon balance.

Beyond ecological benefits, increasing standing stock also provides economic advantages for the seaweed industry. Higher biomass productivity enhances not only carbon sequestration capacity but also harvest yields, which can be utilized for valuable products such as carrageenan and agar. Thus, effective standing stock management supports both climate change mitigation and sustainable marine-based economic development.

Overall, standing stock is a critical parameter linking biomass productivity with carbon sequestration capacity in seaweed cultivation systems, particularly in species such as *Kappaphycus alvarezii*. Increasing standing stock contributes not only to reducing atmospheric carbon but also to maintaining long-term carbon storage within marine ecosystems. Therefore, understanding and managing standing stock effectively is essential for climate change mitigation strategies and sustainable aquaculture development.

The Relationship between P–B Ratio and Carbon Sequestration

The production-to-biomass (P–B) ratio serves as a highly relevant indicator for assessing the efficiency of photosynthesis in autotrophic organisms, including seaweeds such as *Kappaphycus alvarezii*. This ratio reflects the extent to which energy generated through photosynthesis is converted into biomass. A higher P–B ratio indicates greater efficiency in converting light energy into biomass, as well as enhanced capacity to fix carbon dioxide (CO₂) from aquatic environments into organic compounds stored within plant tissues.

Seaweed relies on photosynthesis to produce biomass, utilizing dissolved CO₂ in seawater to synthesize glucose. This glucose is subsequently used for growth and development. A higher P–B ratio suggests that a greater proportion of carbon is incorporated into biomass, which has direct implications for increased carbon sequestration capacity within marine ecosystems.

The P–B ratio is not solely determined by the intrinsic photosynthetic capacity of seaweed but is also strongly influenced by environmental factors. Variables such as light intensity, nutrient availability (particularly nitrogen and phosphorus), water temperature, and salinity play critical roles in regulating photosynthetic efficiency. For instance, increased light intensity can enhance photosynthetic rates, whereas nutrient limitation may constrain growth and metabolic efficiency, thereby reducing the P–B ratio.

Studies by Xiao *et al.* (2019) and Ginovart *et al.* (2023) demonstrate that seaweed cultivation systems receiving sufficient sunlight and optimal nutrient supply exhibit higher P–B ratios, resulting in greater biomass productivity. In the context of climate change mitigation, such systems are more effective in sequestering carbon and reducing CO₂ concentrations in both marine and atmospheric environments.

A high P–B ratio not only promotes seaweed growth but also enhances the capacity of seaweed to store carbon in biomass. Research by Duarte *et al.* (2017) highlights that efficient seaweed cultivation can play a significant role in climate change mitigation through carbon sequestration. The greater the amount of carbon retained within biomass, the lower the proportion of carbon released back into the atmosphere as greenhouse gases.

In the long term, this positions seaweed as an ecosystem-based solution for reducing atmospheric CO₂ concentrations. A high P–B ratio is directly associated with greater carbon-use efficiency, enabling seaweed to function as an effective carbon sink that contributes to mitigating global warming. The success of seaweed cultivation in carbon sequestration largely depends on the ability of these organisms to efficiently and sustainably utilize available environmental resources.

Given the importance of the P–B ratio in enhancing carbon sequestration capacity, it can be used as a practical indicator for managing and optimizing seaweed cultivation systems. By monitoring and improving the P–B ratio, researchers and practitioners can increase biomass productivity and, consequently, enhance the carbon sequestration potential of cultivation systems. Therefore, the P–B ratio represents a key metric in climate change mitigation strategies focused on sustainable natural resource management.

Overall, the P–B ratio plays a crucial role in improving photosynthetic efficiency and carbon sequestration in seaweed cultivation. Environmental factors influencing the P–B ratio also present opportunities to enhance productivity and carbon efficiency. A comprehensive understanding and effective management of the P–B ratio can thus facilitate the development of more efficient seaweed cultivation practices for climate change mitigation and long-term carbon sequestration.

Water Quality

The relationship between carbon sequestration rate, seaweed growth rate, and environmental parameters determines the success of seaweed cultivation, particularly water quality as the primary medium directly influencing growth. These results indicate that carbon sequestration by seaweed is directly associated with internal factors, such as daily growth rate, as well as external factors, including water quality conditions. The analysis of water quality parameters during the study period is presented in Table 7.

Water Transparency

The water transparency values recorded during the study ranged from 1.50 to 3.00 meters, indicating highly favorable conditions for optimal seaweed growth (Table 7). High transparency allows light penetration to reach the bottom of the cultivation area, thereby supporting maximum photosynthesis. According to the Directorate General of Aquaculture (2006), suitable water transparency for the growth and survival of aquatic organisms is greater than 45 cm. Low transparency is generally associated with high turbidity caused by dissolved and suspended organic matter, floating particles, and reduced light intensity.

Good water transparency enhances the photosynthetic process in seaweed. When light penetrates deeper into the water column, seaweed can perform photosynthesis more efficiently. Photosynthesis is the process of carbohydrate synthesis using solar energy, involving complex reactions and multiple macro- and micro-molecules. One of the key reactions in this process is the formation of carbohydrates (monosaccharides) through the reduction of CO₂, utilizing ATP and NADPH generated during the light-dependent reactions (Nickelsen, 2012; Kluge *et al.*, 2015).

pH

The average pH values recorded during the study ranged from 7.25 to 8.20 (Table 7). According to Cahyanurani & Ummah (2020), the optimal pH range for seaweed cultivation lies between 7.0 and 8.5. When seawater pH falls below 7, increased acidity reduces the availability of carbonate and bicarbonate ions, which are essential for seaweed to perform photosynthesis and to form carbon-based structural components. Under such conditions, both growth and carbon sequestration in seaweed may be inhibited.

Conversely, when seawater pH exceeds 8.5, carbonate and bicarbonate concentrations may become excessive. This condition can lead to the precipitation of carbonate minerals on the surface of seaweed, potentially obstructing photosynthesis and inhibiting growth. The observed pH range in this study likely falls within the optimal range for seaweed growth (7.5–8.5), and thus does not significantly affect standing stock. However, in cases of extreme pH decline due to ocean acidification, reductions in photosynthetic efficiency and potential tissue damage may occur (Hurd *et al.*, 2014; El-Manaway & Rashedy, 2022).

Salinity

The results indicate that salinity values during the study ranged from 29.00 to 32.00 ppt (Table 7). Most seaweed species can grow optimally within a salinity range of 25–35 ppt (parts per thousand). According to Patty *et al.* (2015), excessively high salinity may reduce nutrient availability and inhibit the rate of photosynthesis in seaweed. Conversely, low salinity conditions can impair the ability of seaweed to absorb nutrients and dissolved carbon dioxide from seawater, thereby reducing growth rates and the production of organic carbon. Seaweed exposed to salinity levels that are too high or too low may experience physiological stress, increasing the risk of tissue damage and reducing photosynthetic efficiency as well as carbon sequestration capacity. The species *Kappaphycus alvarezii* exhibits a relatively wide salinity tolerance range, approximately 30–35 ppt (Hayashi *et al.*, 2011; Siddiqui *et al.*, 2022, 2024). Since the salinity values observed during this study fall within or close to this optimal range, their effect on standing stock is likely minimal. However, extreme salinity fluctuations (>38 ppt or <25 ppt) may induce osmotic stress, which can ultimately inhibit growth and biomass accumulation.

Temperature

The results indicate that water temperature during the seaweed cultivation period ranged from 28°C to 29°C (Table 7). According to Darmawati *et al.* (2016), the optimal temperature for seaweed cultivation is within the range of 28°C to 30°C. These findings suggest that the cultivation of *Kappaphycus alvarezii* in the Bondo waters was conducted under optimal thermal conditions for growth. Rapid or extreme fluctuations in temperature can adversely affect the ability of seaweed to acclimate and adapt to environmental changes. Such conditions may disrupt photosynthesis and carbon sequestration processes, ultimately influencing growth and productivity. *Kappaphycus alvarezii* exhibits an optimal temperature tolerance range of approximately 25–30°C (Araújo *et al.*, 2014; Li *et al.*, 2016a, b, 2019; Terada *et al.*, 2016; Azizi *et al.*, 2018). When temperature remains within this range, its effect on standing stock is minimal. However, temperatures outside this range—such as excessively high (>32°C) or low (<20°C)—may inhibit growth and reduce biomass accumulation.

Nitrate

The results indicate that nitrate concentrations in the waters during the seaweed cultivation period ranged from 0.18 to 0.54 mg L⁻¹ (Table 7). According to Cahyanurani & Ummah (2020), the optimal nitrate concentration required for seaweed growth ranges from 0.9 to 3.5 mg L⁻¹. This suggests that nitrate levels in the Bondo waters during the cultivation

period were suboptimal. Nitrate concentrations in aquatic systems are influenced by several factors, including water sources, fertilization practices, maintenance of water quality, and biological interactions. According to Pauwah *et al.* (2020), low nitrate availability in seawater can limit seaweed growth and organic carbon production, as seaweed requires sufficient nitrogen for photosynthesis and metabolic processes. Insufficient nitrogen availability can therefore reduce biomass accumulation and carbon sequestration capacity. Conversely, excessively high nitrate concentrations may also negatively affect carbon sequestration in seaweed, as they can stimulate excessive growth while reducing carbon-use efficiency. Under such conditions, the imbalance between nutrient availability and carbon assimilation may limit the effectiveness of carbon sequestration within the biomass.

Phosphate

The results indicate that phosphate concentration during the study was 0.029 mg L⁻¹ (Table 7). When compared with established standards, this suggests that phosphate levels in the Bondo waters were suboptimal, despite phosphate being an essential nutrient for seaweed growth. According to Cahyanurani & Ummah (2020), the optimal phosphate concentration for seaweed cultivation ranges from 0.2 to 1.0 mg. Low phosphate availability can limit metabolic processes, including photosynthesis and biomass formation, thereby reducing growth performance and carbon sequestration capacity. According to Pauwah *et al.* (2020), one of the primary causes of low phosphate concentrations is the limited input of nutrients from terrestrial sources, which reduces nutrient availability in coastal waters.

Relationship between Water Quality and Standing Stock, P–B Ratio, and Carbon Sequestration

The Relationship between Water Quality and Standing Stock

The regression analysis indicates that water current and water transparency have significant effects on standing stock ($p < 0.05$). However, the direction of their influence differs. Water current shows a positive effect, indicating that increased current velocity enhances the standing stock of *Kappaphycus alvarezii*. In contrast, water transparency exhibits a negative effect, suggesting that higher water clarity may reduce standing stock. This phenomenon may be associated with excessive light intensity, which can affect photosynthesis or increase environmental stress on seaweed growth. Other water quality parameters, such as temperature, pH, and salinity, do not show significant relationships ($p > 0.05$) with standing stock (Table 8).

Seaweed cultivation of *Kappaphycus alvarezii* demonstrates significant potential for climate change mitigation through carbon sequestration mechanisms. This study evaluates environmental factors, particularly water quality, that influence standing stock and its relationship with photosynthetic efficiency as the primary pathway for organic carbon storage. The regression results confirm that water current positively affects biomass accumulation, whereas high water transparency negatively impacts seaweed growth.

Increased water current enhances nutrient availability (nitrate and phosphate), reduces sediment accumulation and biofouling, and improves gas exchange efficiency, all of which contribute to higher photosynthetic rates and biomass production (Hayashi *et al.*, 2010; Inoue *et al.*, 2020; James *et al.*, 2022; Rakhasiya *et al.*, 2024). Conversely, high water transparency can increase the risk of photoinhibition due to excessive solar radiation, induce physiological stress from ultraviolet exposure, and reduce nutrient availability, thereby negatively affecting standing stock (Zheng & Gao, 2009; Cabello-Pasini *et al.*, 2011; Xiao *et al.*, 2015; Pereira *et al.*, 2018; Polo & Chow, 2022).

Table 8. Results of Multivariate Regression Analysis of Water Quality on Standing Stock

Dependent Variables	Coefficient (B)	T-statistic	Sig. (p-value)	Note
(X1) Temperature (°C)	76.187	1.069	0.345	Non significant
(X2) pH	-118.219	-1.175	0.305	Non significant
(X3) Salinity (ppt)	-35.781	-0.754	0.493	Non significant
(X4) Transparency (cm)	-976.969	-2.840	0.047*	Significant*
(X5) Current velocity (cm/s)	237.344	4.171	0.014**	Significant**
Constant (Intercept)	-2539.562	-0.913	0.413	
R ²	0.946	-	-	
Adjusted R ²	0.878	-	-	
F-statistic	13.909	-	0.012**	Model significant**

In addition to water current and transparency, parameters such as temperature, pH, and salinity did not show significant effects on the standing stock of *Kappaphycus alvarezii* within the observed ranges. This indicates that as long as these parameters remain within their optimal tolerance ranges (temperature 25–30°C, pH 7.5–8.5, and salinity 30–35 ppt), their variability is insufficient to substantially influence seaweed growth (Pickering, 2006; Kite-Powell *et al.*, 2022). However, under extreme conditions—such as temperature increases above 32°C or significant salinity fluctuations—osmotic stress and reduced efficiency of photosynthesis may occur, thereby inhibiting biomass accumulation and carbon sequestration capacity. Therefore, continuous monitoring of environmental parameters is essential to enhance the potential of seaweed cultivation ecosystems as a nature-based solution for climate change mitigation.

The findings of this study confirm that water current and water transparency are key determinants of biomass productivity in *Kappaphycus alvarezii*, with direct implications for carbon sequestration capacity in aquatic ecosystems. Higher current velocity can be optimized through cultivation strategies that prioritize locations with good water circulation. Meanwhile, the negative effects of excessive water transparency can be mitigated by adjusting cultivation depth or implementing protective systems against ultraviolet radiation.

A deeper understanding of the interactions between environmental factors and seaweed productivity enables the development of ecosystem-based cultivation approaches that simultaneously enhance economic benefits and support blue carbon mitigation strategies. Further research is therefore required to quantitatively assess carbon sequestration capacity across different cultivation systems and to evaluate their long-term effectiveness in carbon storage.

Relationship between NO₃ and PO₄ Concentrations and Standing Stock

The regression analysis indicates that both NO₃ (nitrate) and PO₄ (phosphate) exert significant effects on standing stock (Sig < 0.05; Table 9) in *Kappaphycus alvarezii* cultivation systems. However, their directions of influence differ. Nitrate (NO₃) shows a positive effect, indicating that increased nitrate concentrations support higher seaweed biomass. This finding is consistent with the role of nitrate as a primary nitrogen source required for macroalgal growth, particularly in supporting protein synthesis and metabolic processes associated with photosynthesis. In contrast, phosphate (PO₄) exhibits a negative effect on standing stock, suggesting that higher phosphate concentrations may inhibit seaweed growth. This

phenomenon may be attributed to imbalances in the nitrogen-to-phosphorus (N:P) ratio in the aquatic environment, which can disrupt nutrient uptake efficiency. Additionally, elevated phosphate levels may stimulate the proliferation of microalgae, leading to increased competition for nutrients and light, thereby reducing the growth performance of seaweed. These findings highlight the importance of maintaining balanced nutrient conditions in seaweed cultivation systems. While sufficient nitrogen availability enhances biomass accumulation, excessive phosphate without proportional nitrogen supply may negatively impact standing stock. Therefore, nutrient management—particularly the regulation of N:P ratios—is crucial for optimizing biomass production and supporting efficient carbon sequestration in *Kappaphycus alvarezii* cultivation.

Table 9. Regression Analysis of Nitrate (NO₃) and Phosphate (PO₄) Concentrations on Standing Stock

Independent Variables	Coefficient (B)	T-statistic	Sig. (p-value)	Note
(X1) Nitrate (mg/L)	1189.027	4.190	0.004**	Significant
(X2) Phosphate (mg/L)	-80379.631	-2.800	0.027*	Significant
Constant (Intercept)	2365.550	2.931	0.022*	
R ²	0.872			
Adjusted R ²	0.835			
F-statistic	23.813		0.001**	

Nitrate (NO₃⁻) and phosphate (PO₄³⁻) are essential nutrients that play distinct roles in regulating the growth of *Kappaphycus alvarezii*. The results of this study indicate that increasing nitrate concentrations are positively correlated with standing stock, suggesting that greater nitrogen availability enhances protein synthesis, chlorophyll formation, and photosynthesis activity, ultimately leading to higher seaweed biomass (Falkowski & Raven, 2007). As a primary source of dissolved nitrogen, nitrate supports macroalgal metabolism by supplying key elements required for amino acid synthesis and biochemical processes associated with vegetative growth (McGlathery *et al.*, 2007). However, nitrate limitation is often a major constraint in tropical and subtropical aquatic ecosystems, potentially reducing seaweed productivity and carbon sequestration capacity (Hurd *et al.*, 2014; El-Manaway & Rashedy, 2022). Therefore, sufficient nitrate availability is critical for enhancing biomass production in *Kappaphycus alvarezii*, thereby contributing to climate change mitigation through blue carbon mechanisms.

In contrast, phosphate exhibits a negative influence on standing stock, primarily due to imbalances in the nitrogen-to-phosphorus (N:P) ratio, competition with microalgae, and potential toxicity at elevated concentrations. Nutrient imbalance resulting from excessive phosphate can reduce photosynthetic efficiency by limiting nitrogen availability required for protein and chlorophyll synthesis (Güsewell, 2005; Hidaka & Kitayama, 2013; Singh *et al.*, 2013; Singh & Reddy, 2014; Yan *et al.*, 2015; Mao *et al.*, 2018; Netzer *et al.*, 2019; Liu *et al.*, 2024; Xing *et al.*, 2024). Additionally, high phosphate levels may stimulate blooms of phytoplankton and epiphytic microalgae, which compete with seaweed for nutrients and reduce light penetration necessary for photosynthesis (Flöder *et al.*, 2006; Pasternak *et al.*, 2009; Zaldívar *et al.*, 2009; Zhang *et al.*, 2015; Wei, 2024).

Excessive phosphate concentrations may also disrupt cellular metabolism and osmotic balance, thereby reducing productivity and carbon sequestration efficiency (Xu *et al.*, 2010; Martins *et al.*, 2011; Yagisawa *et al.*, 2016; Suthar *et al.*, 2019). Therefore, maintaining a

balanced ratio of nitrate to phosphate is essential in seaweed cultivation systems to ensure optimal growth of *Kappaphycus alvarezii* and to maximize carbon sequestration.

The Relationship between Water Quality and the P–B Ratio

The production-to-biomass (P–B) ratio represents an important indicator of energy conversion efficiency in seaweed cultivation systems. Analysis of *Kappaphycus alvarezii* shows that most water quality parameters—such as temperature, pH, salinity, and water transparency—do not have a significant effect on the P–B ratio ($p > 0.05$) (Table 10). This suggests that fluctuations within the tolerance range of the species are not sufficiently strong to influence productivity efficiency relative to total biomass.

However, water current demonstrates a significant positive effect on the P–B ratio ($p < 0.05$), indicating that optimal current velocity can enhance growth rates without causing excessive biomass accumulation. Stronger currents improve the distribution and availability of essential nutrients, such as nitrate and phosphate, which are required for photosynthesis and metabolic activity, thereby increasing biomass production while maintaining high photosynthetic efficiency (Falkowski & Raven, 2007).

In addition, increased water movement reduces the accumulation of sediments and biofouling on seaweed surfaces, which can otherwise limit light absorption. By maintaining cleaner thallus surfaces and improving light penetration, water currents further support optimal productivity and enhance the efficiency of biomass production (Hurd *et al.*, 2014).

Table 10. Results of Multivariate Regression Analysis of Water Quality on the P–B Ratio

Independent Variables	Coefficient (B)	T-statistic	Sig. (p-value)	Note
(X1) Temperature (°C)	9.260	2.116	0.102	Not significant
(X2) pH	-0.526	-0.085	0.936	Not significant
(X3) Salinity (ppt)	-1.307	-0.449	0.677	Not significant
(X4) Transparency (cm)	-32.068	-1.519	0.203	Not significant
(X5) Current velocity (cm/s)	9.089	2.602	0.060	Not significant
Constant (Intercept)	-310.281	-1.817	0.143	Not significant
R ²	0.921			
Adjusted R ²	0.823	-	-	
F-statistic	9.349	-	0.025*	Model significant

Although other water quality parameters do not show a significant effect on the P–B ratio, environmental stability remains a critical factor in maintaining the productivity of *Kappaphycus alvarezii*. Within the optimal temperature range of 25–30°C, seaweed is able to sustain efficient photosynthesis, and thus temperature fluctuations within this range do not significantly influence the P–B ratio (McGlathery *et al.*, 2007). Similarly, variations in pH and salinity within the tolerance limits of the species do not substantially affect productivity efficiency relative to total biomass.

In contrast, studies indicate that sufficiently strong water currents enhance gas exchange processes, particularly the diffusion of carbon dioxide (CO₂) and oxygen (O₂), which are essential for photosynthesis and metabolic activity (Han *et al.*, 2020; Khorobrykh *et al.*, 2020; Foyer & Hanke, 2022; Xiong *et al.*, 2024). Improved gas exchange supports higher photosynthetic efficiency and contributes to increased biomass production.

Therefore, in *Kappaphycus alvarezii* cultivation systems, water current management emerges as a key factor in enhancing productivity. This can be complemented by effective nutrient management strategies to further improve carbon sequestration capacity and support climate change mitigation through blue carbon mechanisms.

Relationship between Nitrate and Phosphate and the P–B Ratio

The results indicate that nitrate (NO_3^-) concentration has a significant effect on the P–B ratio ($p < 0.05$), suggesting that increased nitrogen availability enhances seaweed productivity relative to total biomass (Table 11). In *Kappaphycus alvarezii*, nitrogen plays a fundamental role in metabolic processes, as it is required for the synthesis of proteins, chlorophyll, and essential enzymes that support photosynthesis (Falkowski & Raven, 2007).

With sufficient NO_3^- availability, seaweed can improve photosynthetic efficiency, leading to accelerated growth rates without a proportional increase in total biomass. This results in a higher P–B ratio, indicating more efficient energy conversion within the cultivation system. This finding aligns with the limiting nutrient theory, which states that the growth of photosynthetic organisms is often constrained by nitrogen availability in tropical and subtropical aquatic ecosystems (McGlathery *et al.*, 2007).

In cultivation systems, increased nitrogen input typically leads to greater improvements in productivity compared to total biomass accumulation, thereby directly enhancing the P–B ratio and overall energy conversion efficiency in aquatic environments.

Table 11. Regression Analysis of Nitrate (NO_3^-) and Phosphate (PO_4^{3-}) Concentrations on the P–B Ratio

Independent Variables	Coefficient (B)	T-statistic	Sig. (p-value)	Note
(X1) Nitrate (mg/L)	87.830	6.082	0.000**	Significant
(X2) Phosphate (mg/L)	-1066.238	-0.828	0.435	Not significant
Constant (Intercept)	31.549	0.923	0.387	
R ²	0.841	-	-	
Adjusted R ²	0.796	-	-	
F-statistic	18.536	-	0.002**	Model significant

In contrast, phosphate (PO_4^{3-}) does not exhibit a significant effect on the P–B ratio ($p > 0.05$), indicating that increased phosphate availability does not necessarily enhance the productivity of *Kappaphycus alvarezii*. Although phosphate plays a role in ATP formation and nucleic acid synthesis, nitrogen is more frequently the primary limiting nutrient in tropical aquatic ecosystems (Duarte *et al.*, 2017). Previous studies have shown that phosphate enrichment in cultivation systems does not always lead to increased productivity, as phosphate becomes effective only when sufficient nitrogen is available to support photosynthesis (McGlathery *et al.*, 2007).

Therefore, nutrient management strategies in seaweed cultivation should prioritize maintaining a balanced nitrogen-to-phosphorus (N:P) ratio to optimize the P–B ratio. In the context of climate change mitigation, effective nitrogen management in cultivation waters is a key factor in enhancing carbon sequestration capacity and supporting the sustainability of blue carbon-based aquaculture systems.

The Relationship between Water Quality and Carbon Sequestration

Water quality—particularly water current and transparency—plays a crucial role in determining the carbon sequestration capacity of *Kappaphycus alvarezii*. The analysis

indicates that water current has a significant positive effect on carbon sequestration ($p < 0.05$), whereas water transparency shows a negative effect.

Stronger water currents enhance nutrient distribution and reduce sediment accumulation around seaweed thalli, thereby supporting efficient photosynthesis and biomass growth (Hurd *et al.*, 2014). In addition, increased current velocity improves gas exchange, including the availability of carbon dioxide (CO₂), which is essential for photosynthesis. This contributes directly to higher carbon sequestration rates. Therefore, selecting cultivation sites with optimal hydrodynamic conditions represents an effective strategy to enhance both productivity and carbon sequestration capacity, supporting climate change mitigation through blue carbon mechanisms (Duarte *et al.*, 2017).

Conversely, excessively high water transparency may inhibit carbon sequestration due to photoinhibition, where excessive light intensity damages the photosynthetic system of *Kappaphycus alvarezii*, thereby reducing CO₂ assimilation efficiency (Han *et al.*, 2020; Khorobrykh *et al.*, 2020; Foyer & Hanke, 2022; Xiong *et al.*, 2024). High transparency also allows deeper penetration of solar radiation, increasing the risk of oxidative stress that can damage seaweed tissues.

Accordingly, effective water quality management—including controlling water clarity through appropriate cultivation techniques—is necessary to optimize carbon sequestration potential. In conclusion, by regulating water current and transparency within cultivation systems, photosynthetic efficiency and carbon sequestration capacity of *Kappaphycus alvarezii* can be significantly enhanced, reinforcing the role of seaweed aquaculture as an ecosystem-based solution for climate change mitigation.

Table 12. Results of Multivariate Regression Analysis of Water Quality on Carbon Sequestration

Independent Variables	Coefficient (B)	T-statistic	Sig. (p-value)	Note
(X1) Temperature (°C)	28.854	1.308	0.261	Not significant
(X2) pH	-41.885	-1.346	0.250	Not significant
(X3) Salinity (ppt)	-17.448	-1.188	0.301	Not significant
(X4) Transparency (cm)	-348.302	-3.273	0.031*	Significant
(X5) Current velocity (cm/s)	81.010	4.602	0.010**	Significant
Constant (Intercept)	-783.562	-0.911	0.414	
R ²	0.950	-	-	
Adjusted R ²	0.888	-	-	
F-statistic	15.267	-	0.010**	Model significant**

Relationship between Nitrate and Phosphate and Carbon Sequestration

Carbon sequestration by *Kappaphycus alvarezii* is influenced by multiple environmental factors, including the availability of nutrients such as nitrate (NO₃⁻) and phosphate (PO₄³⁻). The results of this study indicate that nitrate has a significant effect on carbon sequestration ($p < 0.05$), whereas phosphate does not show a significant relationship ($p > 0.05$) (Table 13).

Nitrate plays a crucial role in photosynthesis, as it is a key component in the synthesis of proteins and chlorophyll, which directly contribute to the efficiency of carbon sequestration through the conversion of carbon dioxide (CO₂) into biomass (Hurd *et al.*, 2014). Increased

NO_3^- concentrations in the water column enhance photosynthetic productivity in *Kappaphycus alvarezii*, thereby directly increasing carbon sequestration capacity.

This finding is consistent with the limiting nutrient theory, which states that nitrogen availability often acts as the primary constraint on the growth of photosynthetic organisms in tropical and subtropical aquatic ecosystems (McGlathery *et al.*, 2007). Therefore, optimizing nitrogen availability within cultivation systems is essential to enhance carbon sequestration potential, positioning *Kappaphycus alvarezii* as a key component in blue carbon-based climate change mitigation strategies.

Table 13. Regression Analysis of Nitrate And Phosphate Concentrations on Carbon Sequestration

Independent Variables	Coefficient (B)	T-statistic	Sig. (p-value)	Note
(X1) Nitrate (mg/L)	550.849	6.296	0.154	Not significant
(X2) Phosphate (mg/L)	-12448.833	-1.597	0.000**	Significant
Constant (Intercept)	339.390	1.629	0.147	
R ²	0.852	-	-	
Adjusted R ²	0.809	-	-	
F-statistic	20.080	-	0.001**	Model significant

In contrast, phosphate (PO_4^{3-}) does not exhibit a significant effect on carbon sequestration by *Kappaphycus alvarezii*. Although phosphate is an essential nutrient involved in cellular metabolism and ATP synthesis, its role in supporting carbon sequestration is more limited compared to nitrate.

High phosphate availability in aquatic ecosystems is often associated with increased growth of microalgae and phytoplankton, which may compete with *Kappaphycus alvarezii* for nutrients and light, thereby reducing the efficiency of photosynthesis (McGlathery *et al.*, 2007). Furthermore, previous studies indicate that in systems with high phosphate but limited nitrogen availability, seaweed growth remains constrained, as nitrogen is the primary limiting factor for biomass productivity (Duarte *et al.*, 2017).

Therefore, nutrient management strategies in seaweed cultivation should prioritize nitrogen availability rather than solely increasing phosphate concentrations. By maintaining a balanced ratio of NO_3^- and PO_4^{3-} , cultivation systems can be optimized to enhance carbon sequestration capacity, thereby strengthening the role of aquaculture as an ecosystem-based solution for climate change mitigation.

Regulation Impact

This study provides significant contributions to climate change mitigation efforts and the sustainable management of coastal resources. One of the primary implications is the potential integration of *Kappaphycus alvarezii* cultivation into national and international carbon trading schemes. With empirical data on carbon sequestration capacity, seaweed farming can be incorporated into carbon reduction initiatives while simultaneously providing economic incentives for local farmers through carbon credits. This approach not only supports Indonesia's net-zero emissions target by 2060 but also strengthens the country's position in global blue carbon initiatives.

In addition, the findings support the development of blue economy policies that prioritize environmentally sustainable economic growth. Seaweed cultivation can serve as a key component in marine and fisheries development programs by strategically utilizing coastal

resources. Information on carbon sequestration potential can also assist local governments in identifying and managing coastal zones more efficiently, preventing land-use conflicts, and improving resource allocation.

These policy implications are expected to deliver not only environmental benefits but also socio-economic advantages, including job creation and improved livelihoods for coastal communities. Consequently, seaweed cultivation represents a comprehensive sustainability solution that integrates climate mitigation, ecosystem management, and economic development within coastal regions.

Integrated Coastal Development Strategy for the Bondo Area

The development of the Bondo coastal area requires an integrated approach that aligns the presence of the PT. Bhumi Jati Power power plant with the marine and fisheries sector, particularly the cultivation of *Kappaphycus alvarezii*. As one of the major carbon emission sources in the Bondo coastal area—estimated at 6,762,690 tons C per year (EIA of PT. Bhumi Jati Power, 2016)—the Tanjung Jati B power plant holds both responsibility and strategic opportunity to contribute to climate change mitigation through partnerships within the blue economy framework.

In this context, seaweed cultivation of *Kappaphycus alvarezii* can be integrated as a carbon mitigation strategy through blue carbon management. With an estimated carbon sequestration potential of 40,617.79 tons C per year, seaweed farming in the Bondo waters contributes approximately 0.6% of the greenhouse gas emissions generated by PT. Bhumi Jati Power. However, this contribution can be significantly enhanced by expanding cultivation areas in waters surrounding the power plant that are deemed suitable for seaweed farming. Therefore, conducting feasibility assessments for aquaculture site expansion in these areas is essential.

Beyond its role in carbon sequestration, seaweed cultivation also provides substantial economic benefits for coastal communities, thereby helping to offset the environmental impacts of industrial activities. In 2024, approximately 20 seaweed farming households operated in the Bondo waters, producing around 60 tons of dried seaweed annually, with a market price of IDR 14,000 per kg and a total economic value of approximately IDR 840 million per year. This value has strong potential for growth, particularly with the expansion of cultivation areas, which are estimated to reach up to 278 hectares (Jepara Fisheries Office, 2024).

This integrated approach requires collaboration among PT. Bhumi Jati Power, local governments, and coastal farming communities to establish a sustainable synergy. The power plant can contribute through financial support, technological innovation, and capacity-building programs to improve cultivation efficiency, as well as facilitate access to domestic and international markets. In parallel, carbon sequestration data generated from seaweed cultivation can support carbon trading initiatives promoted by the company as part of its sustainability commitments.

Such a strategy offers both ecological and socio-economic benefits, where carbon emission reduction aligns with improved livelihoods for coastal communities. By leveraging the potential of *Kappaphycus alvarezii* as a key blue carbon resource, the Bondo coastal area can serve as a model for sustainable coastal development. This approach also supports Indonesia's net-zero emissions target by 2060 and strengthens the implementation of blue economy programs to enhance the global competitiveness of the country's marine sector.

Ultimately, this integration establishes a comprehensive framework that balances local economic development, environmental conservation, and industrial responsibility—

positioning the Bondo coastal area as a center of sustainability innovation with tangible benefits for all stakeholders involved.

CONCLUSION

1. This study demonstrates that the cultivation of *Kappaphycus alvarezii* in the Bondo waters can sequester 305.21 tons C per cultivation cycle, equivalent to 1,831.27 tons C per year, with an optimal carbon sequestration potential of up to 40,617.79 tons C per year. The carbon content of the seaweed reached its highest value of 43.68% at 28 days of cultivation, but declined with increasing cultivation age.
2. The policy implications of these findings are highly significant, particularly in supporting Indonesia's carbon emission reduction targets through the development of the blue carbon sector. The results provide a scientific basis for integrating seaweed cultivation into international carbon trading systems and for promoting sustainable coastal management.
3. This study also highlights opportunities for collaboration between the private sector and government in supporting blue economy programs, which can generate substantial economic and social benefits for coastal communities.
4. However, this study has limitations, particularly related to the site-specific nature of the research in the Bondo waters and the limited exploration of seasonal variability. Therefore, further research is required, including long-term studies and investigations across different locations or seaweed species, to provide more comprehensive and generalizable data.

ACKNOWLEDGEMENT

The authors would like to express their sincere gratitude to the management of PT. Bhumi Jati Power for financial support of this research through the cooperation agreement entitled "Service Agreement for Feasibility Study of Seaweed Cultivation Program" (Contract No.: C-BJP-21-0024-CSR) between PT. Bhumi Jati Power and Balai Besar Perikanan Budidaya Air Payau Jepara in 2022.

The authors also extend their appreciation to the technicians and laboratory staff at the Physical Chemistry Laboratory of Balai Besar Perikanan Budidaya Air Payau Jepara and the Nutrition Laboratory of Balai Perikanan Budidaya Air Payau Situbondo for their valuable assistance both in fieldwork and laboratory analysis.

The authors would also like to express their gratitude to the Head of for the support provided to the research team during the implementation of this collaborative research project.

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