



Mangrove forest structure and diversity in Tha Kam Island, Bang Pakong Estuary, Chachoengsao Province: implications for conservation and restoration

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Abstract

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This study evaluated species composition, forest structure, and biodiversity of the natural mangrove area (NA) and the mangrove restoration (RA) areas on Tha Kam Natural Island (13.495873°N, 100.981029°E) in the Bang Pakong estuary, Chachoengsao Province, Thailand. Vegetation surveys were conducted using a systematic line transect method with 10 × 10 m sampling plots established along geomorphological gradients. A total of nine mangrove species were recorded across both sites, including eight tree species and one shrub (*Acanthus ilicifolius*). The RA exhibited a higher tree density (31.71±19.01 trees per 100 m²) than the NA (21.71±9.54 trees per 100 m²). However, the NA showed greater structural maturity, as reflected by a higher basal area (0.41 m² per 100 m²) and greater species diversity (Shannon–Wiener index, $H' = 1.140$). In contrast, the RA exhibited lower diversity ($H' = 0.480$) and evenness ($J' = 0.268$), indicating dominance by *Rhizophora mucronata* and reflecting an early successional stage. These findings indicate that although reforestation has increased vegetation density, the restored forest still exhibits lower species diversity and limited structural heterogeneity, reflecting an early successional stage. Enhancing these structural and compositional attributes will be essential for strengthening long-term ecosystem resilience and increasing blue carbon sequestration potential in this estuarine mangrove ecosystem.

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1. Introduction

Mangrove ecosystems are vital coastal wetlands distributed across tropical and subtropical regions worldwide, heavily shaped by tidal dynamics. These ecosystems comprise specialized plant communities with unique physiological and structural adaptations that allow them to thrive in high-salinity, waterlogged, and anaerobic (low-oxygen) environments. Compared to terrestrial vegetation, mangroves exhibit lower freshwater requirements and reduced evapotranspiration rates, enabling persistence in fluctuating saline and brackish conditions [1, 2]. These forests provide essential ecosystem services, such as shoreline stabilization, wave energy attenuation, sediment trapping, and nutrient cycling, all of which enhance ecosystem health [3, 4].

Furthermore, mangroves serve as critical nursery habitats for juvenile marine species, supporting coastal fisheries and local livelihoods. They are recognized as important blue carbon reservoirs because their exceptional sequestration capacity is strongly influenced by species diversity and structural parameters such as tree density and diameter at breast height (DBH). Alongside seagrasses and salt marshes, mangroves sequester atmospheric CO₂ into

both aboveground biomass and long-term belowground sediment storage, where anaerobic conditions facilitate carbon preservation over millennial timescales [5 - 7]. In the Indo-Pacific, which accounts for approximately 40% of global mangrove extent, carbon ecosystem stocks can exceed 1,000 Mg C ha⁻¹ [5, 7]. Mangrove conservation, therefore, represents a key nature-based solution for climate change mitigation [8, 9]. In Thailand, mangrove forests have declined over the past decades due to land-use conversion for aquaculture, salt farming, agriculture, infrastructure development, and urban expansion [10, 11]. Recently, evidence suggests that the rate of mangrove forest decline has begun to stabilize, with indications of gradual recovery in some areas [11 - 13]. Empirical evaluations comparing structural recovery between natural and restoration mangrove stands remain limited, particularly in estuarine environments of the inner Gulf of Thailand.

Despite signs of recovery, mangrove forests in the inner Gulf of Thailand remain vulnerable to anthropogenic disturbance and hydrological variability associated with estuarine dynamics. In Chachoengsao Province, the Bang Pakong Estuary supports remnant mangroves, including Tha

Kham Natural Island (Koh Nok). Formed by natural sediment deposition. While parts of the island have undergone natural regeneration and assisted restoration, ongoing pressures from historical clearing, shrimp farming, industrial discharge, and urban runoff persist. Despite its ecological significance, particularly its role as a foraging ground for endangered marine mammals such as a foraging ground for endangered marine mammals, including the Irrawaddy dolphin (*Orcaella brevirostris*), Indo-Pacific humpback dolphin (*Sousa chinensis*), and Finless porpoise (*Neophocaena phocaenoides*) [11], quantitative assessments of structural and compositional differences between natural and restoration stands remain scarce. The application of wise use principles is integral to fostering sustainable coexistence between communities and estuarine biodiversity. Systematic and continuous monitoring of forest structure and species composition is essential to guide restoration efforts that enhance ecological integrity and long-term resilience.

This study aims to evaluate the community structure and species composition of mangrove ecosystems across natural and restored stands on Tha Kham Island, providing evidence on the ecological effectiveness of mangrove restoration. By comparing key structural attributes between restored and natural stands, this study assesses whether restoration mangroves functionally resemble natural ecosystems. Such ecological evidence is essential for informing climate change mitigation strategies and supporting the achievement of the Sustainable Development Goals (SDGs), particularly Goal 13 (Climate Action) and Goal 14 (Life Below Water). Ultimately, the findings provide baseline ecological data to support long-term monitoring and sustainable coastal resource management through data-driven planning.

2. Materials and Methods

Study Area

The study was conducted on Tha Kam Natural Island (Koh Nok), located in the Bang Pakong Estuary, Chachoengsao Province, Thailand. The island's precise geographic location is centered at GPS coordinates 13.495873°N, 100.981029°E. The mangrove forest on the island was classified into two distinct areas based on management history: (1) a natural mangrove forest area (NA), which represents the mature, original forest structure, and (2) a restoration mangrove forest area (RA), which is an abandoned aquaculture site undergoing natural and assisted recovery since 1992. The study areas were delineated in the field based on observable differences in vegetation structure and land-use history, distinguishing the mature natural mangrove stand from the adjacent restoration area. Within each area, linear transects were established perpendicular to the shoreline, extending from the seaward margin toward the interior forest to capture spatial variation in stand structure.

Vegetation Sampling and Species Identification

Data were collected using a systematic transect sampling method. Two line transects were established—one within

the natural mangrove stand and one within the restoration mangrove stand. Along each transect, five 10 × 10 m square plots were positioned at 50 m intervals, resulting in a total of 10 sampling plots with a combined sampled area of 1,000 m². Within each plot, all trees with a diameter at breast height (DBH) ≥ 4.0 cm were identified and measured. For species with prop roots (*Rhizophora* spp.), diameter was measured at 20 cm above the collar of the highest prop root. For other genera without prop roots (e.g., *Sonneratia*, *Avicennia*, and *Xylocarpus*), DBH was measured at 1.30 m above ground level. Species, total height, and diameter were recorded for all individual trees within each plot [14 - 17]. Species identification was conducted using the floristic manuals of [13, 14, 16 - 20], and nomenclature was cross-checked against the World Flora online (WFO) to ensure the use of currently accepted scientific names [21].

Data Analysis

Data analysis was performed quantitatively in Microsoft Excel. The importance Value Index (IVI) was calculated to assess species dominance and forest structure following standard ecological methods [14 - 16]. Species diversity and community evenness were assessed using the Shannon–Wiener diversity index (H') and Pielou's evenness index (J') [21 - 24]. The IVI was calculated as the sum of relative frequency, relative density, and relative dominance, as presented in Equation (1)

$$IVI = RF + RD + RDo \quad (1)$$

Where RF is the relative frequency, RD is the relative density, and RDo is the relative dominance (calculated from Basal Area).

The Calculation of Relative Values

To enable comparisons among mangrove species across different sampling zones, the primary structural parameters were converted into relative values expressed as percentages, with each parameter summing to 100%. These relative measures included Relative Density (RD), Relative Frequency (RF), and Relative Dominance (RDo), which collectively describe the structural and ecological importance of each species within the mangrove community. The relative values were calculated using the following equations:

$$\text{Relative Frequency (RF)} = \frac{f_i}{\sum f} \times 100 \quad (2)$$

$$\text{Relative Density (RD)} = \frac{n_i}{\sum n} \times 100 \quad (3)$$

$$\text{Relative Dominance (RDo)} = \frac{BA_i}{\sum BA} \times 100 \quad (4)$$

where f_i is the frequency of occurrence of species i , $\sum f$ is the summed frequency of all species, n_i is the total number of individuals of species i recorded in all sampling quadrats, $\sum n$ is the total number of individuals of all species within the

sampled area, BA_i represents the total basal area of species i , and $\sum BA$ is the total basal area of all species. These relative structural values were subsequently integrated to calculate the Importance Value Index (IVI), which provides an overall measure of the ecological significance of each species within the mangrove community.

Species Diversity

The calculation and interpretation of species diversity for each site were performed using the Shannon-Wiener Diversity Index (H') and Pielou's Evenness Index (J') [14, 22 - 24] as equations:

$$H' = -\sum_{i=1}^S p_i (\ln p_i) \quad (5)$$

Pielou's Evenness Index (J')

$$J' = \frac{H'}{\ln S} \quad (6)$$

Where H' is the Shannon-Wiener diversity index, and p_i is the proportion of individuals of the i^{th} species ($p_i = n_i/N$), n_i is the number of individuals of species, N is the total number of individuals of all species, S is the total number of species, and $\ln$ is the natural logarithm. J' is Pielou's evenness index, where the value of J' ranges from 0 to 1, with values closer to 1 indicating a more even distribution of individuals among species.

Species Similarity

The similarity of mangrove species composition between the natural area (NA) and the mangrove restoration area (RA) was assessed using the Sørensen similarity index [14], calculated as follows:

$$C_s = \frac{2C}{A+B} \quad (7)$$

Where A is the total number of species recorded in the natural area, B is the total number of species recorded in the mangrove restoration area, and C is the number of species shared by both areas.

3. Results and Discussion

The vegetation survey on Tha Kam Natural Island recorded a total of nine mangrove species across both the natural area (NA) and the mangrove restoration area (RA), comprising eight tree species and one shrub species, *Acanthus ilicifolius*. The taxonomic composition is summarized in Table 1, with families Rhizophoraceae, Sonneratiaceae, Meliaceae, and Acanthaceae being the most represented. Although species richness was identical in both areas ($n = 9$), the number of species recorded in this study was lower than that reported in the previous survey of the island. This difference may reflect temporal variations in community composition driven by environmental dynamics and disturbance regimes affecting the mangrove ecosystem.

In addition, the present survey focused on trees with a diameter at breast height (DBH) ≥ 4.0 cm within selected sampling plots. It did not encompass the entire island, which may have contributed to the lower number of species recorded compared to earlier studies [10, 11, 13, 18].

Marked differences in stand structure were observed between the two management zones, as detailed in Table 2. The RA exhibited a higher mean tree density (31.71 ± 19.01 individuals per 100 m^2) than the natural mangrove (21.71 ± 9.54 individuals per 100 m^2), likely reflecting the impacts of restoration planting or natural regeneration. Conversely, the NA demonstrated greater structural maturity, with a mean basal area of 0.41 m^2 per 100 m^2 , nearly double that of the RA (0.27 m^2 per 100 m^2). Such structural patterns are commonly associated with different stages of mangrove forest development, where dense stands of smaller trees characterize earlier successional stages, while larger basal area indicates more mature forest conditions [10, 25 - 28]. This pattern is visually substantiated in Fig. 1 (b) - (c), where mature *Rhizophora mucronata* stands exhibit extensive prop root systems that enhance stability in soft alluvial sediments and tidal environments [1, 7]. Additionally, the detailed leaf morphology (Fig. 1 (d)) and propagule development (Fig. 1 (e)) confirm the healthy reproductive state of this dominant mangrove species.

The diversity of the community is further illustrated in Fig. 2 (f) - (l), which highlights the morphological characteristics of several pioneer species essential for early-stage forest establishment. These include the vibrant green canopy and resilient leaf arrangements of pioneer mangrove trees (Fig. 2 (f) and (h)). Significant emphasis is placed on the specialized reproductive and vegetative structures that facilitate rapid colonization in estuarine environments. This includes the globular fruit of *Sonneratia* species (Fig. 2 (g)) and the delicate flowering clusters of *Avicennia* species (Fig. (j)). Furthermore, the detailed leaf morphology of *Avicennia* species is illustrated in Fig. 2 (k) and (l), showing the characteristic elliptic to obovate leaf shape, which is typical of the genus and salt-excreting surfaces that allow these pioneer trees to thrive in high-salinity zones. These pioneer taxa are instrumental in stabilizing alluvial mud, creating a micro-environment suitable for subsequent successional stages on Tha Kam Natural Island. These morphological attributes, summarized in the Graphical Abstract (Fig. 3), serve as key indicators of active forest recovery and are closely linked to the ecosystem's carbon storage potential.

Consistent with previous studies, the structural characteristics observed at Tha Kam Natural Island indicate a high potential for biomass accumulation and carbon storage. Chumriang *et al.* [29] reported that structural maturity and species composition are key drivers of biomass carbon stocks in mangrove forests of central Thailand. Their study in Phetchaburi, further indicates that natural mangrove remnants (NA), characterized by greater basal area and structural complexity, often exhibit higher carbon density than younger restored stands (RA). Diversity and evenness indices were higher in the natural area (NA) than in the restoration area (RA) as presented in Table 2.

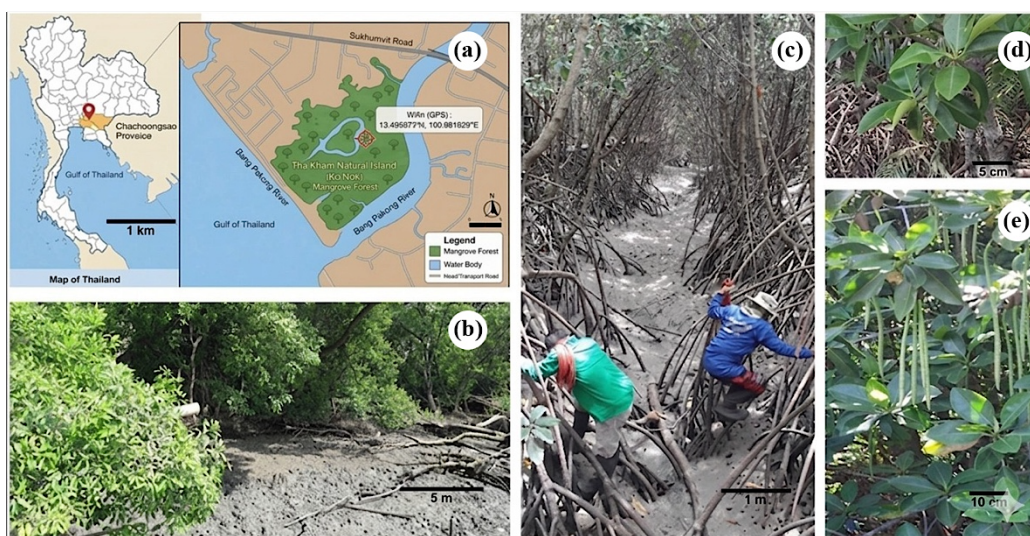


Fig. 1 Geographic location and field characteristics of the study area at Tha Kham Natural Island, Bang Pakong Estuary, Chachoengsao Province, Thailand. (a) Location map showing the study site and GPS coordinates, (b) overview of the fringe mangrove forest, (c) Field measurements conducted within the prop root systems of *Rhizophora mucronata*, (d) Leaf morphology showing the characteristics of the mucronate tip, and (e) Propagule development of *R. mucronata*.

Table 1 Species composition and growth forms of mangrove species recorded in the natural (NA) and restored (RA) areas.

No.	Local Name	Scientific Name	Family
1	Kong Kang Bai Lek	<i>Rhizophora apiculata</i>	Rhizophoraceae
2	Lamphu	<i>Sonneratia caseolaris</i>	Sonneratiaceae
3	Lampan	<i>Sonneratia ovata</i>	Sonneratiaceae
4	Samae Dam	<i>Avicennia officinalis</i>	Acanthaceae
5	Samae Khao	<i>Avicennia alba</i>	Acanthaceae
6	Taboon Khao	<i>Xylocarpus granatum</i>	Meliaceae
7	Taboon Dam	<i>Xylocarpus moluccensis</i>	Meliaceae
8	Kong Kang Bai Yai	<i>Rhizophora mucronata</i>	Rhizophoraceae
9	Ngueak Pla Mo Dok Muang	<i>Acanthus filicifolius</i>	Acanthaceae

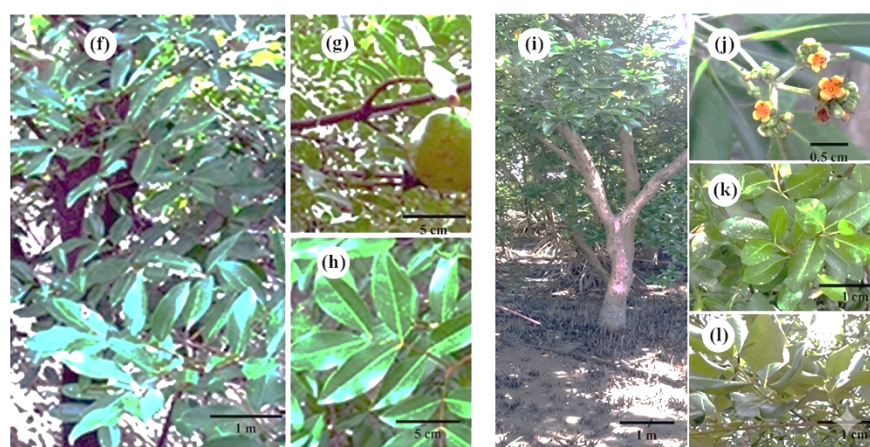


Fig. 2 Morphological characteristics of dominant mangrove species at the study site. (f), (g), and (h) are *Xylocarpus moluccensis*, (f) stem, (g) fruit, and (h) pinnate leaves. (i), (j), (k), and (l) are *Avicennia officinalis*, (i) pencil-like pneumatophores, (j) orange inflorescence, (k) adaxial leaf surface, and (l) the abaxial leaf surface. Scale bars: (f) and (i) 1 m; (g) and (h) 5 cm; (j) 0.5 cm; and (k) and (l) 1 cm.

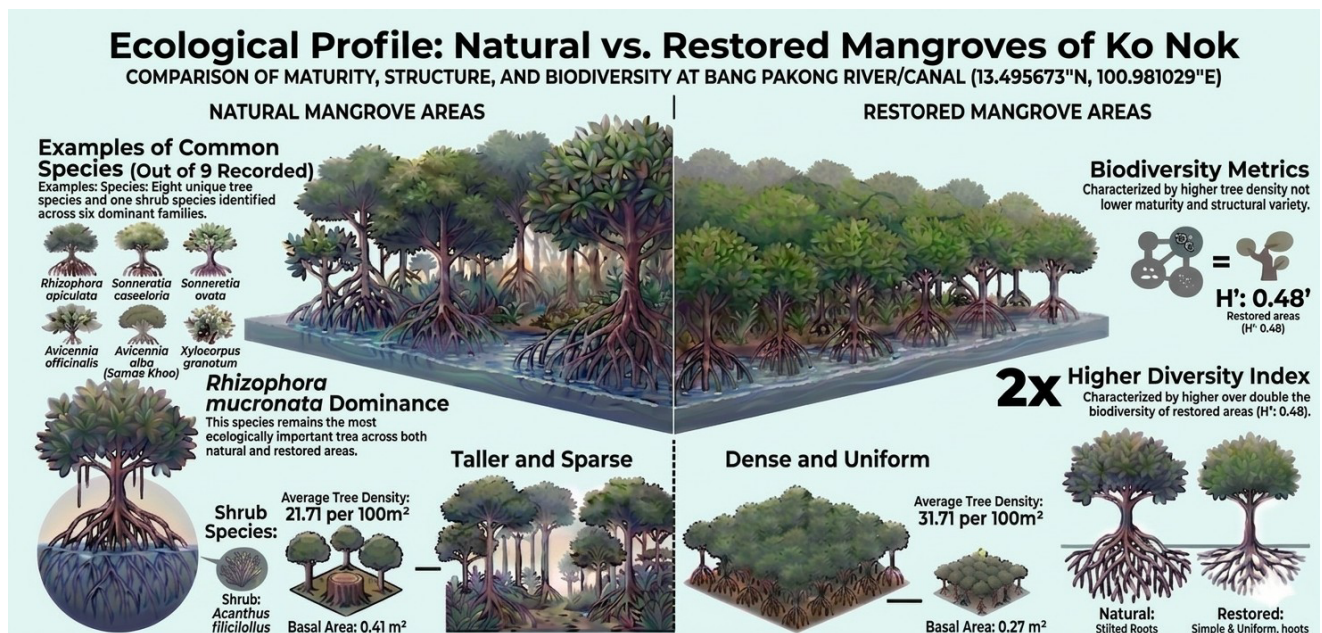


Fig. 3 Comparison of mangrove forest structure and biodiversity between the Natural Area (NA) and the Restoration Area (RA) at Ko Nok.

Table 2 Forest structure parameters and diversity indices of mangrove communities in the restoration area (RA) and natural area (NA) at Tha Kham Natural Island.

Parameters	RA	NA
Tree density (individuals 100 per m ²)	31.71 ± 19.01	21.71 ± 9.54
Basal area (m ² per 100 m ²)	0.27	0.41
Pielou's evenness index (J')	0.27	0.71
Shannon–Wiener diversity index (H')	0.48	1.14
Sørensen similarity index (Cs)	1.00	1.00

The Shannon–Wiener index (H') in the NA was 1.140, whereas the RA showed an exceptionally low value of 0.480. Similarly, Pielou's evenness index (J') was 0.71 in the NA but only 0.27 in the RA. Such low diversity values (H' < 1.0) are commonly associated with early successional stages or environmentally stressed communities [30 - 33]. In the present study, this pattern likely reflects the early successional status of the RA, where the community is dominated by pioneer mangrove species such as *Rhizophora mucronata* and *Avicennia* spp., following its history as an abandoned aquaculture site. In contrast, the NA exhibited higher diversity, indicating a more structurally complex and ecologically stable mangrove community. Structural attributes further support this pattern: the RA exhibited higher tree density (31.71 trees per 100 m²) but lower basal area (0.27 m² per 100 m²), whereas the NA showed a larger basal area (0.41 m² per 100 m²) and greater species diversity. Despite these structural differences, the Sørensen similarity index (Cs = 1.00) indicates that both areas share the same set of mangrove species, indicating that the differences between the RA and NA are primarily related to variations in stand structure, species dominance, and successional stage rather than species presence or absence. Nevertheless, the diversity recorded in the NA remains comparable to values reported in other mangrove ecosystems, such as the Bang Pakong

estuary in Thailand (0.95–1.15) [10] and mangrove forests in India (H' = 1.18) [26].

The Importance Value Index (IVI) indicated that *Rhizophora mucronata* was the most dominant species in both natural and restored mangrove stands (Table 3). The dominance of the family Rhizophoraceae is consistent with mangrove zonation patterns commonly reported in Thai mangrove ecosystems, where the tidal inundation regimes, soil salinity, and sediment characteristics play key roles in determining species distribution [1, 3, 25, 26, 28 - 31, 34]. Higher IVI values for *Avicennia* and *Sonneratia* spp. in the restored mangrove stand indicate their ecological importance during early successional stages. These taxa are widely recognized for their tolerance to disturbed substrates and their specialized root adaptations that facilitate establishment under fluctuating environmental conditions [1, 10, 12, 26, 28, 35].

Despite the successful re-establishment of key mangrove species, the restoration area exhibited limited forest maturity, as reflected by low basal area (0.27 m² per 100 m²) and low species diversity (H' = 0.48) compared with the natural area. Such structural simplicity indicates that ecosystem development remains incomplete, with community composition still dominated by pioneer mangrove species.

The dominance of *Sonneratia* and *Avicennia* in the restored area reflects an active but incomplete recovery trajectory driven primarily by stress-tolerant, fast-colonizing pioneer taxa rather than by late-successional species.

This structural simplicity, together with low basal area and species diversity, indicates that restoration efforts should extend beyond tree establishment to prioritize increasing species diversity and vertical structural heterogeneity to facilitate successional advancement. Based on these findings, evaluating the carbon storage potential of

the restored area is essential for developing robust blue carbon accounting frameworks. This perspective is consistent with Lovelock *et al.* [36], who emphasized the importance of model-based approaches for informing national mangrove restoration strategies. Such function-oriented management is critical for improving long-term ecosystem functioning, ecological resilience, and carbon sequestration capacity, thereby reinforcing the role of mangrove forests as effective blue carbon ecosystems within the Bang Pakong Estuary [8, 9, 16, 26, 28, 33].

Table 3 Importance Value Index (IVI) of key species in Natural (NA) and Restoration area (RA) at Tha Kam Natural Island.

Area/habitat	Species	RDo (%)	RD (%)	RF (%)	IVI
NA	<i>Rhizophora mucronata</i>	62.49	87.39	46.67	196.55
	<i>Sonneratia</i> sp.	28.11	9.91	20.00	58.02
	<i>Avicennia officinalis</i>	7.69	0.90	6.67	15.25
	<i>Avicennia alba</i>	0.23	0.90	13.33	14.46
	<i>Xylocarpus</i> spp.	1.24	0.45	6.67	8.36
RA	<i>Rhizophora mucronata</i>	20.88	55.27	41.67	117.82
	<i>Sonneratia</i> spp.	42.31	20.40	33.33	96.05
	<i>Avicennia officinalis</i>	21.83	15.79	8.33	45.96
	<i>Avicennia alba</i>	10.17	6.58	8.33	25.08
	<i>Xylocarpus</i> spp.	5.59	1.97	8.33	15.90

Note: RD = relative density (%); RF = relative frequency (%); RDo = relative dominance (%); IVI = Important Value Index, calculated as the sum of RD, RF, and RDo.

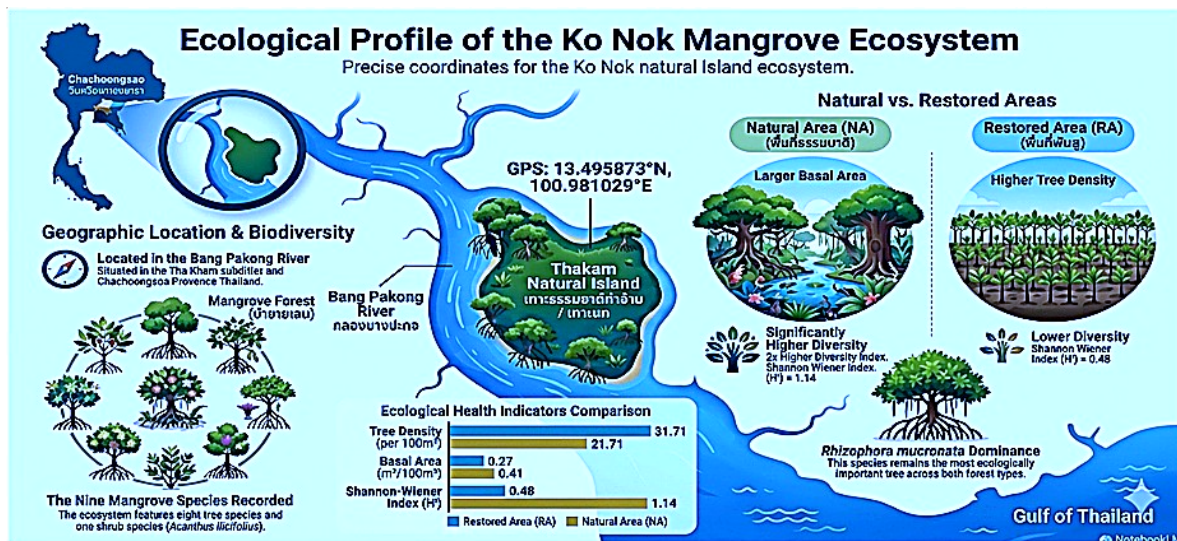


Fig. 4 Graphical summary of the Ko Nok mangrove ecosystem comparing natural (NA) and restoration (RA) areas (13.495873°N, 100.981029°E). The RA shows higher tree density (31.71 trees per 100 m²), whereas the NA exhibits greater structural maturity (basal area = 0.41 m² per 100 m²) and higher biodiversity (Shannon–Wiener index, $H' = 1.14$). Pioneer dominance (*Sonneratia* and *Avicennia*) reflects ongoing ecological succession.

4. Conclusion

As illustrated in Fig.4, the mangrove communities of Tha Kam Natural Island exhibit clear contrasts in structural development and successional status between natural and

restored forests. Although both forest types are dominated by *Rhizophora mucronata* and *Sonneratia* spp., the restored mangrove exhibits high stem density but low basal area and species diversity, indicating an early stage of ecological

succession. In contrast, the natural mangrove shows greater structural maturity, reflecting advanced successional development and more stable ecosystem functioning. These results demonstrate that similarity in dominant species does not necessarily imply functional equivalence. To promote successional advancement and enhance blue carbon potential, restoration strategies should extend beyond density-based planting and emphasize the enrichment of native mangrove species and the development of vertical and compositional heterogeneity. Such function-oriented restoration is critical for strengthening long-term carbon sequestration and reinforcing the role of mangrove ecosystems as effective blue carbon sinks in the Bang Pakong Estuary.

5. Suggestions

This study provides a detailed ecological assessment of the natural and restored mangrove zones on the Tha Kam Natural Islands; however, the sampling transects did not cover the entire Island, which may have led to an underestimation of species richness compared to historical records. Future studies should therefore expand spatial coverage to include the island interior and the distal margins of the Bang Pakong Estuary, and incorporate multi-seasonal sampling to capture temporal variability and transient species. A stratified random sampling design would better represent geomorphological heterogeneity and diverse microhabitats, such as inner mudflats and salt pans. Integrating remote sensing data with field surveys could also improve the assessment of long-term changes in mangrove canopy cover and landscape configuration. Future research should further quantify blue carbon stocks through combined measurements of aboveground biomass and soil organic carbon, together with long-term monitoring of successional dynamics in restored stands.

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7. Declaration of Generative AI in Scientific Writing

The authors declare that generative artificial intelligence was used only for language editing to improve clarity and academic writing style. The use of AI did not affect the study design, data analysis, results, or conclusions. All content and responsibility for the manuscript remain with the authors.

8. CRediT Author Statement

Sureeporn Thummikkaphong: Conceptualization, methodology, investigation, and project administration.

Nutcharin Kleawkla: Conceptualization, methodology, formal analysis, data curation, visualization, writing – original draft, and writing – review & editing. Both authors contributed equally to this work.

9. Research Involving Human and Animal Rights

This study did not involve human participants or live animals; therefore, ethical approval and informed consent were not required.

10. Ethics Approval and Consent to Participate

Not applicable. This study did not involve human participants, human data, or animals.

11. Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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