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ECOLOGICAL PATTERNS OF NIPA PALM (*Nypa fruticans*) IN PEATLAND MANGROVES OF EASTERN SUMATRA

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ABSTRACT

This study examines the ecological patterns of the nipa palm (*Nypa fruticans*) in the peatland ecosystems of Eastern Sumatra. A field survey was conducted at freshwater estuarine zone-1, transitional brackish water zone-2, and the coastal zone-3. Morphometric measurements are frond height, leaf count, and fronds per clump of *N. fruticans*. The study reveals an ecological gradient pattern in zone-1, where the highest clump density is 510 clumps per hectare, the tallest fronds reach 7.32 m, and the highest leaf production is 122 leaves per frond. Zone-2 showed a moderate value of 126 clumps per hectare, 6.11 m frond height, and 110 leaves. Zone-3 exhibited the lowest density of 100 clumps per hectare, shorter fronds 3.57 m, and fewer leaves 90 per frond. These variations in ecological patterns highlight species preferences for freshwater-rich estuarine environments, influenced by hydrological gradients, salinity, and sediment dynamics. Nipa palms provide essential ecosystem services, including carbon storage and sediment stabilization, which support local livelihoods. However, the study's limitations, including a single site and time, call for broader assessments. Management implications stress the need for zone-specific conservation and sustainable resource use. Overall, these findings emphasize the ecological and socio-economic importance of nipa palms for climate adaptation and ecological management in Southeast Asian peatland mangroves.

Keywords: *Nypa fruticans*, peatland, ecological-pattern, Jambi, Sumtra

ISSN: 2455-6939

Volume: 11, Issue: 05 "September-October 2025"

1. INTRODUCTION

Indonesia is home to the world's largest mangrove estate, covering approximately 2.7 million hectares as of 2020. These mangroves are primarily located along mud-rich, low-energy coastlines, notably near major river estuaries and deltas (Basyuni et al., 2022; Sasmito et al., 2023; Eddy et al., 2021a). They provide essential ecosystem services, including shoreline protection against climate-driven hazards, nutrient regulation, high primary productivity, biodiversity support, and erosion reduction (Basyuni et al., 2018; Ouyang et al., 2018; Hochard et al., 2019; Kusmana et al., 2019; Mai et al., 2019; Eddy & Basyuni, 2020; Nwobi et al., 2020; Basyuni et al., 2021).

However, similar to global trends, Indonesia's mangroves have experienced significant loss and degradation since the mid-20th century, primarily due to land conversion for plantations (such as oil palm and coconut), aquaculture, and various forms of coastal development (Friess et al., 2019). This degradation contributes to the global decline of biodiversity within coastal ecosystems (Almond et al., 2020; Cooley et al., 2022). In this ecological context, the nipa palm *Nypa fruticans* Wurmb is recognized as a minor mangrove associate that plays a crucial ecological and socioeconomic role (Tsuji et al., 2011). Environmentally, dense stands of *N. fruticans* serve as shoreline buffers, effectively trapping nutrients and providing essential nursery, feeding, and spawning habitats for various aquatic organisms (Hidayat, 2015; Mantiquilla et al., 2019; Robertson et al., 2020). Socioeconomically, these palms support capture fisheries and aquaculture, offering a diverse array of food resources (Mondal et al., 2017; Sribianti et al., 2021; Khairi et al., 2023). Additionally, sap extracted from the inflorescences can be transformed into palm sugar, vinegar, alcohol, and biopharmaceutical products with antioxidant and antimicrobial properties, and it holds promise for bioethanol production. Furthermore, immature fruits can be used to make jams, juices, and syrups (Nugroho et al., 2022; Hidayat, 2018; Iswari, 2023).

Taxonomically, *N. fruticans* is a monocot mangrove and the only species in the genus Nypa (Wu et al., 2024). Typically occupies tidal rivers and estuaries, forming broad, uniform belts from riverbanks to estuarine waters (Widodo et al., 2020; Mantiquilla et al., 2022; Lestari & Noor'an, 2019; Fithria et al., 2022). Its Indo-West Pacific distribution extends from Sri Lanka through Southeast Asia to northern Australia (Clemente, 2013; Hossain & Islam, 2015), with stand structure and density influenced by factors such as salinity, pH, currents, substrate, and nutrient regimes (Takarina et al., 2019) and peatland acidicity gradients (Hartoko et al., 2022a; 2022b). Indonesia is home to extensive populations of *N. fruticans*, which occur throughout a significant fraction of the national mangrove estate (Megumi, 2018; Wijana et al., 2023). In eastern Sumatra, notable examples can be found in peat-influenced coastal wetlands, such as Pangkal Babu and in South Sumatra, including the Air Telang Protected Forest (ATPF) (Eddy et al., 2022).

ISSN: 2455-6939

Volume: 11, Issue: 05 "September-October 2025"

2. MATERIAL AND METHODS

Sampling was conducted in Pangkal Babu, Jambi, using purposive sampling, which entails selecting samples based on the research objectives while adhering to principles of even distribution, representativeness, and accessibility (Fig 1). The study area was divided into three distinct zones: Zone 1, located near the estuary/river mouth and adjacent to freshwater areas; Zone 3, situated along the coastal region; and Zone 2, positioned at the central part, serving as a transition zone.

In total, ten observation sampling-points were established in each zone with total of 30 sampling-points, with each sampling-point chosen based on at least two of the three criteria to effectively represent the variation of Nipa conditions within the study site. At each observation sampling-point in every zone, a Nipa clump was selected as a sample. Leaf sampling was performed on each frond within the selected clump. Subsequently, the weight of the Nipa fronds was measured, the height of the fronds was recorded, and the number of leaves on each frond from the same clump was counted. All measurement results were documented per zone and sampling-point to ensure comparability among zones 1, 2, and 3 are estuarine, transitional, and coastal, in alignment according the study design.

Figure 1: Study Location at Pangkal Babu, Jambi, East Sumatra Coastal Area

ISSN: 2455-6939

Volume: 11, Issue: 05 "September-October 2025"

3. RESULTS AND DISCUSSION

3.1 RESULTS

3.1.1 Pangkal Babu Mangrove Forest Area, West Tanjung Jabung Regency, East Sumatra Indonesia

This research was conducted in the Pangkal Babu Mangrove Forest Area, Tungkal-I Village, Tungkal Ilir Subdistrict, Tanjung Jabung Barat Regency, Jambi Province a coastal area on the east coast of Sumatra that borders the Berhala Strait and is affected by daily tides. Geographically, the center of the study area is located at approximately 0°49′34.8″ S; 103°32′30.7″ E. Aims For analysis and sampling purposes, the area was divided into three ecological zones based on the hydrology-salinity gradient: zone 1 is estuarine, near freshwater inflow; high density, zone 2 is transitional; medium density, and zone 3 is toward the coast; low density. This zoning reflects the mixture of local mangrove habitats formed by the mixing of freshwater and saltwater.

The ecological characteristic feature of this location is the dominance of Nipah (*Nypa fruticans*) along riverbanks, tributaries, and periodically flooded swamps. Morphologically, Nipah is a monocotyledonous palm with creeping rhizomes that form dense clumps and are tolerant of flooding; its fronds are elongated with closely arranged leaflets.

Low salinity preferences cause nipah stands to be thickest in zone 1, decreasing in zone 2, and relatively rare in zone 3, which is more exposed to waves and sea salinity. The observation design in this thesis is characterized by the following measurements: frond height, frond weight, number of fronds per clump, and number of leaves per frond at sampling-points in each zone.

From a physical-chemical perspective, the Pangkal Babu substrate is characterized by a transition from silty clay to wet peat, resulting from the accumulation of organic matter in water-saturated and anaerobic conditions that store large amounts of soil carbon. Tidal dynamics and estuarine flows encourage sediment trapping by nipah stands, stabilize the coastline, and influence canopy heterogeneity and chlorophyll levels. In addition to its ecological value, Pangkal Babu has socio-economic value for coastal communities. Nipa palms are used as a material for weaving and roofing, a source of palm sap or sugar, and a support for fishing and mangrove ecotourism. At the same time, the role of nipa palms as blue carbon sinks and stores makes this area important for regional climate change resilience strategies.

ISSN: 2455-6939

Volume: 11, Issue: 05 "September-October 2025"

Figure 2: Pangkal Babu Mangrove Forest Area, West Tanjung Jabung Regency, East Coast of Sumatra

This field context is captured in Figure 2: (a) A turbid, sediment-rich estuarine canal flanked by dense nipah stands; (b) the gate to the Pangkal Babu Mangrove tourist area as an access corridor to the research site; (c) a footpath with nipah stands representing the transition zone; and (d) a management information board under the nipah canopy confirming the existence of socio-economic activities and area management. This visual documentation confirms the existence of a gradient in nipah density from the estuary towards the coast and the relevance of the three-zone division in the analysis in the results chapter.

3.1.2 The Composition and Structure of *Nypa fruticans* Vegetation in Pangkal Babu, Jambi

Zone 1, situated near freshwater inflows, exhibits high vegetation density due to the abundance of nutrients and stable hydrology. Zone 2 serves as a transitional area between the estuary and the coast, characterized by moderate density resulting from a mix of freshwater and seawater. Zone 3 leads to the open coast, characterized by low density influenced by high wave exposure and salinity, along with limited nutrients. This zoning facilitated the analysis of nipah vegetation structure in relation to biophysical parameters such as biomass and carbon content (Fig 2).

ISSN: 2455-6939

Volume: 11, Issue: 05 "September-October 2025"

Figure 3a: The Distribution of Nipah in Pangkal Babu Using a DJI Phantom 4 Pro Drone

In Zone 1, dense nipah stands exhibit a homogeneous structure with minimal land openings. Clumps form a continuous line along the tidal canal, with saplings densely packed at the edges and underneath mature trees. Table 1. Measurements taken at 10 observation sampling-points indicate an average frond height of 7.32 m (range 6.30–9.12 m), an average of 122 leaves per frond (range 118–130), and 12 fronds per clump (range 10–14). The total frond height recorded was 73.22 m, along with 1,223 leaves and 122 fronds, illustrating a dense canopy in Zone 1.

ISSN: 2455-6939

Volume: 11, Issue: 05 "September-October 2025"

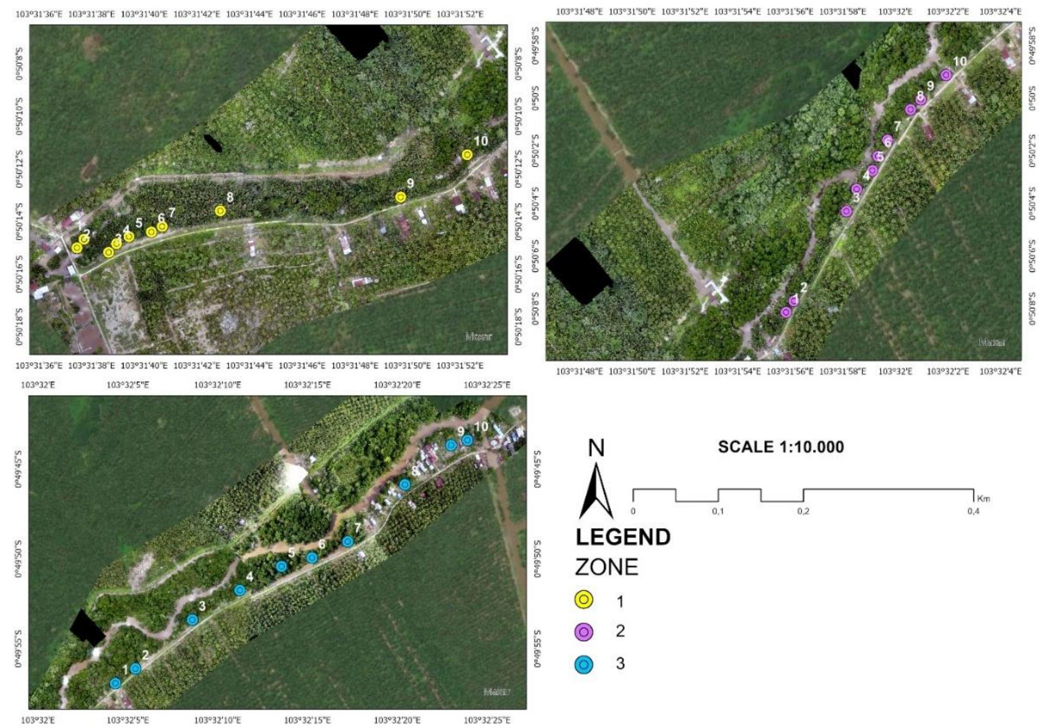

Figure 3b: The Distribution of Sampling Point Nipah in Pangkal Babu Using a DJI Phantom 4 Pro Drone

Table 3: Morphometric Composition of *Nypa fruticans* Clumps in Zone 3 of the East Coast of Sumatra, Pangkal Babu Jambi, 2025

ZONE/SAMPLING-POINT	Frond Height (m)	Total leaf	Total Frond in Nipah Clumps
Z1P1	9.12	130	12
Z1P2	7.80	120	10
Z1P3	7.00	125	10
Z1P4	7.40	118	14
Z1P5	7.20	118	14
Z1P6	6.60	118	14
Z1P7	6.80	126	12
Z1P8	8.00	118	10
Z1P9	7.00	125	12
Z1P10	6.30	125	14
Total	73.22	1223	122
Average	7.32	122	12

ISSN: 2455-6939

Volume: 11, Issue: 05 "September-October 2025"

Table 2 demonstrates that, across 10 observation sampling-points, the average height of the fronds was 6.11 meters, with a range from 5.50 to 7.00 meters (the highest measurement being 7.00 meters at Z2P8 and the lowest at 5.50 meters at Z2P4).

The average number of leaves per frond was 110, ranging from 100 to 132 leaves, with the highest count recorded at 132 leaves at Z2T1. Additionally, the average number of fronds per clump was 8, with a range of 7 to 9 fronds per clump. In total, the data from the 10 sampling-points yielded 61.10 meters of frond height, 1,096 leaves, and 78 fronds.

Structurally, the clusters in zone 2 consist of approximately eight fronds, each with around 110 leaves. This pattern aligns with the mixed canopy observed in visual documentation, where nipah clumps are found alongside other mangrove species and coastal shrubs, with greater distances between clumps compared to those in Zone 1. When comparing Zone 2's summary with that of zone 1, it is observed that the average frond height and the number of fronds per clump in zone 2 tend to be lower.

Table 2: Morphometric Composition of *Nypa fruticans* Clumps in Zone 2 of the East Coast of Sumatra, Pangkal Babu Jambi, 2025

ZONE/SAMPLING-POINT	Frond Height (m)	Total leaf	Total Frond in Nipah Clumps
Z1P1	9.12	130	12
Z1P2	7.80	120	10
Z1P3	7.00	125	10
Z1P4	7.40	118	14
Z1P5	7.20	118	14
Z1P6	6.60	118	14
Z1P7	6.80	126	12
Z1P8	8.00	118	10
Z1P9	7.00	125	12
Z1P0	6.30	125	14
Total	73.22	1223	122
Average	7.32	122	12

ISSN: 2455-6939

Volume: 11, Issue: 05 "September-October 2025"

Table 3: Morphometric Composition of *Nypa fruticans* Clumps in Zone 3 of the East Coast of Sumatra, Pangkal Babu Jambi, 2025

ZONE/SAMPLING-POINT	Frond Height (m)	Total leaf	Total Frond in Nipah Clumps
Z3P1	3.80	96	5
Z3P2	3.50	84	7
Z3P3	4.00	98	7
Z3P4	4.20	80	8
Z3P5	4.30	116	6
Z3P6	2.80	84	4
Z3P7	4.00	88	7
Z3P8	3.20	84	7
Z3P9	2.90	90	6
Z3P10	3.00	84	7
Total	35.70	904	64
Average	3.57	90	6

Table 3 indicates that the average frond height at 10 observation sampling-points was 3.57 m (± 0.6 m), ranging from 2.80 to 4.30 m, with the highest at Z3P5 and the lowest at Z3P6. The total height accumulated across the sampling-points was 35.70 m, reflecting a narrow height distribution consistent with the discontinuous canopy. Regarding leaf quantity, fronds averaged 90.40 leaves (range 80–116), totaling 904 leaves. The average number of fronds per clump was 6.40 (range 4–8), accumulating a total of 64 fronds. Values were primarily dominated by seven fronds per clump, correlating with more open areas. Overall, the data confirm zone 3's low-density structure, characterized by shorter frond height and fewer leaves compared to other zones, which describes the Nipah stands in the Pangkal Babu coastal sector.

ISSN: 2455-6939

Volume: 11, Issue: 05 "September-October 2025"

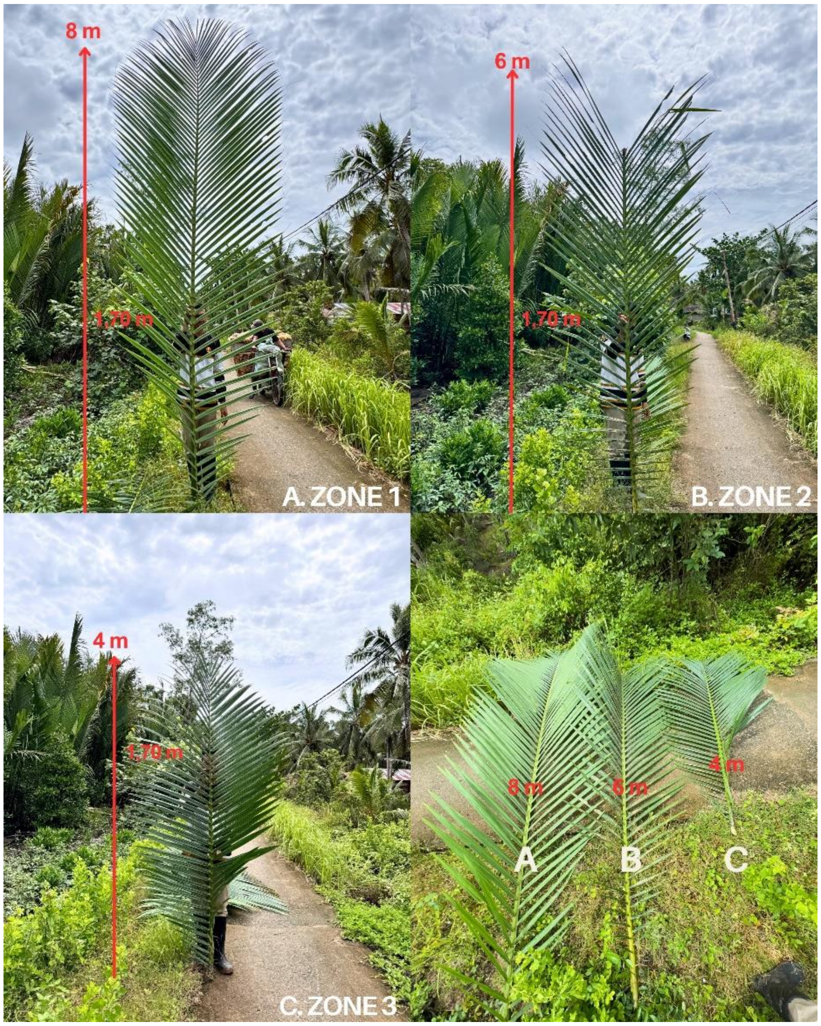

Figure 4: Comparison of the Height of Nipah Palm Fronds in Zones 1, 2, and 3

Sections A–C in Figure 4 provide examples of nipah fronds measured in the field across different zones, using a reference height of 1.70 m. The red arrow indicators highlight the height ranges: Zone 1 (estuarine, dense) shows a range of 8 meters, Zone 2 (transitional, moderate) has a range of 6 meters, and Zone 3 (coastal, sparse) displays a range of 4 meters. The composite panel at the bottom correctly positions the three fronds (A–B–C) side by side, clearly illustrating the height differences between the zones in a single view.

This visual comparison is supported by the data summarized in Tables 4.1 through 4.3. The average frond heights recorded were 7.32 m in Zone 1 (range: 6.30–9.12 m), 6.11 m in Zone 2 (range: 5.50–7.00 m), and 3.57 m in Zone 3 (range: 2.80–4.30 m).

ISSN: 2455-6939

Volume: 11, Issue: 05 "September-October 2025"

Additionally, the average number of leaves per frond was 122 in zone 1, 110 in zone 2, and 90.4 in Zone 3. The average number of fronds per clump was 12 for zone 1, 8 for zone 2, and 6.4 for zone 3. Overall, Figure 4 illustrates a gradual decrease in the height of Nipah fronds from the estuary to the coast, as reflected in the field measurements.

Table 4: Area, Density, and Morphometric Characteristics of *Nypa fruticans* Clumps per Research Zone on the East Coast of Sumatra, Pangkal Babu Jambi, 2025

Zone	Area (ha)	Density (clumps/ha)	x̄ Frond height (m)	x̄ Total Leaf	x̄ Total Frond in Nipah Clumps
Zone 1	1.0	510	7	122	12
Zone 2	0.9	126	6	110	8
Zone 3	0.7	100	4	90	6
Total	2.6	736	17	322	26
Average	0.9	245	6	107	9

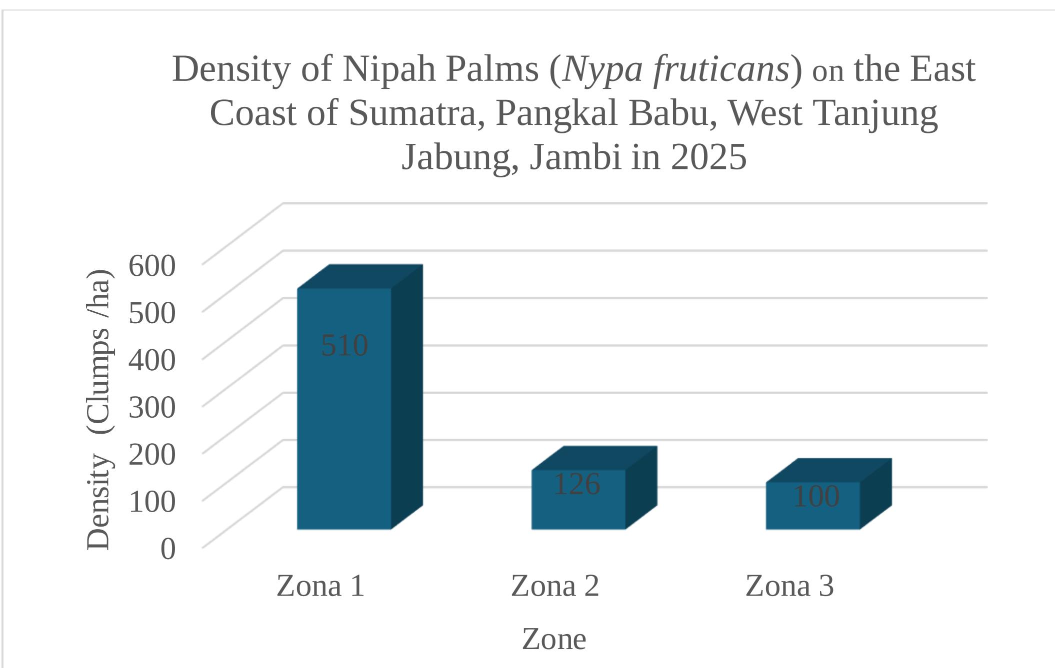

Figure 5: 3D Bar Chart of *Nypa fruticans* Clump Density in Three Observation Zones in Pangkal Babu, Jambi in 2025

ISSN: 2455-6939

Volume: 11, Issue: 05 "September-October 2025"

Table 4 shows the distribution of area and attributes of Nipah stands per zone with updated areas: zone 1 = 1.0 ha, zone 2 = 0.9 ha, and zone 3 = 0.7 ha. The total observation area was 2.6 ha with an average of 0.867 ha per zone. Proportionally, the contribution of each zone's area was ±38.5% (Zone 1), ±34.6% (Zone 2), and ±26.9% (Zone 3), indicating that the sample was relatively balanced, with a slight dominance in the estuarine sector.

The density of nipah clumps shows a gradation pattern consistent with the position of the zones (Figure 5). The highest density value was found in zone 1, namely 510 clumps/ha, followed by zone 2 with 126 clumps/ha, and zone 3 with 100 clumps/ha. Relatively, the density of zone 1 was about 4.05 times higher than that of zone 2, and 5.10 times higher than that of zone 3. The density of zone 2 remained 1.26 times higher than that of zone 3. The average density across zones was 245 clumps/ha, with a clear dominance in zone 1.

Morphometric parameters show a decreasing pattern from estuarine to coastal areas. The average frond height is 7 m zone 1, 6 m zone 2, and 4 m zone 3, respectively—a decrease of approximately 3 m, or around 43%, from zone 1 to zone 3. The average number of leaves per frond was 122 → 110 → 90 (a decrease of ±26% from zone 1 to zone 3), and the number of fronds per clump was 12 → 8 → 6 (a decrease of 50% from zone 1 to zone 3). On average across zones, the height of the frond was recorded at 6 m, the number of leaves per frond was 107, and the number of fronds per clump was 9.

3.2 DISCUSSION

3.2.1 Morphometric Variations of *Nypa fruticans* Across Three Ecological Zones

Clear zonation in *Nypa fruticans* structure along the estuary–coast gradient indicates consistent differences in canopy stature and stand organization across zones. Inner estuarine settings exhibited taller fronds, greater leaves per frond, and higher clump density, whereas coastal margins showed compressed canopies and reduced density. The ranked pattern (estuarine > transitional > coastal) remained stable across morphometric attributes, reflecting a robust seaward decline in structural performance.

Clump density was highest in zone 1, averaging approximately 510 clumps per hectare, but significantly decreased to around 126 clumps per hectare in zone 2 and further to about 100 clumps per hectare in zone 3. A similar pattern was observed in frond height, which declined from 7.32 meters in zone 1 to 6.11 meters in zone 2, and then to 3.57 meters in Zone 3. The number of leaves per frond displayed a comparable trend, decreasing from 122 in zone 1 to 110 in zone 2, and finally to 90 in zone 3. Meanwhile, the average number of fronds per clump decreased from 12 in Zone 1 to 8 in Zone 2 and to 6 in Zone 3 (Yuvaraj et al. 2017 ; Rahardjanto et al. 2020)

ISSN: 2455-6939

Volume: 11, Issue: 05 "September-October 2025"

These morphometric variations highlight the adaptive plasticity of *N. fruticans* in response to changing environmental conditions. The larger frond dimensions and higher clump density in zone 1 suggest optimal growth conditions in freshwater-dominated estuarine environments, where salinity stress is minimal, and nutrient availability is relatively high (Senger et al. 2021). In contrast, the reduced frond size and density observed in coastal zone 3 indicate physiological constraints due to increased salinity and greater hydrodynamic exposure. These structural gradients carry functional significance for ecosystem services. Denser, taller fronds near freshwater influence enhance sediment trapping, bank stabilization, and organic carbon accumulation, thereby supporting blue-carbon storage and estuarine habitat quality. Shorter, sparser stands toward coastal margins imply lower carbon stocks and diminished shoreline protection, increasing exposure to wave energy and erosion risk. Consequently, morphometric indicators frond height, leaves per frond, fronds per clump, and clump density serve as practical bioindicators of ecological condition and service provision in peat-influenced mangrove mosaics (Moudingo et al., 2020).

Beyond serving as structural indicators, these morphometric traits also reflect broader ecosystem functioning along the estuarine–coastal continuum. Dense and tall nipa clumps in the inner estuary not only indicate favorable growth conditions but also enhance sediment retention, nutrient trapping, and bank stabilization, thereby supporting higher habitat quality for estuarine organisms. Conversely, the shorter fronds and lower clump density in coastal zones correspond to reduced canopy cover and diminished carbon storage potential, thereby reinforcing the link between morphometric decline and reduced ecosystem services. Such patterns emphasize that maintaining freshwater inflows and minimizing salinity intrusion are critical not only for sustaining the vitality of nipa palms but also for safeguarding the ecological roles and blue-carbon contributions of peatland mangroves in Eastern Sumatra (Numbre, 2023).

3.2.2 Ecological Drivers to Zonation Patterns

Morphometric declines along the estuary–coast continuum are consistent with interacting environmental filters that intensify seaward. Rising salinity and hydrodynamic exposure toward coastal margins impose osmotic and mechanical constraints that limit canopy development and clonal expansion. Peat-driven acidity and nutrient limitation further exacerbate stress by restricting nutrient availability (notably P and trace elements) and elevating metabolic costs for tolerance, diverting resources from growth to maintenance. Additional water-column properties associated with peat drainage elevated colored dissolved organic matter (CDOM) and turbidity, reducing light penetration and photosynthetic efficiency, compounding growth limitations under higher salinity and wave energy (e.g., Wang et al., 2024; Friess et al., 2019; Gandois et al., 2020; Zhou et al., 2021; Sanwlani et al., 2022; Martin et al., 2021).

Substrate and geomorphic context reinforce these trends: fine silts and low-energy conditions in inner estuaries promote propagule retention and dense clonal spread, whereas coarser, reworked sediments and more decisive wave action near the coast hinder establishment and reduce stand continuity (Balke et al., 2015; Hsiung et al., 2024; Lovelock, 2024). Collectively, these filters provide a coherent mechanistic basis for the observed seaward decline in canopy stature, leaf production, and clump density.

Strengthened inference requires direct measurement of key covariates and complementary statistics as recommended in peer review. Priority variables include soil chemistry (pH, available N and P, exchangeable Al), continuous salinity and water-level records, and optical properties linked to peat-derived DOM. Generalized linear or mixed-effects models can test zone effects under hierarchical sampling, with non-parametric alternatives available when assumptions are violated. Multivariate ordination and permutational frameworks (e.g., RDA, PERMANOVA) can partition variance among co-varying drivers and identify interactions among them. Spatial replication across peat-influenced estuaries and seasonal resampling will improve generalization and capture hydroclimatic variability in freshwater discharge, salinity intrusion, and turbidity.

Coupling permanent plots with remote sensing (canopy-height proxies, stand extent, shoreline change) and low-cost sensor networks enables scalable monitoring and early warning of hydrological alteration. Operational implications follow a zone-specific logic. Estuarine belts warrant conservation priority to maintain freshwater connectivity and peat hydrology and to avoid canalization or drainage that elevates salinity. Transitional zones benefit from buffer management that limits disturbance, sustains mixed canopies, and regulates leaf and sap harvest intensity. Coastal margins represent restoration frontiers where soft-engineering that attenuates wave energy and traps sediments can create microsites for assisted *Nypa* regeneration and mixed-species establishment. These actions address reviewer calls for clearer practical strategies and align nipa-based indicators with blue-carbon objectives and climate-resilience planning in peatland mangroves.

4. CONCLUSION

Ecological and morphometric patterns of nipa palm *Nypa fruticans* in the peat-influenced mangroves of Pangkal Babu show a notable decline from the inner estuary to the coastal margin. The inner estuary zone 1 has the highest clump density, the most enormous fronds, and the best leaf production, while the coastal margin zone 3 experiences reduced density and shorter fronds due to increased salinity stress. Optimal growth occurs under oligohaline conditions 0.5–5.0‰, with higher salinity >15‰ causing physiological stress that limits growth. Key factors influencing zonation include salinity, peat-derived organic matter, turbidity, and hydrodynamic conditions. Frond height, leaves per frond, and clump density are valuable bioindicators for habitat assessment and blue-carbon storage. Management should focus on conserving freshwater connectivity in estuarine areas, regulating transitional buffers, and implementing sediment-trapping interventions at coastal margins to promote Nypa regeneration and the establishment of mixed species. While the findings provide a baseline, they are limited by the single-site approach and lack of inferential testing, necessitating further multi-site and seasonal studies to enhance understanding and validation of mechanisms.

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