Jurnal Manajemen Hutan Tropika, *31*(1), 25–33, January 2025
EISSN: 2089-2063
DOI: 10.7226/jtfm.31.1.25

Scientific Article
ISSN: 2087-0469

Avicennia alba, an Additional Potential Carbon Sequester in Mangrove Ecosystems

Nur Hasyimah Ramli[1], Nursyazni Abdul Rahim[1], Nur Azimah Osman[1], Norrizah Jaafar Sidik[2], Nabilah Mawi[1], Nor Bazilah Razali[4], Farah Ayuni Farinordin[3*]

[1]Pusat Pengajian Sains, Fakulti Sains Gunaan, Universiti Teknologi MARA Cawangan Negeri Sembilan, Kampus Kuala Pilah, Kuala Pilah, Negeri Sembilan, Malaysia 72000
[2]Fakulti Sains Gunaan, Blok C, Kompleks Sains 2, Universiti Teknologi MARA, Shah Alam, Selangor, Malaysia 40450
[3]Pusat Pengajian Sains, Fakulti Sains Gunaan, Universiti Teknologi MARA Cawangan Pahang, Kampus Jengka, Bandar Tun Abdul Razak Jengka, Pahang, Malaysia 26400
[4]Bahagian Perubahan Iklim, Pusat Gas Rumah Kaca Kebangsaan, Kementerian Sumber Asli dan Kelestarian Alam, Blok F11, Kompleks F, Presint 1, Pusat Pentadbiran Kerajaan Persekutuan, Wilayah Persekutuan Putrajaya, Malaysia 62000

Received September 14, 2024/Accepted December 25, 2024

Abstract

Mangrove forests have exceptional carbon sequestration capacity for mitigating climate change impacts. Increased atmospheric CO_2 *can accelerate crop growth, improve water-use efficiency, and disrupt soil-plant balance. The performance of Avicennia alba in terms of morphometrics and biomass under environmental stresses such as elevated* CO_2 *was poorly understood. Thus, this study aims to determine the growth response and survivability of A. alba by examining height, leaf number, and growth rate under elevated* CO_2 *in the early stages of development. A number of 120 seed samples of A. alba was divided into two groups; 60 germinated seeds were placed in a* CO_2 *incubator and 60 in a shade house as a control. The growth rate, plant height, leaf number, and mortality were compared between the two groups and statistical analyses were conducted. The treated seedlings exhibited significantly greater mean height (11.98 ± 1.09 cm), improved growth rates (1.09 ± 0.76 vs. 1.07 ± 0.46), and higher survivability (*$U = 1470$*, p-value < 0.05). There is a significant positive relationship between height and number of leaves (*$\beta = 0.298$*,* $R^2 = 0.535$*, p-value < 0.001), indicating that taller seedlings tend to produce more leaves. A comprehensive understanding of the balance between enhanced growth and reduced leaf production under elevated* CO_2 *levels provides valuable insights into how plants may adapt or respond to changing environmental conditions in future climate change scenarios.*

Keywords: *blue carbon, climate change, elevated* CO_2*, growth rate*

**Correspondence author, email*: *farahayuni2506@uitm.edu.my, tel. +609-4602273*

Introduction

Climate change, driven by the unprecedented rise in greenhouse gas emissions from human activities, poses a significant global challenge. In response, forest-based natural climate solutions have garnered increasing attention as a vital means of achieving the carbon reduction targets outlined in the 2015 Paris Agreement (Griscom et al., 2020; Andrea, 2022). Among these solutions, "blue carbon ecosystems"—which include mangrove forests, tidal marshes, and seagrass beds—are particularly important due to their exceptional carbon sequestration capacity per unit area (Lovelock & Duarte, 2019; Gu et al., 2023). Mangroves, known for their remarkable ability to store carbon both in their biomass and sediments, have been identified as a key, self-sustaining, forest-based strategy to mitigate the impacts of global climate change (Atwood et al., 2017; Gu et al., 2023).

Mangroves are salt-tolerant species that thrive in the intertidal zones between terrestrial and marine environments along tropical and subtropical coastlines (Khairnar et al., 2013; Pratolongo, 2022). These ecosystems support a wide array of marine species, contributing to rich biodiversity, and provide numerous benefits to human communities, including enhanced fisheries, ecotourism opportunities, coastal protection, and significant carbon storage (Worthington et al., 2020; Seary et al., 2021; Basyuni et al., 2022). However, despite their potential, efforts to restore and manage mangroves have often been hindered by a lack of expertise, particularly in the areas of species selection and site suitability, leading to frequent failures in rehabilitation initiatives (De Rezende et al., 2015; Lovelock et al., 2022).

The effects of increased atmospheric CO_2 on the growth of mangroves have been largely explored, and existing evidence suggests that not all mangrove species will respond in the same way (Gu et al., 2023). While elevated CO_2 can accelerate the growth of trees, pastures, and crops, it also enhances water-use efficiency, which could potentially disrupt the soil-plant water balance in areas with saline groundwater (Ball & Munns, 1992; Liang et al., 2022). However, recent studies have provided better insights into these dynamics. Arifanti (2020) found that certain mangrove species may experience enhanced productivity under higher atmospheric CO_2 levels, leading to increased biomass, larger stems, and leaves with greater surface area. These effects are associated with higher root-to-shoot ratios, relative growth rates, and net assimilation rates.

Research on mangroves in Malaysia remains scarce, with several key species still underexplored. This gap is evident in previous studies, such as Zarawie et al. (2015), which focused on the biomass of mangroves like *Rhizophora apiculata*, *Bruguiera parviflora*, *B. gymnorrhiza*, and *Avicennia marina* in Merbok, Malaysia, to understand their role in carbon storage. Among these species, *A. alba* stands out for its critical ecological functions. As a pioneer or colonizing species, *A. alba* is particularly well-suited for shoreline restoration, owing to its rapid growth and remarkable ability to establish itself in challenging coastal environments (Hsiung et al., 2024). Locally, mangroves stabilize shorelines and prevent erosion with their dense root systems, while globally, species like *A. alba* are known for their exceptional carbon sequestration abilities, out-performing most terrestrial forests (Mathur et al. 2023). Filling these knowledge gaps is considered essential for the understanding of *A. alba*'s resilience and its potential to mitigate climate change. Conservation strategies can be refined; its role as a global carbon sink can be highlighted by prioritizing research on *A. alba.*

This study aimed to determine the growth response and survivability of *A. alba* by examining height, leaf number, and growth rate under conditions of elevated CO_2 from the early stages of development. Our goal is to identify mangrove species with a high capacity for carbon sequestration, which could significantly contribute to carbon sink efforts and enhance mangrove forest management and restoration practices.

Methods

Seed sample collection and germination preparation The study was carried out over a 12-week period at the Biology Laboratory of UiTM Negeri Sembilan Branch, located at the Kuala Pilah Campus in Negeri Sembilan, Malaysia. Seed samples of *A. alba*, each measuring approximately 4 cm, were collected from the mangrove area at Morib Beach, Selangor (Figure 1). The length of the seeds was measured in centimeters (cm) using a ruler. Seed sizes were recorded, and images were captured using a Canon EOS 1200D DSLR camera.

Around 120 seed samples were prepared and divided into two groups; control and treatment. These seeds were initially placed in the prepared trays (30 cm × 25 cm) that were lined with cotton soaked in seawater. Once the seeds germinated, which took about a week, they were transferred into cups filled with mangrove soil. Each seed was placed at the center of the soil surface and gently pressed to a depth of 12.7 mm.

Study design and growth measurement Sixty control samples were kept in a shade house with an ambient CO_2 concentration of 400 ppm. The remaining 60 germinated seeds, labelled as treated samples, were placed in a CO_2 incubator set to 1,000 ppm. Current CO_2 levels are around 420 ppm (as of 2023). The increase in CO_2 levels indirectly leads to rising temperatures and impacts the environment, for example, through phenomena such as polar ice melting. According to the Intergovernmental Panel on Climate Change, CO_2 levels are projected to exceed 800–1,000 ppm by the end of the century under high-emission scenarios, either RCP8.5 or SSP5-8.5 (Intergovernmental Panel on Climate Change, 2014; 2023). Additionally, the 1,000 ppm threshold is commonly employed in experimental setups to investigate the impacts of elevated CO_2 on plant growth and carbon sequestration, providing a standardized framework for comparative analysis across studies (Ainsworth & Rogers, 2007).

The CO_2 was introduced from a gas tank into the incubator twice daily, a process that took about 15 minutes each time. The samples were exposed to CO_2 continuously for 24 hours a day. Both control and treated samples were monitored under controlled lighting conditions (1,000 µmol m^{-2} s^{-1} PAR) using two LED grow lights following Tamimia et al. (2019), with the temperature set to 32 °C to simulate daytime conditions for 12 hours.

The seeds were watered once a day with 500 ml of seawater in both the CO_2 incubator and the laboratory room, reflecting the natural habitat of mangroves, which are halophytic plants adapted to saline environments (Kim et al., 2016). Then, both control and treated seed samples were observed twice daily. All changes observed during these periods were meticulously recorded. The samples were closely monitored until the first plumule emerged. The stem length (in cm), measured from the ground to the tip of the plant, and the number of leaves on each seedling were recorded. Additionally, the count of live and dead samples was monitored and recorded. If any seedlings became infected with fungus, they were cleaned, and the incubator was sterilized to prevent the spread of infection. The method was repeated weekly for a total of 12 weeks.

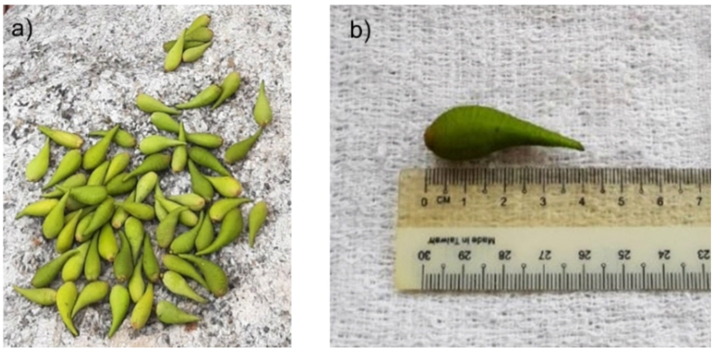

Figure 1 *Avicennia alba* (a) collection of samples from Morib Beach, (b) measurement of seed size.

Data analysis The growth rate of the seedlings was calculated by subtracting the initial measurement from the second measurement and dividing the result by the time interval. The Mann-Whitney test was employed to compare plant height, leaf number, and growth rate between the control and treated groups. This test was also applied to evaluate differences in these parameters concerning plant survivability and to compare mortality between the two groups. To determine whether leaf number was influenced by plant height, a linear regression analysis was performed. All statistical analyses were conducted using R version 4.4.0 (R Development Core Team, 2024). The data are presented as mean ± SE.

Results and Discussion

The growth rate, height, and number of leaves for the seedlings were summarized as mean ± SE for both control and treated groups (Table 1). The treated seedlings demonstrated a significantly higher mean height (11.98 ± 1.09 cm) compared to the control group (11.43 ± 1.33 cm), indicating that the treatment positively influenced stem elongation (Mann-Whitney U = 228012, *p*-value < 0.05) and enhanced survivability (Mann-Whitney U = 263226, *p*-value < 0.05). Similarly, the growth rate was significantly greater in the treated group (1.09 ± 0.76) than in the control group (1.07 ± 0.46), suggesting improved growth under treatment conditions (Mann-Whitney U = 241699, *p*-value < 0.05) and

Table 1 The survivability and the mean (± SE) height, number of leaves, and growth rate of *Avicennia alba*

Seedling ID	Height (cm)	NOL	GR (cm week^{-1})	Survivability (at week 12)
01C	5.78 ± 1.44	2.17 ± 0.58	0.23 ± 1.27	D
02C	9.02 ± 0.90	3.33 ± 0.38	0.88 ± 0.23	A
03C	9.05 ± 0.84	3.33 ± 0.38	0.85 ± 0.25	A
04C	7.18 ± 0.64	1.83 ± 0.17	0.61 ± 0.23	A
05C	5.27 ± 0.46	1.83 ± 0.17	0.44 ± 0.15	A
06C	5.84 ± 1.01	2.83 ± 0.52	0.20 ± 0.85	D
07C	6.38 ± 1.10	2.67 ± 0.51	0.20 ± 0.92	D
08C	10.65 ± 1.00	3.5 ± 0.36	0.95 ± 0.37	A
09C	8.61 ± 0.82	3.5 ± 0.36	0.70 ± 0.25	A
10C	11.43 ± 1.33	3.5 ± 0.36	1.07 ± 0.46	A
11C	2.91 ± 0.69	1.17 ± 0.30	0.17 ± 0.51	D
12C	6.86 ± 0.63	2.67 ± 0.38	0.58 ± 0.17	A
13C	0.20 ± 0.20	0.17 ± 0.17	0.00 ± 0.31	D
14C	-	-	-	D
15C	-	-	-	D
16C	6.79 ± 0.73	3.17 ± 0.39	0.65 ± 0.19	A
17C	11.27 ± 1.09	3.5 ± 0.36	1.05 ± 0.37	A
18C	9.2 ± 0.92	3.5 ± 0.36	0.85 ± 0.28	A
19C	0.52 ± 0.37	0.17 ± 0.17	0 ± 0.46	D
20C	7.5 ± 0.82	3 ± 0.39	0.74 ± 0.22	A
21C	7.02 ± 0.60	3.33 ± 0.38	0.62 ± 0.23	A
22C	5.1 ± 0.42	3.17 ± 0.39	0.42 ± 0.13	A
23C	6.49 ± 0.48	1.83 ± 0.17	0.52 ± 0.19	A
24C	1.24 ± 0.57	0.5 ± 0.26	0 ± 0.53	D
25C	4.11 ± 0.86	2.67 ± 0.51	0.66 ± 0.20	A
26C	6.79 ± 0.64	2.17 ± 0.30	0.6 ± 0.20	A
27C	10.15 ± 0.97	3.5 ± 0.36	0.96 ± 0.29	A
28C	6.8 ± 0.68	3 ± 0.46	0.67 ± 0.14	A
29C	2.66 ± 0.73	1.17 ± 0.30	0 ± 0.56	D
30C	8.74 ± 0.93	3.33 ± 0.38	0.89 ± 0.26	A
31C	2.77 ± 0.64	1.5 ± 0.44	0.21 ± 0.51	D
32C	-	-	-	D
33C	0.38 ± 0.26	0.17 ± 0.17	0 ± 0.31	D
34C	0.63 ± 0.35	0.33 ± 0.22	0.15 ± 0.33	D
35C	4.38 ± 0.34	3 ± 0.39	0.31 ± 0.11	A
36C	2.63 ± 0.65	1.5 ± 0.44	0.19 ± 0.54	D
37C	-	-	-	D
38C	5.25 ± 0.50	3.33 ± 0.28	0.45 ± 0.10	A
39C	4.4 ± 0.31	2.67 ± 0.38	0.31 ± 0.06	A
40C	-	-	-	D
41C	5.94 ± 0.58	3.17 ± 0.39	0.6 ± 0.10	A

Note: C = control; T = treatment; NOL = number of leaves; GR = growth rate; - = indicate dead sample

Table 1 The survivability and the mean (± SE) height, number of leaves, and growth rate of *Avicennia alba* (continued)

Seedling ID	Height (cm)	NOL	GR (cm week^{-1})	Survivability (at week 12)
42C	5.23 ± 0.72	3 ± 0.46	0.7 ± 0.21	A
43C	3.27 ± 0.83	2 ± 0.55	0.15 ± 0.64	D
44C	1.79 ± 0.47	1 ± 0.30	0.18 ± 0.33	D
45C	5.59 ± 0.57	3 ± 0.39	0.57 ± 0.06	A
46C	1.78 ± 0.57	0.83 ± 0.30	0 ± 0.50	D
47C	2.31 ± 0.34	1.5 ± 0.26	0.29 ± 0.14	A
48C	1.82 ± 0.50	1 ± 0.30	0.14 ± 0.37	D
49C	0.38 ± 0.27	0.17 ± 0.17	0 ± 0.34	D
50C	5.07 ± 0.76	2.83 ± 0.46	0.77 ± 0.15	A
51C	5.93 ± 0.91	3 ± 0.46	0.91 ± 0.11	A
52C	2.08 ± 0.81	1.17 ± 0.52	0.18 ± 0.66	D
53C	0.42 ± 0.29	0.17 ± 0.17	0 ± 0.36	D
54C	-	-	-	D
55C	-	-	-	D
56C	5.79 ± 0.54	3.17 ± 0.39	0.53 ± 0.10	A
57C	2.73 ± 0.77	1.83 ± 0.58	0 ± 0.61	D
58C	4.59 ± 0.42	2.67 ± 0.38	0.44 ± 0.05	A
59C	0.81 ± 0.36	0.5 ± 0.26	0 ± 0.32	D
60C	3.34 ± 0.41	1.83 ± 0.30	0.45 ± 0.14	A
01T	6.47 ± 0.55	1.67 ± 0.22	0.49 ± 0.31	A
02T	3.97 ± 0.47	1.5 ± 0.26	0.18 ± 0.53	D
03T	5.42 ± 0.43	0.67 ± 0.14	0.42 ± 0.19	A
04T	5.91 ± 0.54	0.58 ± 0.15	0.5 ± 0.25	A
05T	7.08 ± 0.53	1.67 ± 0.22	0.52 ± 0.38	A
06T	7.02 ± 0.55	1.67 ± 0.22	0.52 ± 0.39	A
07T	7.97 ± 0.69	0.67 ± 0.28	0.39 ± 0.56	A
08T	4.72 ± 0.76	0.33 ± 0.22	0.22 ± 0.70	D
09T	4.93 ± 0.34	1.67 ± 0.22	0.35 ± 0.16	A
10T	4.3 ± 0.77	1.17 ± 0.30	0.55 ± 0.66	A
11T	3.04 ± 0.53	0.5 ± 0.19	0.39 ± 0.35	A
12T	7.29 ± 0.58	1.67 ± 0.22	0.55 ± 0.38	A
13T	11.98 ± 1.09	2.92 ± 0.45	1.09 ± 0.76	A
14T	7.3 ± 0.64	1.67 ± 0.22	0.57 ± 0.56	A
15T	2.41 ± 0.80	0.42 ± 0.23	0.2 ± 0.62	D
16T	3.95 ± 0.68	0.33 ± 0.22	0.18 ± 0.71	D
17T	3.88 ± 0.42	1.67 ± 0.22	0.45 ± 0.23	A
18T	2.88 ± 1.07	0 ± 0.00	0 ± 0.85	D
19T	4.5 ± 0.82	0.83 ± 0.21	0.62 ± 0.34	A
20T	5.79 ± 0.72	1.25 ± 0.22	0.68 ± 0.25	A
21T	8.07 ± 0.63	1.5 ± 0.26	0.6 ± 0.33	A
22T	4.1 ± 0.48	1.42 ± 0.32	0.55 ± 0.20	A
23T	3.6 ± 0.63	1.33 ± 0.28	0.45 ± 0.35	A
24T	3.23 ± 0.33	0 ± 0.00	0.36 ± 0.20	A
25T	6.13 ± 0.44	1.67 ± 0.22	0.46 ± 0.41	A
26T	4.28 ± 0.49	1.33 ± 0.28	0.59 ± 0.31	A
27T	0.49 ± 0.34	0.33 ± 0.22	0 ± 0.40	D
28T	5.55 ± 0.56	1.67 ± 0.22	0.61 ± 0.14	A
29T	3.39 ± 0.32	0.67 ± 0.22	0.12 ± 0.45	A
30T	4.77 ± 0.40	1.17 ± 0.46	0.49 ± 0.21	A
31T	5.47 ± 0.51	0.33 ± 0.22	0.25 ± 0.54	A
32T	3.89 ± 0.57	0.5 ± 0.23	0.04 ± 0.46	A
33T	2.35 ± 0.42	0 ± 0.00	0.32 ± 0.28	A
34T	4.47 ± 0.28	1.67 ± 0.22	0.25 ± 0.21	A
35T	6.47 ± 0.64	1.67 ± 0.22	0.56 ± 0.28	A

Note: C = control; T = treatment; NOL = number of leaves; GR = growth rate; - = indicate dead sample

Table 1 The survivability and the mean (± SE) height, number of leaves, and growth rate of *Avicennia alba* (continued)

Seedling ID	Height (cm)	NOL	GR (cm $week^{-1}$)	Survivability (at week 12)
36T	4.96 ± 0.43	1.5 ± 0.26	0.41 ± 0.18	A
37T	1.83 ± 0.40	0 ± 0.00	0.27 ± 0.24	A
38T	-	-	-	D
39T	7.50 ± 1.00	2.67 ± 0.51	0.22 ± 0.92	D
40T	8.61 ± 1.12	1.42 ± 0.31	0.23 ± 1.13	D
41T	5.98 ± 0.41	1.67 ± 0.22	0.48 ± 0.19	A
42T	3.59 ± 0.87	0.75 ± 0.28	0.2 ± 0.54	D
43T	9.24 ± 1.22	1.33 ± 0.28	0.22 ± 1.14	D
44T	9.44 ± 0.74	2 ± 0.35	0.77 ± 0.58	A
45T	3.06 ± 0.31	0.33 ± 0.22	0.32 ± 0.24	A
46T	3.07 ± 0.33	0.5 ± 0.26	0.32 ± 0.24	A
47T	6.46 ± 1.11	0.92 ± 0.26	0.86 ± 0.42	A
48T	-	-	-	D
49T	4.54 ± 0.52	1.5 ± 0.26	0.21 ± 0.58	D
50T	5 ± 0.79	1.33 ± 0.28	0.22 ± 0.60	D
51T	0 ± 0.00	0.17 ± 0.17	0 ± 0.00	D
52T	4.88 ± 0.37	1.67 ± 0.22	0.35 ± 0.13	A
53T	9.69 ± 0.81	1.67 ± 0.22	0.8 ± 0.54	A
54T	10.93 ± 0.95	2 ± 0.30	0.95 ± 0.58	A
55T	7.62 ± 0.63	2.5 ± 0.44	0.57 ± 0.28	A
56T	7.25 ± 0.65	2.17 ± 0.37	0.7 ± 0.21	A
57T	3.66 ± 0.66	1.33 ± 0.28	0.55 ± 0.34	A
58T	4.82 ± 0.28	1.67 ± 0.22	0.25 ± 0.22	A
59T	1.87 ± 0.48	0.83 ± 0.30	0 ± 0.42	D
60T	2.17 ± 0.57	1.17 ± 0.46	0 ± 0.47	D

Note: C = control; T = treatment; NOL = number of leaves; GR = growth rate; - = indicate dead sample

better survivability (Mann-Whitney U = 202753, *p*-value < 0.05). However, the control group had a higher number of leaves (3.50 ± 0.36), indicating reduced leaf production under treatment conditions (Mann-Whitney U = 321313, *p*-value < 0.05) and a potential impact on survivability (Mann-Whitney U = 235068, *p*-value < 0.05).

A linear regression analysis was conducted to examine the relationship between the number of leaves and the height of the seedlings. The model revealed a significant positive relationship between height and number of leaves ($\beta = 0.298$, SE = 0.007, $t_{(1438)} = 40.68$, *p*-value < 0.001). The regression equation accounted for approximately 53.5% of the variance in NOL ($R^2 = 0.535$, adjusted $R^2 = 0.5347$), indicating a moderate to strong fit. An ANOVA test further confirmed that height significantly predicted number of leaves ($F_{(1,\ 1438)} = 1654.6$, *p*-value < 0.001). The residual standard error was 1.021, suggesting that the model's predictions were reasonably accurate. The significant positive coefficient implies that as the height of the seedlings increases, the number of leaves also tends to increase.

The survivability of seedlings was assessed between the control and treated groups (Figure 2). In the control group, 32 seedlings survived while 28 did not. In the treated group, 43 seedlings survived while 17 did not. To determine whether there was a significant difference in survivability between the two groups, a Mann-Whitney U test was conducted. The results indicated that there was a statistically significant difference in survivability between the control and treated groups (Mann-Whitney U = 1470, *p*-value < 0.05).

The results of this study suggest that the treatment had a differential impact on various growth parameters of *A. alba* seedlings. Specifically, while the treatment appeared to enhance height and overall growth rate, it concurrently led to a reduction in the number of leaves. This dual effect highlights the complex physiological responses of *A. alba* to the treatment conditions.

Recent years have seen a rise in greenhouse gases, driving global climate change. In response, the restoration and management of mangroves have been recognized as a self-sustaining, forest-based natural climate solution to mitigate these changes (Gu et al., 2023). Extensive research has been conducted on mangrove species like *R. apiculata* (Ball et al., 1997; Tamimia et al., 2019), *A. germinans* (Snedaker & Araujo, 1998; McKee & Rooth, 2008; Reef et al., 2015; 2016), and *A. marina* (Jacotot et al., 2018; Jacotot et al., 2019) to examine the effects of elevated CO_2 concentrations on various performance parameters, including growth rate (Friess et al., 2022), biomass estimation (Suardana et al., 2022), leaf area (Gu et al., 2023), salinity (Dittmann et al., 2022), temperature (Inoue et al., 2022), and their potential for carbon sequestration (Gu et al., 2023). The elevated CO_2 levels significantly increased plant height, stem and shoot weight, and total biomass in fast-growing species (Singh et al., 2019; Major & Mosseler, 2019; Inoue et al., 2024). These findings are consistent with the results of this study, particularly in terms of enhanced height and growth rate. This is attributed to the species' ability to absorb carbon from the external environment and

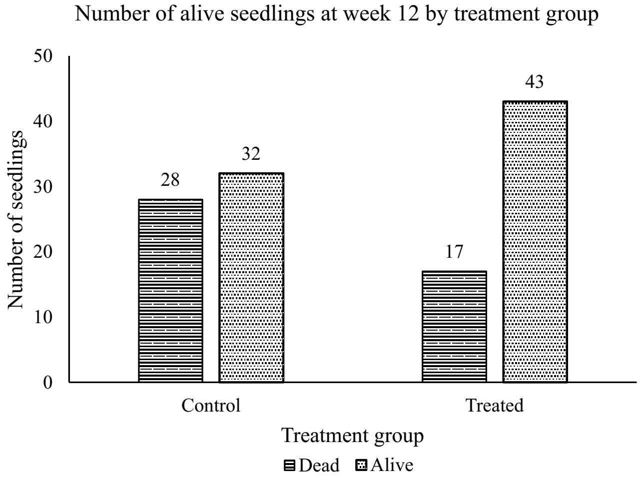

Figure 2 The survivability of *Avicennia alba* seedlings in the control and treated groups at week 12.

incorporate it into various plant structures, promoting the expansion of shoots and roots (Wahidah et al., 2021). Elevated CO_2 enhances the plant's carbon uptake, stimulating photosynthesis and typically resulting in increased growth. Research comparing species or cultivars with varying sink capacities has shown that growth rates are higher when the sinks are larger (Angela et al., 2016). The increase in height and growth rate suggests that the treatment created favorable conditions for vertical growth. This might be due to improved nutrient uptake or more efficient photosynthesis. Wahidah et al. (2021) mentioned that elevated CO_2 levels typically enhance the rate of photosynthesis, which in turn boosts the growth rate of the plant (Wahidah et al., 2021).

However, the accompanying reduction in leaf number suggests a potential trade-off, where resources were allocated more towards stem elongation rather than leaf production. This phenomenon could be a strategic adaptation to optimize light capture or reduce respiratory costs under the specific treatment conditions. High irradiance and elevated CO_2 levels enhance the rate of photosynthesis per unit of leaf mass (Long, 1991; Gu et al., 2023). This increase in photosynthetic activity leads to a surplus of fixed carbon, which is partly allocated towards growth and partly stored as non-structural carbohydrates (Körner et al., 1995; Gu et al., 2022). The enrichment of CO_2 may also elevate the plant's nutrient requirements due to the accelerated growth rate (Poorter & Nagel, 2000; Gu et al., 2023). Interestingly, the observed reduction in leaf number might suggest that the seedlings were under some form of stress, prompting them to limit leaf production. In environments with limited resources, such as water or nutrients, plants often reduce leaf area to conserve water or decrease the metabolic demands of maintaining a larger leaf surface. In this scenario, the treatment may have inadvertently triggered a stress response, resulting in fewer leaves despite the overall increase in height. Some studies have shown that elevated CO_2 can reduce transpiration, leading to a decrease in leaf mass fraction. This reduction occurs because the need for water uptake diminishes, reducing the necessity to allocate more biomass to roots (Morison, 1998; Poorter & Nagel, 2000; Wu et al., 2024). Therefore, further research on leaf number and leaf mass fraction is essential to fully understand the performance of mangrove species under elevated CO_2 conditions.

The impact of elevated CO_2 on plant growth rates is frequently influenced by the duration of exposure (Wahidah et al., 2021). Prolonged exposure to elevated CO_2 can cause photosynthetic acclimation. This includes increased stomatal resistance, carbohydrate buildup, and reduced chlorophyll levels. It may also lead to feedback inhibition or physical damage to chloroplasts, ultimately reducing photosynthetic capacity (Ravi, 2019; Wang et al., 2022). This aligns with the observed growth pattern in *A. alba*, where growth was significantly stimulated during the first three months of treatment, followed by the eventual decline of 17 individuals. Although 43 seedlings survived until week 12 under daily exposure to 1,000 ppm CO_2, indicating *A. alba*'s resilience to elevated CO_2 levels, further research is needed. Long-term health, reproductive success, and overall physiological responses should be assessed to strengthen and validate these preliminary findings.

The findings of this study emphasize the practical applications of *A.* alba in mangrove restoration projects, particularly its adaptability to diverse environmental conditions. The species' plasticity in growth strategy, including the trade-off between height and leaf number, highlights the importance of resource allocation and site preparation in optimizing growth and resilience. These traits can guide effective planting strategies, such as adjusting densities and spacing to balance carbon sequestration and habitat provision (Bosire et al., 2013). By supporting biodiversity and contributing to coastal protection and carbon storage, *A. alba* plays a pivotal role in addressing local and global ecological challenges.

Conclusion

The results of this study reveal the nuanced physiological responses of *A. alba* seedlings to elevated CO_2 conditions. While the treatment effectively enhanced height and overall growth rate, it simultaneously led to a reduction in leaf number, suggesting a complex trade-off in resource allocation. This finding highlights the species' ability to adjust its growth strategy, possibly as an adaptation to optimize light capture or reduce metabolic demands under the given conditions. The observed responses align with broader research on mangrove species and underscore the importance of understanding the effects of elevated CO_2 on various growth parameters. The reduction in leaf number may indicate a stress response or a strategic shift in biomass allocation, pointing to the need for further investigation. Specifically, future studies should focus on understanding how elevated CO_2 influences other physiological processes, such as photosynthetic acclimation, nutrient uptake efficiency, and root development. These long-term experiments are essential to assess whether growth strategies are sustainable and how they impact reproductive success, which is critical for population dynamics and ecosystem stability. Given the critical role of mangroves in climate change mitigation through carbon sequestration, understanding the specific impacts of elevated CO_2 on species like *A. alba* is essential. The study's findings contribute to the growing body of knowledge needed to optimize mangrove restoration and afforestation efforts, ensuring these ecosystems continue to thrive in a changing climate. Future research should explore the species' carbon storage capacity under elevated CO_2 and how this varies across different environmental conditions, such as salinity and temperature stress. Moreover, integrating genetic studies to identify traits associated with resilience to climate stressors could guide the selection of optimal genotypes for restoration projects.

Acknowledgment

We would also like to express our sincere gratitude to Universiti Teknologi MARA for providing the research grant that made this study possible, under research code 600-RMC/GPM-LPHD-5/3(118/2021).

References

Ainsworth, E. A. & Rogers, A. (2007). The response of photosynthesis and stomatal conductance to rising (CO_2): Mechanisms and environmental interactions. *Plant Cell Environment*, *30*(3), 258–270. https://doi.org/10.1111/j.1365-3040.2007.01641.x

Andrea, V. (2022). Mediterranean forest policy beyond the Paris Climate Agreement. *Land Use Policy*, *112*, Article 105797. https://doi.org/10.1016/j.landusepol.2021.105797

Angela, C. W., Alistair, R., Mark, R., & Colin, P. O. (2016). How can we make plants grow faster? A source-sink perspective on growth rate. *Journal of Experimental Botany*, *67,* 31–45. https://doi.org/10.1093/jxb/erv447

Arifanti, V. B. (2020). Mangrove management and climate change: A review in Indonesia. *IOP Conference Series: Earth and Environmental Science*, *487*, Article 012022. https://doi.org/10.1088/1755-1315/487/1/012022

Atwood, T. B., Connolly, R. M., Almahasheer, M., Carnell, P. E., Duarte, C. M., Lewis, C. J. E., Irigoien, X., Kelleway, J. J., Lavery, P. S., Macreadie, P. I., Serrano, O., Sanders, C. J., Santos, I., Steven, A. D. L., & Lovelock C. E. (2017). Author correction: Global patterns in mangrove soil carbon stocks and losses. *Natural Climate Change*, *7*(7), 523–528. https://doi.org/10.1038/nclimate3326

Ball, M. C., Cochrane, M. J., & Rawson, H. M. (1997). Growth and water use of the mangroves *Rhizophora apiculata* and *R. stylosa* in response to salinity and humidity under ambient and elevated concentrations of atmospheric CO_2. *Plant, Cell & Environment*, *20*(9), 1158–1166. https://doi.org/10.1046/j.1365-3040.1997.d01-144.x

Ball, M. C. & Munns, R. (1992). Plant responses to salinity under elevated atmospheric concentrations of CO_2. *Australian Journal of Botany*, *40*(5), 515–525. https://doi.org/10.1071/BT9920515

Basyuni, M., Sasmito, S. D., Analuddin, K., Ulqodry, T. Z., Saragi-Sasmito, M. F., Eddy, S., & Milantara, N. (2022). Mangrove biodiversity, conservation and roles for livelihoods in Indonesia. In S. C. Das, Pullaiah, & E. C. Ashton (Eds.), *Mangroves: Biodiversity, livelihoods and conservation* (pp. 397–445). Singapore: Springer Nature Singapore.

Bosire, J. O., Kaino, J. J., Olagoke, A. O., Mwihaki, L. M., Ogendi, G. M., Kairo, J. G., Berger, U. & Macharia, D. (2013). Mangroves in peril: Unprecedented degradation rates of peri-urban mangroves in Kenya. *Biogeosciences*, *10*, 16371–16404. https://doi.org/10.5194/bgd-10-16371-2013

De Rezende, C. E., Kahn, J. R., Passareli, L., & V´asquez, W. F. (2015). An economic valuation of mangrove restoration in Brazil. *Ecological Economics*, *120*, 296–302. https://doi.org/10.1016/j.ecolecon.2015.10.019

Dittmann, S., Mosley, L., Stangoulis, J., Nguyen, V. L., Beaumont, K., Dang, T., Guan, H., Gutierrez-Jurado, K., Lam-Gordillo, O., & McGrath, A. (2022). Effects of extreme salinity stress on a temperate mangrove ecosystem. *Frontiers in Forests and Global Change*, *5*, Article p.859283. https://doi.org/10.3389/ffgc.2022.859283

Gu, X., Zhao, H., Peng, C., Guo, X., Lin, Q., Yang, Q., & Chen, L. (2022). The mangrove blue carbon sink potential: Evidence from three net primary production assessment methods. *Forest Ecology and Management*, *504*, Article 119848. https://doi.org/10.1016/j.foreco.2021.119848

Gu, X., Qiao, P., Krauss, K. W., Lovelock, C. E., Adams, J. B., Chapman, S. K., Jennerjahn, T. C., Lin, Q., & Chen, L. (2023). Changes in mangrove blue carbon under elevated atmospheric CO_2. *Ecosystem Health and Sustainability*, *9*, Article 0033. https://doi.org/10.34133/ehs.0033

Friess, D. A., Adame, M. F., Adams, J. B., & Lovelock, C. E. (2022). Mangrove forests under climate change in a 2 C world. *Wiley Interdisciplinary Reviews: Climate Change*, *13*(4), Article e792. https://doi.org/10.1002/wcc.792

Griscom, B. W., Jonah, B., Susan, C., Cook-Patton, S. C., Ellis, P. W., Funk, J., Leavitt, S. M., Guy, L., Turner, W. R., Melissa, C., & Jens, E. (2020). National mitigation potential from natural climate solutions in the tropics. *Philosophocal Transactions of the Royal Society B*, *375(1794)*, Article 20190126. https://doi.org/10.1098/rstb.2019.0126

Hsiung, A. R., Ong, O. X. J., Teo, X. S., Friess, D. A., Todd, P. A., Swearer, S. E & Morris, R. L. (2024). Determinants of mangrove seedling survival incorporated within hybrid living shorelines. *Ecological Engineering*, *202*, Article 107235. https://doi.org/10.1016/j.ecoleng.2024.107235

Inoue, T., Akaji, Y., & Noguchi, K. (2022). Distinct responses of growth and respiration to growth temperatures in two mangrove species. *Annals of Botany*, *129*(1), 15–28. https://doi.org/10.1093/aob/mcab117

Inoue, T., Fujimura, T., & Noguchi, K. (2024). Growth, morphology and respiratory cost responses to salinity in the mangrove plant *Rhizophora stylosa* depend on growth temperature. *Plant, Cell & Environment*, *48*(2), 965–977. https://doi.org/10.1111/pce.15184

Intergovernmental Panel on Climate Change. (2014). *Climate change 2014: Synthesis report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, R. K. Pachauri, & L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland. Retrieved form https://www.ipcc.ch/site/assets/uploads/2018/05/SYR_AR5_FINAL_full_wcover.pdf

Intergovernmental Panel on Climate Change. (2023). *Climate change 2023: Synthesis report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, H. Lee, & J. Romero (eds.)]. IPCC, Geneva, Switzerland. https://doi.org/10.59327/IPCC/AR6-9789291691647

Jacotot, A., Marchand, C., Gensous, S., & Allenbach, M. (2018). Effects of elevated atmospheric CO_2 and increased tidal flooding on leaf gas-exchange parameters of two common mangrove species: *Avicennia marina* and *Rhizophora stylosa. Photosynthesis Research*, *138*(2), 249–260. https://doi.org/10.1007/s11120-018-0570-4

Jacotot, A., Marchand, C., & Allenbach, M. (2019). Increase in growth and alteration of C:N ratios of *Avicennia marina* and *Rhizophora stylosa* subject to elevated CO_2 concentrations and longer tidal flooding duration. *Frontiers in Ecology and Evolution*, *7*, Article 98. https://doi.org/10.3389/fevo.2019.00098

Khairnar, S. O., Solanki, B. V., & Junwei, L. (2013). Mangrove ecosystem-Its threats and conservation. In *Aquafind, College of Fisheries, Ocean University of China, Qingdao, Shandong, Peoples Republic of China*. Retrieved from https://www.researchgate.net/profile/Sachin-Khairnar/publication/324908831_MANGROVE_ECOSYSTEM-Its_Threats_and_Conservation/links/ 60d85e7f299bf1ea9ec46546/MANGROVE-ECOSYSTEM-Its-Threats-and-Conservation.pdf

Kim, K., Seo, E., Chang, S. K., Park, T. J. & Lee, S. J. (2016). Novel water filtration of saline water in the outermost layer of mangrove roots. *Scientific Reports*, *6*, Article 20426. https://doi.org/10.1038/srep20426

Körner, C., Pelaez-Riedl, S., & Van Bel, A. J. E. (1995). CO_2 responsiveness of plants: A possible link to phloem loading. *Plant, Cell and Environment*, *18*, 595–600. https://doi.org/10.1111/j.1365-3040.1995.tb00560.x

Liang, J., Farquhar, G. D., & Ball, M. C. (2022). Water use efficiency in mangroves: Conservation of water use efficiency determined by stomatal behavior across leaves, plants, and forests. In S. Shabala (Ed.), *Advances in botanical research* (pp. 43–59). Academic Press. https://doi.org/10.1016/bs.abr.2022.02.017

Long, S. P. (1991). Modification of the response of photosynthetic productivity to rising temperature by atmospheric CO_2 concentrations: Has its importance been underestimated? *Plant, Cell and Environment*, *14*, 729–739. https://doi.org/10.1111/j.1365-3040.1991.tb01439.x

Lovelock, C. E. & Duarte, C. M. (2019). Dimensions of blue carbon and emerging perspectives. *Biology Letters*, *15(3)*, Article 20180781. https://doi.org/10.1098/rsbl.2018.0781

Lovelock, C. E., Barbier, E., & Duarte, C. M. (2022). Tackling the mangrove restoration challenge. *PLoS Biology*, *20*(10), Article e3001836. https://doi.org/10.1371/journal.pbio.3001836

Major, J. E. & Mosseler, A. (2008). Interactive effects of CO, and soil water treatments on growth and biomass allocation in pines and spruces. *Forest Ecology and Management*, *442*, 21–33. https://doi.org/10.1016/j.foreco.2019.03.056

Mathur, A., Sharma, J. V., Priyanka, & Tyagi, A. (2023). *Scope and potential of coastal ecosystem towards mitigating climate change*. New Delhi: The Energy and Resources Institute (TERI). Retrieved from https://www.teriin.org/sites/default/files/2021-02/blue-carbon-climate-change.pdf

McKee, K. L & Rooth, J. E. (2008). Where temperate meets tropical: Multifactorial effects of elevated CO_2, nitrogen enrichment, and competition on a mangrove-salt marsh community. *Global Change Biology*, *14*(5), 971–984. https://doi.org/10.1111/j.1365-2486.2008.01547.x

Morison, J. I. L. (1998). Stomatal response to increase atmospheric CO_2. *Journal of Experimental Botany*, *49,* 443–452.

Poorter, H. & Nagel, O. (2000). The role of biomass allocation in the growth response of plants to different levels of light, CO_2, nutrients and water: A quantitative review. *Australian Journal of Plan Physiology*, *27*, 595–607. https://doi.org/10.1071/PP99173_CO

Pratolongo, P. D. (2022). Salt marshes and mangroves: Tidal saline wetlands dominated by vascular plants. In J. Pan, & P. D. Pratolongo (Eds.), *Marine biology: A functional approach to the oceans and their organisms* (pp. 211–231). CRC Press.

R Development Core Team. (2024). R: A language and environment for statistical computing. Vienna: R Foundation for Statistical Computing.

Ravi, S. (2019). The ecophysiology of the New Zealand mangrove, *Avicennia marina* (Forssk.) Vierh. subsp. *australasica* (Walp.) J. Everett [dissertation]. Auckland University of Technology.

Reef, R., Slot, M., Motro, U., Motro, M., Motro, Y., Adame, MF., Garcia, M., Aranda, J., Lovelock, C.E., & Winter, K. (2016). The effects of CO_2 and nutrient fertilisation on the growth and temperature response of the mangrove *Avicennia germinans*. *Photosynthesis Research*, *129*(2), 159–170. https://doi.org/10.1007/s11120-016-0278-2

Reef, R., Winter, K., Morales, J., Adame, M. F., Reef, D. L., & Lovelock, C. E. (2015). The effect of atmospheric carbon dioxide concentrations on the performance of the mangrove *Avicennia germinans* over a range of salinities. *Physiologia plantarum*, *154*(3), 358–368. https://doi.org/10.1111/ppl.12289

Seary, R., Spencer, T., Bithell, M., & McOwen, C. (2021). Measuring mangrove-fishery benefits in the Peam Krasaop Fishing Community, Cambodia. *Estuarine, Coastal and Shelf Science*, *248*, Article 106918. https://doi.org/10.1016/j.ecss.2020.106918

Singh, A. K., Rai, A., Kushwaha, M., Chauhan, P. S., Pandey, V., & Singh, N. (2019). Tree growth rate regulate the influence of elevated CO_2, on soil biochemical responses under tropical condition. *Journal of Environmental Management*, *231*, 1211–1221. https://doi.org/10.1016/j.jenvman.2018.11.025

Snedaker, S. C. & Araujo, R. J. (1998). Stomatal conductance and gas exchange in four species of Caribbean mangroves exposed to ambient and increased CO_2. *Marine and Freshwater Research*, *49*(4), 325–327. https://doi.org/10.1071/MF98001

Suardana, A. M. A. P., Anggraini, N., Aziz, K., Nandika, M. R., Ulfa, A., Wijaya, A. D., As-syakur, A. R., Winarso, G., Prasetio, W., & Dewanti, R. (2022). Biomass estimation model and carbon dioxide sequestration for mangrove forest using Sentinel-2 in Benoa Bay, Bali. *International Journal of Remote Sensing and Earth Sciences (IJReSES)*, *19*(1), 91–100.

Tamimia, B., Wan Juliana, W. A., Nizam, M. S., & Che Radziah, C. M. Z. (2019). Elevated CO_2 Concentration and air temperature impacts on mangrove plants (*Rhizophora apiculata*) under controlled environment. *Iraqi Journal of Science*, *60(8)*, 1658–1666. https://doi.org/10.24996/ijs.2019.60.8.1

Wahidah, M. N. L., Nizam, M. S., Che Radziah, C. M. Z., & Wan Juliana, W. A. (2021). Growth responses of light demanding and shade tolerant peat swamp forest saplings to elevated CO_2. *Journal of Environmental Biology*, *42*, 735–743. http://doi.org/10.22438/jeb/42/3(SI)/JEB-01

Wang, C. W., Wong, S. L., Liao, T. S., Weng, J. H., Chen, M. N., Huang, M. Y., & Chen, C. I. (2022). Photosynthesis in response to salinity and submergence in two Rhizophoraceae mangroves adapted to different tidal elevations. *Tree Physiology*, *42*(5), 1016–1028. https://doi.org/10.1093/treephys/tpab167

Worthington, T. A., Andradi-Brown, D. A., Bhargava, R., Buelow, C., Bunting, P., Duncan, C., Fatoyinbo, L., Friess, D. A., Goldberg, L., Hilarides, L., Lagomasino, D., Landis, E., Longley-Wood, K., Lovelock, C. E., Murray, N. J., Narayan, S., Rosenqvist, A., Sievers, M., Simard, M., ..., & Spalding, M. (2020). Harnessing big data to support the conservation and rehabilitation of mangrove forests globally. *One Earth*, *2*(5), 429–443. https://doi.org/10.1016/j.oneear.2020.04.018

Wu, S., Gu, X., Peng, X., & Chen, L. (2024). Comparative analysis of water-use strategies in three subtropical mangrove species: A study of sap flow and gas exchange monitoring. *Tree Physiology*, *44*(9), Article tpae102. https://doi.org/10.1093/treephys/tpae102

Zarawie, T. T., Suratman, M. N., Jaafar, J., Hasmadi, I. M., & Abu, F. (2015). Field assessment of above ground biomass (AGB) of mangrove stand in Merbok, Malaysia. *Malaysian Applied Biology*, *44*(3), 81–86.