



Enhancement of carbon sequestration capacity by restoring mangroves in Kaohsiung Jhongdu Wetland Park

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ABSTRACT: This study examines the enhancement in carbon sequestration capacity of three mangrove species restored in the Jhongdu Wetland Park, Kaohsiung City. Among them, *Avicennia marina* demonstrated the highest carbon sequestration capacity, followed by *Rhizophora stylosa* and *Lumnitzera racemosa*. When compared to the carbon sequestration rates of natural mangroves along other coastal areas of Taiwan, the restored mangroves in the wetland park exhibited significantly higher rates. However, current maintenance practices treat the park primarily as an urban landscape park, involving extensive pruning and removal when vegetation becomes overly dense. This study confirms that the mangroves in the wetland park function as effective carbon sinks, highlighting their ecological value and ecosystem services they provide in urban environments. It is therefore recommended that proper thinning and management practices be adopted to enhance Kaohsiung City's capacity for reducing greenhouse gas emissions. It is recommended to support its inclusion as a nature-based solution in urban climate strategies.

KEY WORDS: carbon sink, constructed wetland, greenhouse gas emission, maintenance and management, mangrove forest.

INTRODUCTION

In February 2022, the Intergovernmental Panel on Climate Change (IPCC) released its Sixth Assessment Report (AR6), emphasizing that global warming is projected to reach 1.5°C above pre-industrial levels within the next 20 years. This warming is expected to exacerbate multiple climate hazards, including extreme weather events, heatwaves, and biodiversity loss, with no region on Earth spared from these impacts. The United Nations Climate Conference has urged all countries to adopt more urgent climate actions—halving global greenhouse gas (GHG) emissions by 2030 and achieving net-zero emissions by 2050—in order to keep global temperature rise below 1.5°C and mitigate the high-risk impacts of the climate emergency. Blue carbon refers to the carbon stored in marine ecosystems. By conserving and restoring coastal ecosystems, blue carbon efforts can address global CO₂ imbalances and help mitigate climate change (Nellemann *et al.*, 2009). Blue carbon is generally recognized as being stored in mangroves, salt marshes, and seagrass beds—in both aboveground and belowground living biomass, soils, and detrital materials (McLeod *et al.*, 2011). Coastal and estuarine ecosystems sequester an estimated 16.5 million tons of CO₂ annually—nearly half the amount emitted by global transportation—making them among the most efficient carbon storage systems (Nellemann *et al.*, 2009). These vegetated habitats play a critical role in the global and

regional carbon cycle (Chiu *et al.*, 2013; Huang *et al.*, 2015; Li *et al.*, 2018). Unlike terrestrial systems, coastal ecosystems can store large quantities of carbon in soils over long periods (Chou *et al.*, 2022). This is largely due to their anoxic environments and slow rates of organic decomposition (Duarte *et al.*, 2005; Lo Iacono *et al.*, 2008; Duarte and Agustí, 2011). Mangroves play a significant role in carbon sequestration and climate change mitigation. In addition, they can provide various ecosystem functions and services, such as coastal protection, water purification, nutrient cycling, carbon storage, and support for fisheries (Alongi, 2008; Yulianto, 2016; Herrera-Silveira, 2020). Coastal ecosystems sequester carbon at 2–4 times the rate of tropical forests, and their carbon stocks can be 3–5 times greater (Donato *et al.*, 2011). Among tropical forest systems, mangroves are recognized as one of the richest in carbon storage (Kauffman *et al.*, 2011). Despite accounting for only 0.5% of total coastal area, mangroves store approximately 14% of the carbon found in oceanic ecosystems, highlighting their exceptional carbon sequestration potential (Alongi, 2012).

However, economic development has led to widespread destruction of mangrove habitats—converted into fish ponds, agricultural land, or dredged seagrass beds—especially along global coastlines. These disturbances expose sediments to air and water, leading to the decomposition of previously stored organic carbon and the release of CO₂ and other GHGs into the atmosphere and

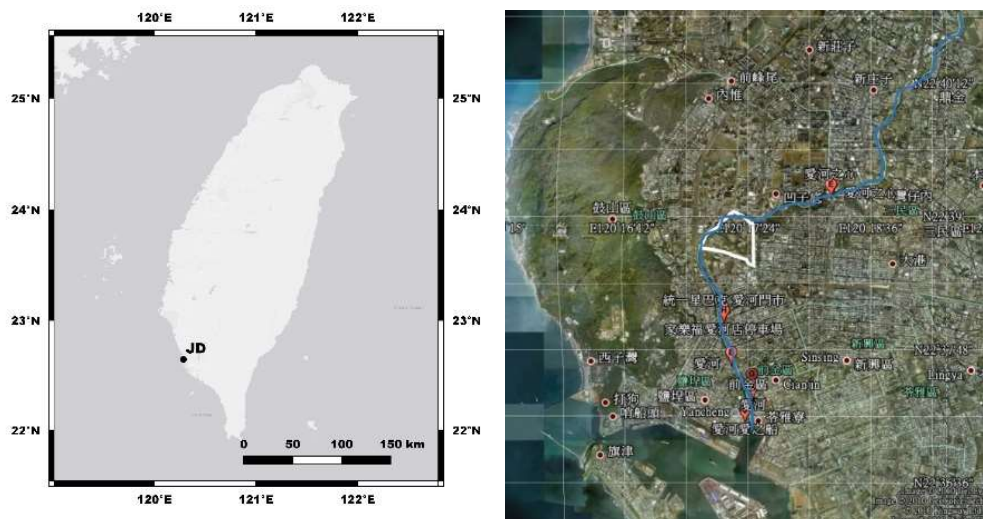


Fig. 1. Map of the study site: Jhongdu Wetland Park is located in Kaohsiung City, Taiwan, approximately 2.5 kilometers from the estuary of the Love River. The map shows the restored mangrove area within Jhongdu Wetland Park. The boundaries of the park (12 ha) are outlined by the white polygon. The blue line represents the Love River. (Map sources: Left – QGIS 2.18.14; Right – Google Earth)

oceans (Yu and Chmura, 2009). Over the past century, approximately 35% of mangrove habitats have been lost (Valiela *et al.*, 2001), with losses continuing at an annual rate of 1–3% (McLeod *et al.*, 2011). This loss not only compromises biodiversity and coastal protection, but also significantly reduces carbon sink capacity (Nellemann *et al.*, 2009). The degradation of mangroves accelerates the decomposition of stored carbon, resulting in substantial GHG emissions (Lovelock *et al.*, 2011; Sidik and Lovelock, 2013). To mitigate mangrove degradation, numerous restoration projects have been implemented to enhance carbon storage and vegetation structure (Ellison, 2000; Irving *et al.*, 2011). Quantifying the carbon sequestration capacity of restored mangrove ecosystems is critical for effective management, conservation, and climate change mitigation strategies (Erwin, 2009; Alongi, 2011).

On Earth Day 2021, the Taiwanese government declared that the 2050 net-zero transition is a shared goal of both the global community and Taiwan. Taiwan has developed 12 key strategies to achieve this transition, among which natural carbon sinks play a central role. These include afforestation, ecological management, the development of negative-carbon agriculture, and the conservation and restoration of marine habitats and biodiversity. Such strategies aim to reduce atmospheric CO₂ concentrations, prevent soil erosion, and enhance the carbon sequestration function of ecosystems. The coastal region of Kaohsiung City, Taiwan, was historically characterized by lagoons and bays, making it one of the most important mangrove habitats in Taiwan. All four mangrove species native to Taiwan can flourish here. However, during the Japanese colonial period and particularly after the 1950s, rapid urban development, land reclamation, and port construction led to the

destruction of these estuarine and coastal mangrove habitats. The goal of the Jhongdu Artificial Wetland Park is to restore these mangrove species and their ecosystems. In addition to reviving a segment of Taiwan's lost tropical natural environment, this restoration project is expected to enhance carbon sequestration capacity in the surrounding urban ecosystem. The functions of wetlands are diverse. In urban areas, they can play special roles such as carbon sequestration, water purification, climate regulation, and flood retention. This study aims to explore the potential of artificial urban wetlands to function as carbon sinks. This study aims to: (1) quantify the increase in carbon sequestration capacity resulting from the restoration of mangroves in Jhongdu Wetland Park; and (2) provide recommendations for the management of mangroves in coastal urban park settings.

MATERIALS AND METHODS

Study Site

Jhongdu Wetland Park is located in Kaohsiung City, approximately 2.5 km from the estuary of the Love River (Figure 1). Within the wetland, the main waterway is connected to the Love River through two sluice gates, and the tidal fluctuations in the wetland's channels mirror those of the Love River. Jhongdu Wetland Park covers an area of approximately 12 hectares, with around 5 hectares restored with mangroves. In 2011, four mangrove species were replanted, including *Kandelia obovata*, *Rhizophora stylosa*, *Avicennia marina*, and *Lumnitzera racemosa* using nursery-raised seedlings (Figure 2). The mangrove seedlings were primarily planted along both banks of the newly constructed waterway. Since completion, the replanted mangroves have thrived, with some terrestrial vegetation gradually forming into forests. A central island



Fig. 2. In the Jhongdu Wetland Park development project, aside from preserving existing large trees, all other vegetation in the wetland was newly planted and began growing from scratch. Mangrove seedlings were established on the riparian flats along both sides of the river channel. (Photo credit: Laboratory For Environment & Form)



Fig.3. Location map of mangrove sampling plots in the Jhongdu Wetland Park, Kaohsiung City. Location map of species-specific mangrove sampling plots within Jhongdu Wetland Park, categorized by canopy composition and topography. (@Google Earth)

was constructed in the wetland, with its base consisting of construction waste deposited during Kaohsiung's early urban development. This was overlaid with one meter of loam to support vegetation, which has since exhibited healthy growth.

Sampling setup

The carbon sequestration capacity of restored mangroves in the Jhongdu Wetland Park was studied with reference to the methods of previous studies (Li *et al.*, 2018; Lin *et al.*, 2023). During the field survey conducted in September 2019, only five individual *Kandelia obovata* were found in the wetland and were excluded from further study due to their poor condition. Therefore, this study focused on three other mangrove species: *Avicennia marina*, *Lumnitzera racemosa*, and *Rhizophora stylosa*. To compare the carbon sequestration rates among the three mangrove species, three species-

specific monitoring plots were established within the wetland (Figure 3). Each plot was further subdivided into subplots based on local topography. For *Avicennia marina* and *Lumnitzera racemosa*, three subplots measuring 5 m × 2 m each were delineated. Due to the smaller distribution area of *Rhizophora stylosa*, only one subplot measuring 20 m × 1 m was established. All subplots were located within the intertidal zone. Sampling was conducted during the following periods to cover the whole seasonal variation for a year: autumn (September 26–27, 2019), spring (April 27–28, 2020), summer (July 23–24 and August 31–September 1, 2020), and winter (December 16, 2020). Water quality sampling was conducted at nine designated sites (LR1, LR2, G1, G2, D1, D2, D3, D4, and F). At each site, measurements were performed 1.5 hours prior to both high and low tides during each season. The water quality probe was immersed in the sampled water, and readings were recorded after stabilization of the measured values. Each measurement was replicated three times. Seawater salinity was determined using a conductivity meter (WTW Cond 3210, Germany).

Mangrove carbon sequestration rate

(1) Carbon sequestration rate of mangrove biomass

In this study, mangrove biomass was measured by assigning an identification number to every individual mangrove tree within each plot for the three target species. The parameters required for species-specific allometric equations, previously established in the literature shown below, were measured for each tree. These parameters were then used to calculate the aboveground biomass (AGB) and belowground biomass (BGB). Different allometric equations were applied for each species due to interspecific variation. The allometric equations used for each mangrove species are as follows:

A. Avicennia marina

$$AGB \text{ (kg)} = 0.308 \times (DBH^{2.11}) \text{ (Comley and McGuinness, 2005) (Equation 1)}$$



BGB = $1.28 \times (\text{DBH})^{1.17}$ (Comley and McGuinness, 2005) (Equation 2)
 where DBH: Diameter at Breast Height (DBH) at 1.3 m

B. *Lumnitzera racemosa*

AGB = $0.184 \times (\text{DBH})^{2.384}$ (Kangkuso *et al.*, 2016) (Equation 3)

BGB = $0.196 \times \rho \times 0.899 \times (\text{DBH})^{1.11}$ (Komiya *et al.*, 2005) (Equation 4)

where ρ : Trunk Density (tonne/m³), DBH: Diameter at Breast Height (DBH) at 1.3 m

C. *Rhizophora stylosa*

AGB = $0.045 \times (\text{D}_{0.3})^{2.868}$ (Gevaña and Im, 2016) (Equation 5)

BGB = $0.134 \times (\text{D}_{0.3})^{2.4}$ (Gevaña and Im, 2016) (Equation 6)

where $\text{D}_{0.3}$: Stem diameter measured at 30 cm above the highest prop root (cm)

The measurement method used in this study involved applying species-specific allometric equations to the parameters measured from each tree within the mangrove plots to estimate mangrove biomass. The seasonal change in biomass was then used to calculate the carbon sequestration rate in plant biomass by multiplying the biomass difference between seasons by the carbon content of the vegetation. This yielded the seasonal carbon sequestration rate (tonne C ha⁻¹ season⁻¹). By summing the seasonal values, the annual carbon sequestration rate in plant biomass was obtained (tonne C ha⁻¹ yr⁻¹).

(2) Soil carbon burial rate of mangroves

In each season, soil samples were collected using a soil corer to a depth of 30 cm. The samples were analyzed for soil organic matter (ash-dried, Lin *et al.*, 2020a), soil organic carbon content (dry combustion, Li *et al.*, 2018), bulk density (Lin *et al.*, 2020a), and moisture content (Lin *et al.*, 2020a). By calculating the differences in soil organic carbon content between seasons, the seasonal soil carbon burial rate (tonne C ha⁻¹ season⁻¹) was estimated. Summing the seasonal values yielded the annual soil carbon burial rate (tonne C ha⁻¹ yr⁻¹).

(3) Soil greenhouse gas emissions

A portable gas analyzer (LGR915-0001, Los Gatos Research, San Jose, CA, USA) connected to a closed chamber was used to measure in situ soil GHG emissions within the plots (Lin *et al.*, 2020b, 2021a). Field data were used to estimate GHG fluxes based on the ideal gas law. Each measurement lasted approximately 7 minutes (Lin *et al.*, 2020a, 2021b) to avoid excessive humidity or temperature buildup inside the chamber. This study found no significant difference in CH₄ emission rates between light and dark conditions. Therefore, the CH₄ measurements were conducted mainly under light conditions. Gas fluxes were calculated using the slope of gas concentration over time, the volume of the enclosed space, and the surface area of the chamber base, resulting in GHG fluxes expressed per unit time and per unit area.

$F = (\text{flux} \times V \times c_1) / (RT \times A)$ (Equation 7)

where **F** = GHG flux (μmol CH₄ m⁻² h⁻¹), **flux** = slope of the regression line (change in concentration over time), **V** = volume of the enclosed chamber (L), **c₁** = time unit conversion factor = 3,600 (to convert s⁻¹ to h⁻¹), **R** = ideal gas constant (0.082 L atm K⁻¹ mol⁻¹), **T** = gas temperature inside the chamber (K, absolute temperature), and **A** = surface area of the chamber base (m²).

Methane (CH₄) concentrations were converted to carbon dioxide equivalents (CO₂e) by multiplying the flux by the global warming potential (GWP-100) coefficient (CH₄ = 27.9, Smith *et al.*, 2021). This conversion allows quantification of CH₄ emissions in terms of their impact on the carbon sequestration capacity. Seasonal CH₄ fluxes (tonne C ha⁻¹ season⁻¹) were estimated by multiplying the measured CH₄ flux by 90 days (assuming one season = 90 days). The annual GHG emissions (tonne C ha⁻¹ yr⁻¹) were then obtained by summing the seasonal values.

(4) Mangrove Carbon Sequestration Capacity

Mangrove carbon sequestration rate (tonne C ha⁻¹ yr⁻¹) = Carbon sequestration rate in mangrove biomass + Carbon burial rate in mangrove soils – GHG emission from mangroves

A positive GHG flux indicates emission, while a negative value indicates uptake. Conversely, a positive carbon sequestration value indicates carbon uptake (sink), and a negative value indicates carbon release (source).

To assess seasonal variations in CH₄ emission for each tree species and to evaluate the overall differences in emission between the mangrove species, a non-parametric Kruskal–Wallis analysis and Tukey's honestly significant difference (HSD) test were conducted. Statistical tests were significant when the calculated *p*-value was less than 0.05.

RESULTS

Mangrove restoration status

In the Jhongdu Wetland Park, mangroves were replanted in a ring-shaped zone surrounding the central island. The designed width of the mangrove planting belt was approximately 10–15 meters, with an initial planting density of 5 trees m⁻² using 20 cm tall seedlings. After ten years of natural growth, mortality, and management pruning, substantial structural changes were observed in the mangrove stands. The current average tree densities are approximately 1.5 trees m⁻² for *A. marina*, 1.7 trees m⁻² for *L. racemosa*, and 1.0 tree m⁻² for *R. stylosa*. The average height of all mangrove species exceeded 3 meters. (Table 1). Salinity taken during high tide at the same time across the four seasons showed a significant variation. In autumn, the salinity at site LR1 near the Love River was 6.33 psu, while at site D1 within the wetland it reached 27.1 psu. The large seasonal fluctuations indicate that the water from the Love River is not effectively exchanged with the wetland, suggesting poor hydrological circulation.



Table 1. Basic information of mangrove sampling plots.

Species	Density (trees m ⁻²)	Average DBH (cm)	Average height (m)	Average AGB (Mg/ha)
<i>Avicennia marina</i>	1.5	6.28	4.01	11.073
<i>Lumnitzera racemosa</i>	1.7	2.70	3.05	2.825
<i>Rhizophora stylosa</i>	1.0	3.29	3.55	4.007

Table 2. Changes in the proportion of mangrove area in Kaohsiung Jhongdu Wetland Park (2011–2020)

Species	2011		2020	
	area (m ²)	Proportion (%)	area (m ²)	Proportion (%)
<i>Avicennia marina</i>	1,200	0.310	6,419.48	0.557
<i>Lumnitzera racemosa</i>	1,870	0.483	5,036.85	0.437
<i>Rhizophora stylosa</i>	800	0.206	60.65	0.005

This study focused on *A. marina*, *L. racemosa*, and *R. stylosa* as the primary research subjects. An investigation into the natural growth and decline of these three mangrove species within the park revealed that, during the early seedling restoration phase, *A. marina* exhibited lower abundance and smaller coverage than *L. racemosa*. Over time, however, both species expanded their coverage areas, and in the present survey, *A. marina* had surpassed *L. racemosa* in coverage extent. In contrast, *R. stylosa* showed a decline in both abundance and coverage (Table 2). These results indicate that *A. marina* has become the dominant species in the Jhongdu Wetland (Figure 4).

Carbon sequestration by mangrove biomass

The highest biomass carbon sequestration rate was observed in *A. marina* (39.04 tonne C ha⁻¹ yr⁻¹), while *L. racemosa* (5.83 tonne C ha⁻¹ yr⁻¹) and *R. stylosa* (6.28 tonne C ha⁻¹ yr⁻¹) exhibited similar lower rates. For *A. marina* and *L. racemosa*, carbon sequestration was predominantly allocated to the aboveground biomass, whereas in *R. stylosa*, it was primarily stored in the belowground biomass (Figure 5).

Carbon burial in mangrove soil

The soil carbon burial rate exhibited seasonal fluctuations, with a noticeable decrease observed from spring to summer in 2020. Among the three mangrove species studied, *R. stylosa* (17.51 tonne C ha⁻¹ yr⁻¹) had the highest annual soil carbon burial rate, followed by *L. racemosa* (12.02 tonne C ha⁻¹ yr⁻¹), while *A. marina* showed the lowest rate, with a net loss of -5.65 tonne C ha⁻¹ yr⁻¹ (Figure 6).

Soil Greenhouse Gas Emissions

In the Jhongdu Wetland Park, seasonal variations in CH₄ emissions from mangrove soils showed that all three mangrove species released the most CH₄ during summer. *A. marina* exhibited the highest emission (Figure 7A),



Fig. 4. Distribution map of mangrove species in the Jhongdu Wetland Park.

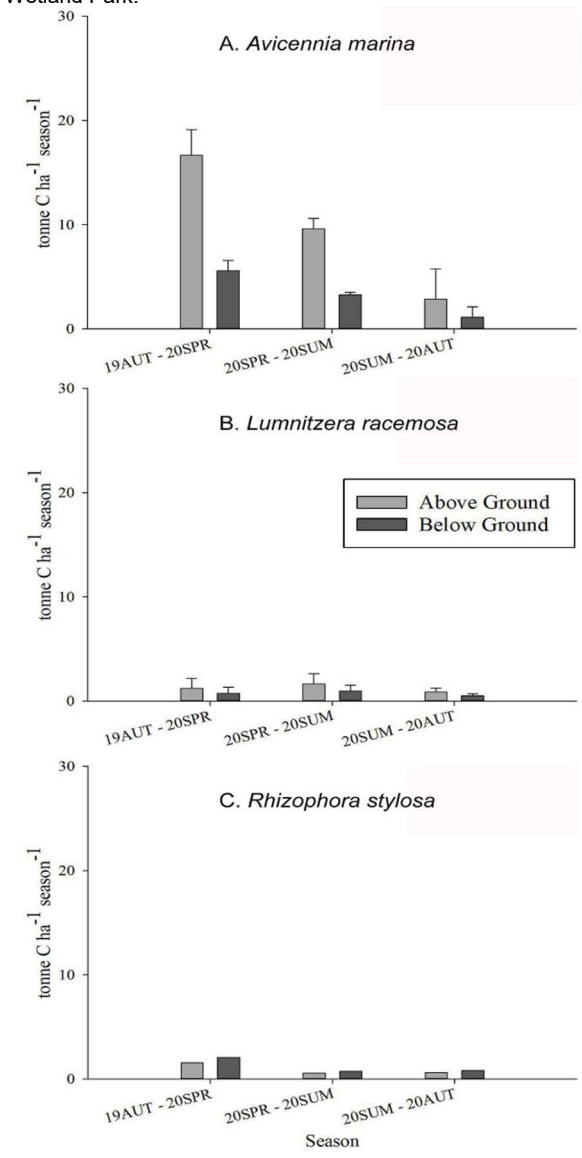


Fig. 5. Carbon sequestration rates of mangrove biomass. **A.** *Avicennia marina* **B.** *Lumnitzera racemosa* **C.** *Rhizophora stylosa* (mean ± standard deviation)

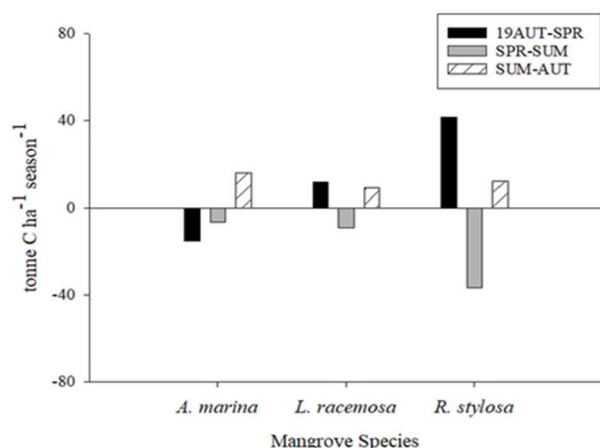


Fig. 6. Soil carbon burial rates in the Jhongdu Wetland Park

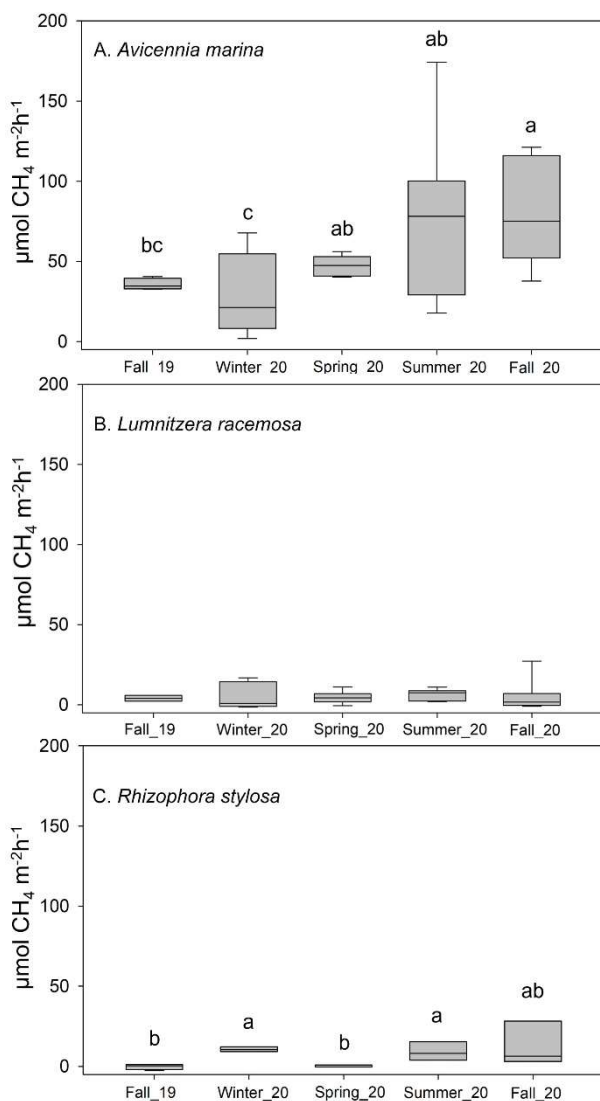


Fig. 7. Methane fluxes from the soils of mangroves of **A. *Avicennia marina***. **B. *Lumnitzera racemosa***. **C. *Rhizophora stylosa***. Different letters indicate significant seasonal differences with the Kruskal–Wallis test and Dunn's test (p -value < 0.05). The English letters represent the results of the post-hoc test.

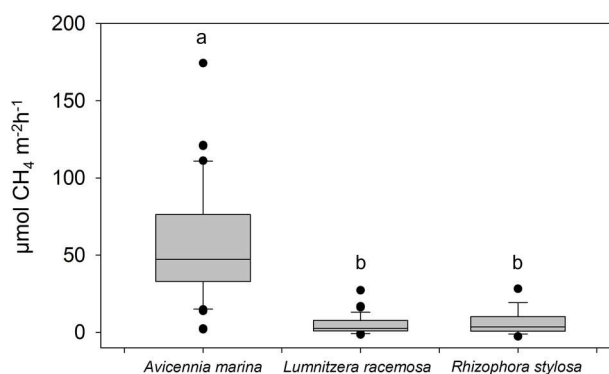


Fig. 8. CH₄ emissions from the *Avicennia marina*, *Lumnitzera racemosa*, and *Rhizophora stylosa* mangrove soils. Different letters represent significant differences among mangrove species with the Kruskal–Wallis test and Dunn's test (p -value < 0.05). The English letters represent the results of the post-hoc test.

followed by *R. stylosa* (Figure 7B) and *L. racemosa* emitted the least (Figure 7C). This is likely due to the structure of their aerial roots, which provide channels for gas exchange from soil respiration through the root system. Figure 8 is a summary of Figure 7, intended for the comparative analysis of CH₄ emissions across the three tree species. By converting the average methane emission measured during each sampling ($\mu\text{mol CH}_4 \text{ m}^{-2} \text{ h}^{-1}$), the seasonal CH₄ emission (tonne C ha⁻¹ season⁻¹) can be obtained. The sum of these seasonal greenhouse gas emissions yields the annual methane emission rate (tonne C ha⁻¹ yr⁻¹). Annual CH₄ emissions were highest in *A. marina* (0.49 tonne C ha⁻¹ yr⁻¹), while both *R. stylosa* (0.06 tonne C ha⁻¹ yr⁻¹) and *L. racemosa* (0.05 tonne C ha⁻¹ yr⁻¹) had similar and lower emission rates.

Carbon sequestration capacity of mangroves

The results showed that the carbon sequestration capacity of the three mangrove species in the Jhongdu Wetland Park is 32.90 tonne C ha⁻¹ yr⁻¹ for *A. marina*, 17.80 tonne C ha⁻¹ yr⁻¹ for *L. racemosa*, and 23.72 tonne C ha⁻¹ yr⁻¹ for *R. stylosa*. Among them, *A. marina* had the highest rate and *L. racemosa* the lowest. Considering the percentage of area covered by mangroves (*Avicennia marina*: 55.74 %; *Lumnitzera racemosa*: 43.73 %; *Rhizophora stylosa*: 0.53 %), the total annual carbon sequestration rate for the entire mangrove wetland at Jhongdu is 26.25 tonne C ha⁻¹ yr⁻¹ (96.26 tonne CO₂e ha⁻¹ yr⁻¹) (Table 3)

DISCUSSION

This study compared the carbon sequestration capacity of the Jhongdu Wetland Park with that of other mangrove systems. According to Li (Li *et al.*, 2018), the annual carbon sequestration rate of Danshui mangroves was 10.86 tonne C ha⁻¹ yr⁻¹, while that of the mangroves in the Jhongdu Wetland Park reached 26.25 tonne C ha⁻¹ yr⁻¹—approximately 2 times higher. When compared with

**Table 3.** Carbon sequestration capacity in Kaohsiung Jhongdu Wetland Park (2019–2020)

Species	Seasons	Carbon sequestration (tonne C ha ⁻¹ season ⁻¹) (A)			Soil Greenhouse gas emissions (tonne C ha ⁻¹ season ⁻¹) (B)	Carbon sequestration capacity (tonne C ha ⁻¹ season ⁻¹) (C) (C= A - B)	CO ₂ e equivalent (tonne CO ₂ e ha ⁻¹ season ⁻¹) (D) D = C × 44/12
		Mangroves		Soil	CH ₄		
		Aboveground	Belowground				
<i>Avicennia marina</i>	19Autumn -Spring	16.65*	5.57*	-15.20*	0.09 0.07	6.86	25.15
	Spring-Summer	9.60	3.27	-6.49	0.12	6.26	22.94
	Summer-Autumn	2.84	1.11	16.04	0.20	19.79	72.56
Summation (tonne CO ₂ e ha ⁻¹ yr ⁻¹)						32.90	120.65
<i>Lumnitzera racemosa</i>	19Autumn -Spring	1.19*	0.73*	11.91*	0.01 0.01	13.80	50.60
	Spring-Summer	1.63	0.95	-9.07	0.01	-6.50	-23.85
	Summer-Autumn	0.85	0.49	9.18	0.02	10.51	38.53
Summation (tonne CO ₂ e ha ⁻¹ yr ⁻¹)						17.80	65.28
<i>Rhizophora stylosa</i>	19Autumn -Spring	1.53*	2.05*	41.53*	3.30 × 10 ⁻⁴ 0.03	45.08	165.28
	Spring-Summer	0.55	0.72	-36.53	1.05 × 10 ⁻³	-35.26	-129.29
	Summer-Autumn	0.61	0.82	12.51	0.02	13.91	50.99
Summation (tonne CO ₂ e ha ⁻¹ yr ⁻¹)						23.72	86.98

Note: A positive value for greenhouse gas emissions indicates emission, while a negative value indicates sequestration; a positive value for carbon sequestration indicates sequestration, while a negative value indicates emission. *: Due to the absence of winter measurements for biomass and soil carbon stock, the plant and soil carbon sequestration rates represent the summation values for the 19Autumn -Spring period.

the natural mangroves at Chiku, which had an annual rate of 12.64 tonne C ha⁻¹ yr⁻¹ (Li *et al.*, 2018), the carbon sequestration rate of the mangroves in the Jhongdu Wetland Park was approximately 2 times greater. A further comparison was made with other nearby restored *A. marina* mangroves designed for wastewater purification in Dapeng Bay and the Datan Wetland Park in Pintung. The annual carbon sequestration rates were 8.04 tonne C ha⁻¹ yr⁻¹ for Dapeng Bay and 6.09 tonne C ha⁻¹ yr⁻¹ for Datan (Yang, 2018). *A. marina* in the Jhongdu Wetland Park exhibits a significantly higher rate of 32.90 tonne C ha⁻¹ yr⁻¹, exceeding those of both Dapeng Bay and Datan. The relatively higher carbon sequestration capacity of the Jhongdu Wetland Park compared with other mangrove ecosystems may be attributed to its unique substrate characteristics. The base layer of the wetland is composed of concrete and brick debris, combined with an engineered water circulation system that maintains a high level of dissolved oxygen. Mangrove ecosystems are characterized by high productivity and slow soil decomposition rates, enabling them to function as efficient carbon sinks. In addition, because the Jhongdu Wetland receives urban wastewater from the Love River, the water contains elevated concentrations of organic matter and nutrients. This eutrophic condition may stimulate high net primary productivity and substantial litterfall input, thereby enhancing the overall carbon sequestration capacity of the mangrove system. Furthermore, the higher carbon sequestration rate observed in this study compared with previously reported values may be attributed to differences in species composition, latitudinal environmental factors, and the relatively young age of the mangrove stands in the

Jhongdu Wetland, which are currently in a rapid growth phase. Therefore, continuous long-term monitoring and systematic assessment are essential to track future variations in carbon dynamics and ecological succession.

This reduction in density allows each tree greater exposure to sunlight, promoting efficient photosynthesis. The ample growing space also supports robust root system development. Furthermore, since the substrate of the Jhongdu Wetland consists of concrete and previously cleared waste materials, its porous structure differs significantly from that of natural coastal mangrove mudflats. This is presumed to be one of the reasons for the faster mangrove growth and the higher carbon sequestration rate observed compared to other natural mangroves.

Biochemical processes are primarily driven by anaerobic microorganisms that decompose and transform organic matter under anoxic and reductive conditions, resulting in CH₄ production. Compared with the previous study of Livesley and Andrusiak (2012), which reported an annual CH₄ emission flux of 0.22 Mg C ha⁻¹ yr⁻¹ in wetlands, the emission levels in the Jhongdu Wetland Park are considerably lower. In this study, the reduced CH₄ emissions are likely to result from the construction characteristics of the Jhongdu Wetland Park, where large-pore concrete blocks were retained as the soil foundation and the installation of water circulation and aeration systems in 2015, known as “Jhongdu Wetland Park Water Quality Improvement Project.” This project included the implementation of overflow structures, water transport pipelines, submersible wastewater pumps, and cascading pebble drops designed to promote aeration and improve poor water exchange. These interventions reduced



anaerobic conditions within the wetland, and the resulting increase in water dissolved oxygen is believed to be a key factor contributing to the lower CH₄ emissions observed.

The substrate of the Jhongdu Wetland Park consists of construction-grade concrete blocks, and the overlying soil layer has relatively large particle sizes, which contribute to higher GHG fluxes. To enhance the wetland's carbon sequestration capacity, it is recommended to amend the substrate with finer materials such as sand and clay to improve carbon burial potential. Natural wetlands possess inherent characteristics that allow carbon to be buried in the soil. However, the artificial soil conditions of the Jhongdu Wetland Park may instead lead to increased CO₂ emissions due to their physical structure. Nonetheless, the water and soil conditions in the Jhongdu Wetland Park still support favorable mangrove growth. These conditions promote high net primary productivity, which exceeds carbon losses, thus achieving a state where carbon inputs surpass outputs, meeting the requirements for the wetland to function as an effective carbon sink.

This study shows that substantial seasonal variation in water salinity levels during high tide, indicating poor water exchange between the Love River and the Jhongdu Wetland Park. The primary reason is that the Jhongdu Wetland Park has been in operation for over ten years, during which time sedimentation of soil and organic matter has altered the elevation of the wetland bottom compared to its original design. As a result, tidal fluctuations from the Love River are insufficient to drive water movement through the entire wetland, especially at its far end, leading to stagnant conditions and inadequate water exchange.

Currently, the Jhongdu Wetland Park is maintained primarily for urban park aesthetics, with large-scale pruning and removal of mangroves conducted when litter biomass accumulation becomes excessive. One of the key factors influencing carbon sequestration capacity in mangroves is tree density. In the Erlin River estuary in Changhua, Ho *et al.* (2018) found that thinning could enhance the carbon sequestration capacity of mangroves. Specifically, the carbon sequestration rate of individual trees was significantly higher under heavy thinning compared to moderate thinning. This suggests that, following heavy thinning, the overall stand density is greatly reduced, thereby minimizing intraspecific competition and allowing the remaining trees to receive more sunlight and nutrients. As a result, individual trees exhibited increased net primary productivity, which in turn raised their carbon sequestration rate. Analysis of the relationship between aboveground carbon sequestration capacity and tree density revealed that the carbon sequestration rate of individual tree decreased as tree density increased. Consequently, heavy thinning, which resulted in the lowest tree density, led to the highest per-tree carbon sequestration. However, from the perspective of the entire mangrove ecosystem and in pursuit of maximizing ecosystem-level carbon sequestration services, moderate

thinning was found to be more appropriate. In the Jhongdu Wetland Park, current tree density, particularly for *A. marina*, is maintained at approximately ≥ 1.5 trees m² through a combination of human management and natural succession. When balancing both individual performance and overall ecosystem function, moderate thinning appears to be the most effective strategy for optimizing carbon sink services.

Furthermore, based on the findings of this study, it is recommended that future mangrove restoration projects implemented under similar environmental conditions in Taiwan adopt a planting density of three seedlings per square meter during the initial establishment phase.

CONCLUSIONS

All three mangrove species in the Jhongdu Wetland Park function as effective carbon sinks, fulfilling the carbon sequestration objectives envisioned during the wetland's planning and design. The wetland possesses the capacity to offset part of Kaohsiung City's per capita GHG emissions, thereby contributing to the city's climate adaptation capability. Based on the measurements of this study, the mangroves in the Jhongdu Wetland Park were found to sequester 26.25 tonne C ha⁻¹ yr⁻¹, which is equivalent to 96.26 tonnes of CO₂-equivalent (CO₂e) ha⁻¹ yr⁻¹. This study confirms that the mangroves in the Jhongdu Wetland Park provide a high level of carbon sequestration capacity. It is recommended that future coastal areas prioritize mangrove planting for CO₂ removal purposes and actively promote mangroves as nature-based climate solutions. In particular, the mangroves in the Jhongdu Wetland Park should be further managed through appropriate thinning strategies to optimize carbon sequestration capacity. It is recommended that the thinning density of mangroves within the park be maintained at 1–2 trees/m², with thinning carried out once every year.

In 2025, Taiwan officially adopted a national methodology for mangrove afforestation-based carbon reduction, thereby establishing a scientific framework for quantifying marine carbon sinks. This methodological advancement provides a fundamental reference for integrating blue carbon data into the national greenhouse gas (GHG) inventory and carbon reduction certification mechanisms. The findings of this study offer important empirical support for local governments in incorporating mangrove carbon sink assessments into regional climate mitigation and adaptation policies.

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