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Dynamics of Mangrove Growth in the Coastal Region of Riau: A Comparative Study Across Four Regencies in Riau Province

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ABSTRACT

Mangrove ecosystems are vital for coastal stability in tropical regions such as Indonesia. This study analyzes mangrove growth dynamics across four coastal regencies in Riau Province by assessing vegetative structure and biophysical conditions. A quantitative approach using systematic plot sampling and field observations was conducted in six villages (May–June 2024). Results show survival variation, with Sonde highest (73.34%) and Tanjung Bunga lowest (27.36%). *Avicennia alba* dominated, while growth is influenced by substrate conditions and anthropogenic pressure, highlighting the need for participatory management and monitoring.

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1. INTRODUCTION

Mangrove forests are among the most strategic coastal ecosystems, supporting ecological, economic, and social stability for coastal communities, especially in tropical regions like Indonesia (Permana et al., 2024). As a unique system, mangroves can adapt to extreme environmental conditions such as high salinity, tidal fluctuations, and muddy substrates (Harefa et al., 2022). Beyond their ecological function, mangrove vegetation is a vital habitat for numerous coastal species and offers natural protection against coastal erosion, seawater intrusion, and natural disasters like tsunamis (Alongi et al., 2020; Hapsari, A.S et al., 2022). In addition to their ecological role, mangroves provide significant social and economic benefits, including carbon sequestration, sources of local raw materials, and livelihood support particularly in the fisheries sector and non-timber forest product industries (Farista and Virgota, 2021).

Given this vital role, Indonesia's status as the country with the largest mangrove area globally positions it as a key region for global mangrove conservation and sustainable utilization. Indonesia holds approximately 3.31 million hectares of mangrove forest, accounting for about 22.6% of the world's total mangrove coverage (Vogt et al., 2019).

One of the Indonesian regions with considerable mangrove wealth is Riau Province, located on the eastern coast of Sumatra, bordering the Malacca Strait a region known for its estuarine and delta ecosystems highly suitable for mangrove growth (Widagti et al., 2021). This geographic setting makes Riau a crucial habitat within Indonesia's national coastal ecological system (Putra et al., 2022). The diverse coastal landscapes across this province give rise to variations in biophysical conditions and ecological pressures in each regency, including differences in salinity levels, substrate temperature, tidal activity, and the intensity of human intervention. These variations influence the local structure and dynamics of mangrove vegetation and present valuable scientific opportunities for conducting inter-regional comparative analysis.

Further, according to data from Dinas Lingkungan Hidup dan Kehutanan (DLHK) Riau Province, four coastal regencies in Riau possess dominant mangrove coverage: Meranti Islands, Pelalawan, Indragiri Hilir, and Rokan Hilir. Each regency features distinct biophysical characteristics and socio-economic pressures that significantly influence mangrove growth dynamics and ecosystem conditions (Oktorini et al., 2022). For instance, the Meranti Islands are known for relatively pristine mangrove areas, yet it is increasingly threatened by settlement expansion and climate change, particularly seawater intrusion and rising sea levels (Efriyeldi et al., 2023). Similarly, Pelalawan mangrove ecosystems along the Kampar River face pressure from unregulated traditional aquaculture (Hidayatuddin et al., 2021).

Meanwhile, although Indragiri Hilir has the most extensive mangrove coverage in Riau, it faces significant challenges such as land conversion to palm oil and coconut plantations and weak conservation enforcement (Susilo et al., 2020). Rokan Hilir Regency, on the other hand, suffers from severe coastal abrasion and mangrove degradation in the Panipahan and Sinaboi areas, an issue ongoing since the early 2000s due to encroachment and land conversion pressures (Warningsih et al., 2020). The continuous retreat of the coastline in these areas has led to increased vulnerability of coastal communities to tidal flooding and erosion, which in turn threatens the sustainability of local economies and infrastructure (Jalaludin et al., 2020).

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This condition illustrates that despite the substantial mangrove forest potential in Riau, anthropogenic pressures such as land conversion, coastal reclamation, illegal logging, and industrial and domestic pollution remain the primary factors contributing to the decline in mangrove forest area in the region. (Efriyeldi et al., 2018). This decline not only affects ecological aspects like coastal erosion and the loss of marine habitats but also reduces the economic productivity of coastal communities, especially in fisheries and mangrove-based microenterprises (Saputra et al., 2021). Nevertheless, some areas in Riau have shown success in mangrove regeneration both naturally and through community and government-led rehabilitation programs. However, such efforts remain sporadic and are not yet integrated into long-term monitoring and evaluation systems (Nabilla et al., 2021).

Given these conditions, the dynamics of mangrove growth in the coastal areas of Riau are essential to monitor regularly. These dynamics encompass changes in area coverage, density, tree height, species composition, and the rate of natural regeneration. Regular monitoring can provide early indications of ecological disturbances and the success of rehabilitation interventions implemented by the government and local communities (Wijaya et al., 2023). Accordingly, studies on mangrove growth dynamics serve as a robust scientific foundation for evaluating the effectiveness of conservation policies, coastal zone management, and the development of ecosystem service-based economic activities, such as ecotourism and blue carbon initiatives (Phelan et al., 2020).

Previous studies have emphasized the importance of long-term mangrove monitoring. For example, research has (Ibharim et al., 2024) demonstrated that an integrative approach combining satellite imagery and field measurement (ground checking) effectively captures spatial changes in mangrove ecosystems. Meanwhile, (Friess et al., 2019) argued that interregional comparative approaches are effective in establishing conservation priorities and local condition-based rehabilitation strategies. However, most mangrove research in Indonesia is localized and partial, with few studies addressing growth dynamics comprehensively at the inter-regency level.

In this case, Riau Province is an ideal location for comparative studies on mangrove growth dynamics. The physical, anthropogenic, and policy variations across its regencies enable cross-regional analyses that provide more representative information. Therefore, this study aims to describe and compare mangrove growth dynamics in four coastal regencies, Rokan Hilir, Pelalawan, Meranti Islands, and Indragiri Hilir, through vegetative monitoring and biophysical observation, supporting a comprehensive understanding of land cover dynamics. The findings from this study are expected to serve as scientific recommendations for ecosystem-based coastal management policies. Amid the challenges of climate change and regional development pressures, a scientific approach to mangrove monitoring is highly relevant to support national agendas for sustainable coastal resource management (Rahmadi et al., 2024). This study thus occupies a strategic position in addressing regional research gaps, capturing the actual conditions of mangrove ecosystems, and opening opportunities for multisectoral collaboration in mangrove conservation in Riau

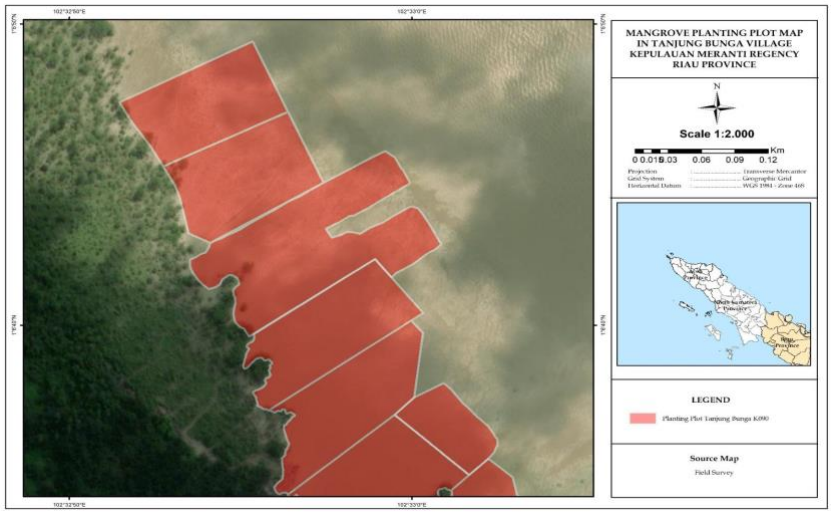
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2. METHODS

This study employed a descriptive quantitative approach, involving direct in-situ vegetative monitoring and biophysical observations to evaluate mangrove growth dynamics across selected Riau Province locations. The research was conducted from May to June 2024, primarily focusing on collecting accurate and representative primary data related to mangrove community structure, natural regeneration levels, and biophysical environmental conditions influencing mangrove vegetation growth. A descriptive quantitative design was chosen to quantify variation in key growth metrics such as tree density and height, thereby enabling objective comparisons and the identification of patterns related to environmental gradients (Waldock et al., 2022). This approach captures spatial variability and supports data-driven conservation and management strategies for mangrove ecosystems. Research locations were selected using purposive sampling, based on the criteria of dominant mangrove cover and varying degrees of anthropogenic pressure in each regency. Six villages representing four major coastal regencies in Riau Province were chosen as study sites:

Tanjung Bunga Village, Pulau Merbau District, in Kepulauan Meranti Regency





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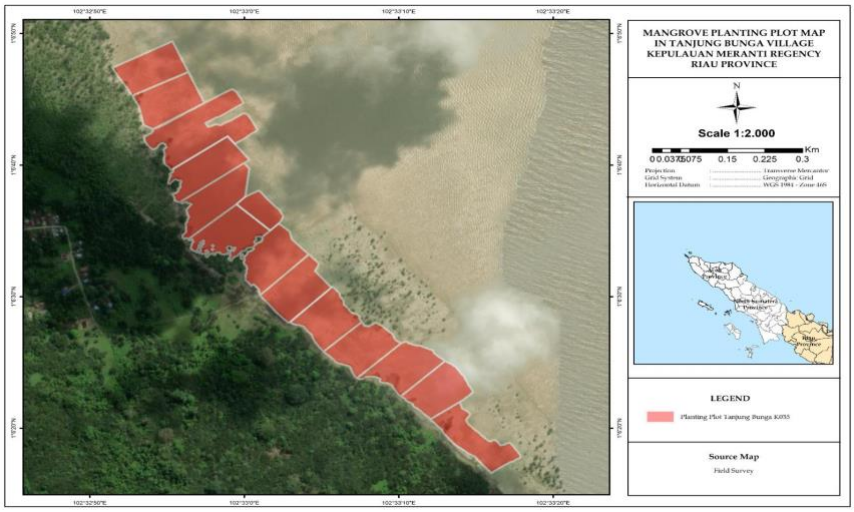


Figure 1. *Sampling plot Map 1, Map 2 and Map 3 Tanjung Bunga village*

Sonde Village, Rangsang Barat District, in Kepulauan Meranti Regency

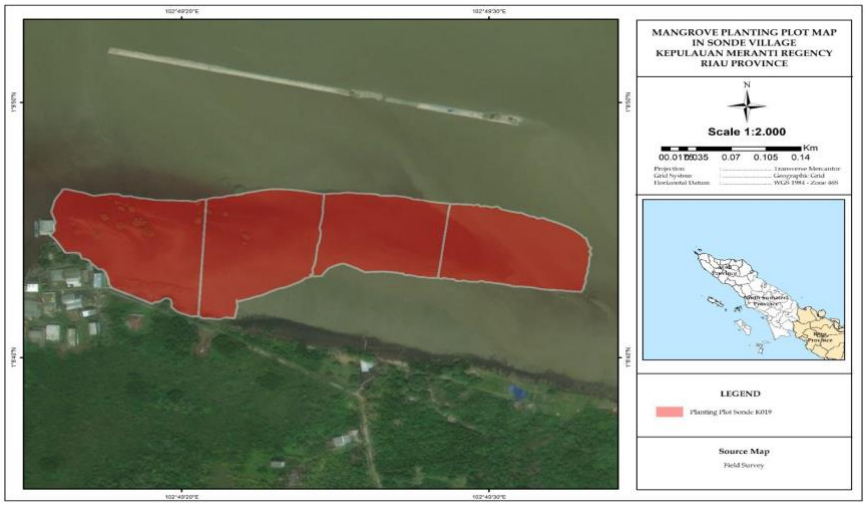
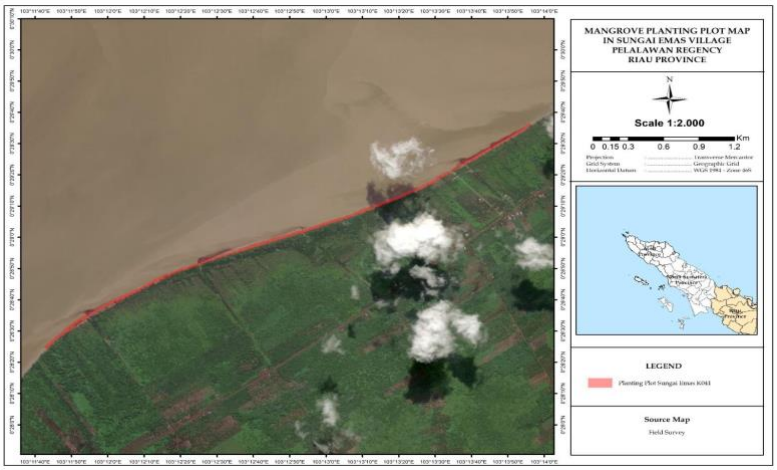


Figure 2. *Sampling plot Sonde village*

Sungai Emas Village, Kuala Kampar District, in Pelalawan Regency



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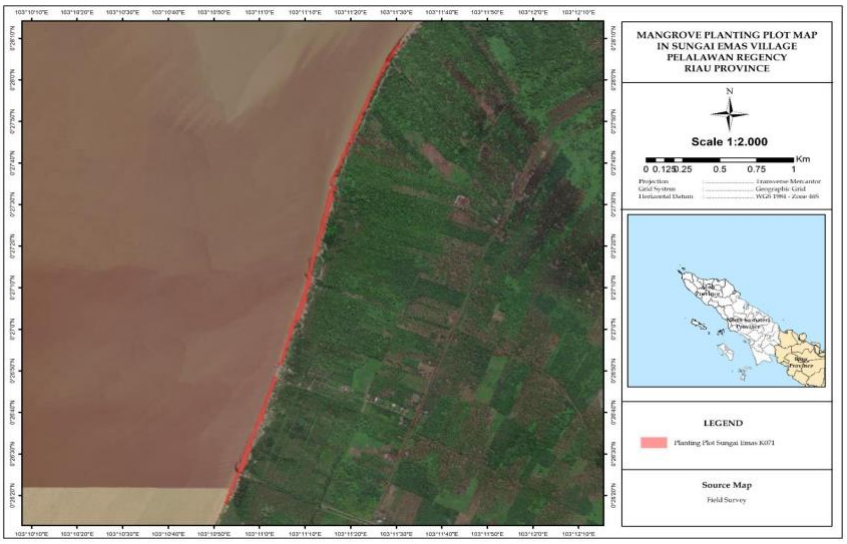


Figure 3. *Sampling plot Map 1 and Map 2, Sungai Emas village*

Sungai Upih Village, Kuala Kampar District, in Pelalawan Regency

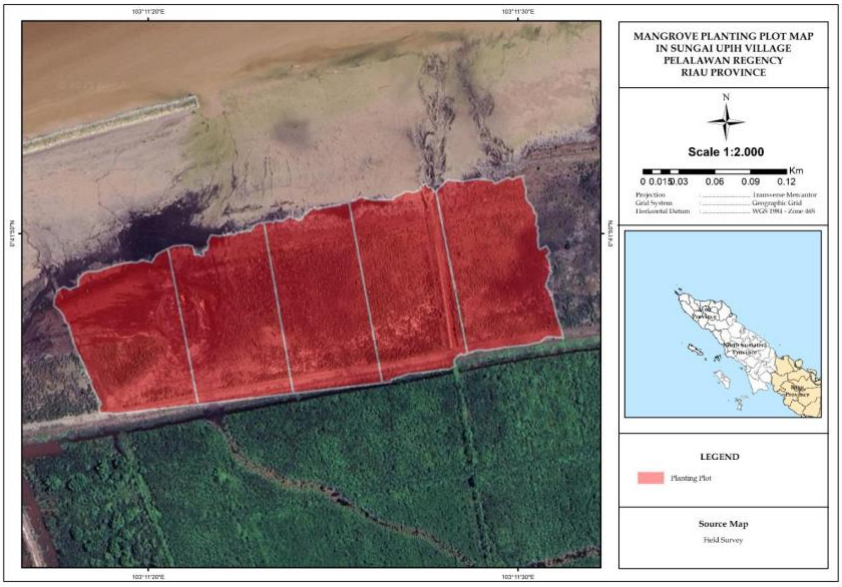
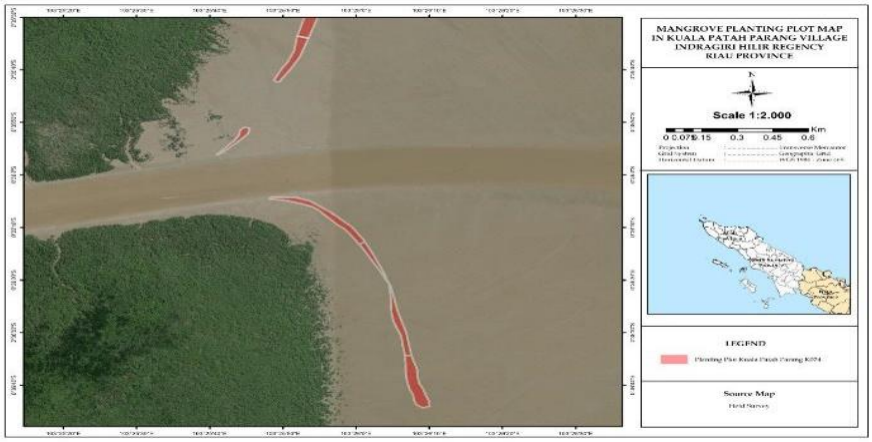


Figure 4. *Sampling plot Sungai Upih village*

Kuala Patah Parang Village, Sungai Batang District, in Indragiri Hilir Regency



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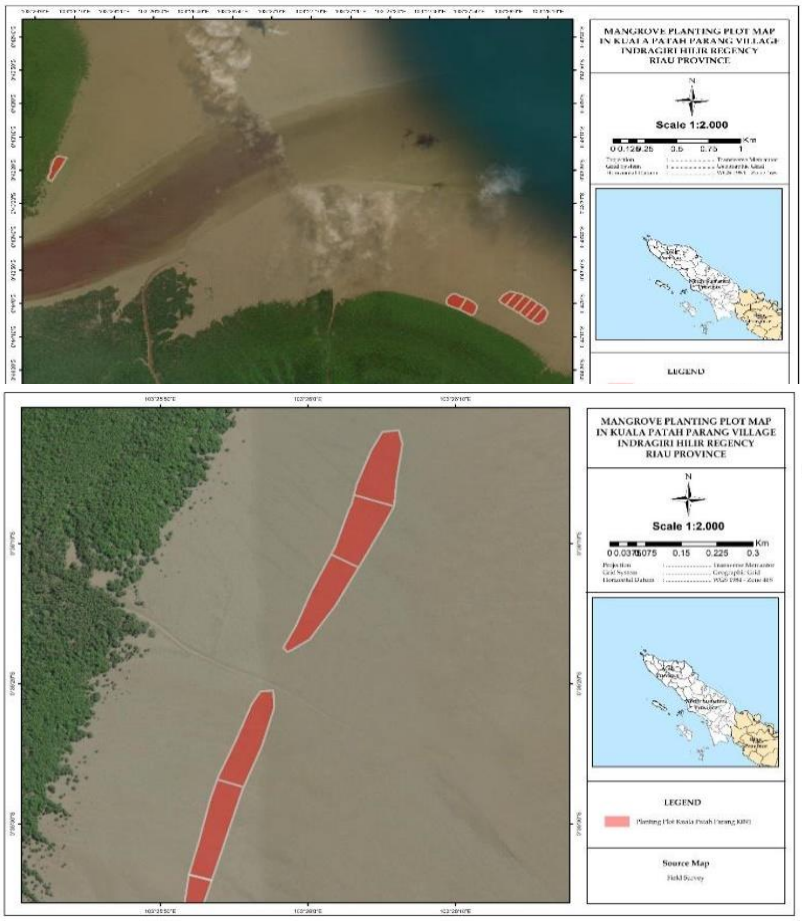
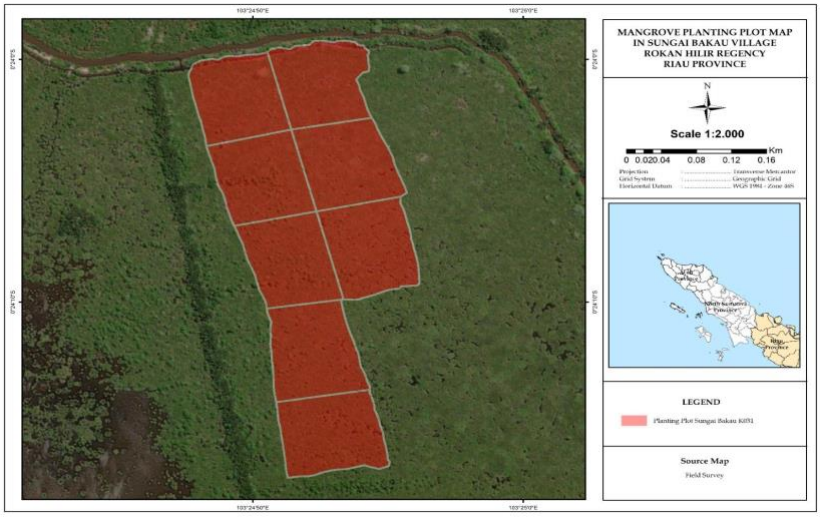


Figure 5. *Sampling plot Map 1, Map 2 and Map 3 Kuala Patah Parang village*

Sungai Bakau Village, Sinaboi District, in Rokan Hilir Regency.



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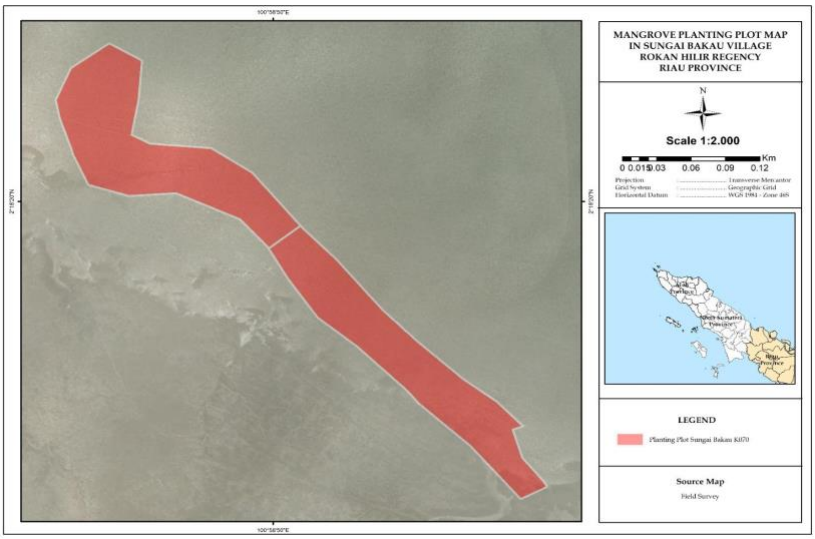


Figure 6. *Sampling plot Map 1 and Map 2 Sungai Bakau village*

Vegetative data collection was conducted through systematic plot sampling techniques, using 10 × 10 meter plots arranged linearly from the coastline inland up to ±100 meters, adjusted to the width of the mangrove belt at each site. Within each plot, all mangrove tree individuals with a diameter at breast height (DBH) ≤ 2 cm were identified and measured to obtain data on tree height, DBH, stand density, and species composition. This threshold was chosen because trees with DBH ≤ 2 cm are considered to have passed the initial regeneration phase and have begun to contribute to stand structure and biomass potential. Natural regeneration was assessed using 1 × 1-meter subplots, where the number of seedlings, saplings, and other young individuals was recorded. The basal area of trees was calculated using the following formula:

$$Basal\ Area=(\pi \times DBH2)/(4 \times 10.000).$$

This value was subsequently used to determine each species' relative dominance. Ecological importance values for each species were assessed through analyses of relative density, relative frequency, and relative dominance, which were then summarized into the Importance Value Index (IVI) a key indicator of ecological dominance at each site.

$$IVI = Relative\ Density + Relative\ Frequency + Relative\ Dominance$$

Source: (Mangore et al., 2022)

Biophysical observations were conducted simultaneously with vegetative measurements to collect environmental data, including substrate type, salinity level (measured using a refractometer), and light intensity (measured using a lux meter). In addition, anthropogenic pressures such as land encroachment, aquaculture activities, settlement development, and mangrove tree logging were recorded. All data were analyzed using descriptive quantitative methods to describe each village's vegetation structure and natural regeneration levels, and the ecological characteristics and environmental conditions among the study locations were compared.

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3. RESULTS AND DISCUSSION

a. Results

Based on field data from six villages in four coastal regencies of Riau Province, vegetative monitoring and biophysical observations conducted between May and June 2024 revealed significant variations in mangrove growth dynamics. Physical environmental characteristics, the intensity of anthropogenic pressures, and the effectiveness of rehabilitation efforts influenced these variations. Vegetative data collected included parameters such as tree height, diameter at breast height (DBH), stand density, and species composition. Meanwhile, biophysical observations covered substrate moisture, pH, air and substrate temperature, salinity, and light intensity.

1. Tanjung Bunga Village, Pulau Merbau District, Kepulauan Meranti Regency

As the most extreme site, Tanjung Bunga Village recorded the lowest mangrove survival rate, ranging between 10% and 27%. Monitoring results showed very high substrate temperatures (39.3–39.9°C) and low humidity (10%), which directly caused thermal and physiological stress on mangrove seedlings. The combination of extreme heat, high salinity (20‰), and dry substrate created highly unfavorable conditions for initial seedling growth. Interestingly, from a biodiversity perspective, the site still supported benthic fauna such as clams, mudskippers (*Periophthalmus spp.*), and small crabs (*Uca spp.*), indicating that despite poor vegetative growth, the beach substrate remained suitable for bottom-dwelling fauna. Compared to other villages like Sonde or Kuala Patah Parang, Tanjung Bunga presented the most unstable and extreme physicochemical conditions.

2. Sonde Village, Rangsang Pesisir District, Kepulauan Meranti Regency

In contrast, Sonde Village recorded the highest survival rate at 73.34%. Although substrate temperatures were relatively high (35.6°C) and moisture remained low (10%), natural protective features such as stone barriers and coastal morphology that dampened wave energy contributed significantly to microhabitat stability. This finding reinforces that substrate conditions are not the sole determinants of rehabilitation success coastal morphology and physical protection also play crucial roles (Dewi et al., 2021). Biodiversity in this village was pretty good, although not as rich as in Kuala Patah Parang. Sonde's success proves that physical protection from wave pressure significantly supports mangrove regeneration.

3. Sungai Emas Village, Kuala Kampar District, Pelalawan Regency

Sungai Emas Village presented different challenges. The mangrove survival rate here was low, around 10–11%, even though the substrate temperature was in a moderate range (30.7–31.3°C). The main issues at this site were extremely low substrate moisture (1.5–3%) and frequent wave disturbances caused by boat traffic on the Kampar River. Additionally, the soil's high pH level (8.01–8.88) indicated an alkaline condition that is not conducive to optimal metabolic processes in mangrove plants. Compared to Sungai Upih, this site showed more ecologically unfavorable conditions.

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4. Sungai Upih Village, Kuala Kampar District, Pelalawan Regency

Conditions in Sungai Upih were more favorable, with lower substrate temperatures (29.4°C) and a lower salinity level of just 15‰, resulting in a relatively high survival rate of 59.95%, especially compared to Sungai Emas. The mangrove ecosystem in Sungai Upih benefited from stone barriers, similar to those in Sonde Village, which helped protect the mangroves from wave impact. However, biodiversity was more limited, with only mudskippers and crabs observed. Although substrate moisture remained low (10%), the cooler temperatures and lower salinity significantly enhanced plant survival. Overall, Sungai Upih demonstrated better ecological conditions and growth outcomes than Sungai Emas.

5. Kuala Patah Parang Village, Sungai Batang District, Indragiri Hilir Regency

Kuala Patah Parang Village exhibited the highest biodiversity and the most balanced ecosystem structure among all sites. The survival rate here ranged widely from 36% to 72%, depending on the plot and local anthropogenic pressures. Substrate temperatures ranged between 33°C and 34°C, with a salinity level of 20‰ and moisture levels of 4–5%, considered moderate. The substrate's neutral pH (7.1–7.8) supported optimal growth of dominant species like *Avicennia alba*. Low external pressures, such as coastal erosion or development activities, made this location one of the most promising for sustainable rehabilitation programs.

6. Sungai Bakau Village, Sinaboi District, Rokan Hilir Regency

Finally, Sungai Bakau Village displayed a unique dynamic. The substrate temperature was relatively low (27.4–27.9°C), and the humidity was comparatively higher (6–7%). However, this site faced the highest salinity among all villages, at 24‰. Despite this, the survival rate remained moderate, between 57% and 67%, indicating species- specific tolerance to high-salinity conditions. This suggests proper species selection and appropriate planting techniques can improve rehabilitation success, even under intense environmental stress.

Table 1. Research results on the condition of the mangrove ecosystem

Location	Average Height (cm)	DBH (cm)	Substrate Temperature (°C)	Salinity (‰)	Survival Rate (‰)	Dominant Pressure
Tanjung Bunga	25–45	0.8	39.7	20	27.36	High substrate temperature, dry and sandy soil (sersai)

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Sonde	45–60	1.27	35.6	20	73.34	Appropriate seedlings, stable coastal morphology
Sungai Emas	30–35	0.5	31.3	15	58.32	Mild abrasion
Sungai Upih	29–30	0.5	29.4	15	65.81	Coastal settlement
Kuala Patah Parang	55–90	1.6	33.2–34.3	20	36.57	Small boat (pompong) traffic, sea currents
Sungai Bakau	20–55	0.7	27.4–27.9	24	57.47	Thick mud (lanyau), boat traffic

Source: Field Survey, 2024

b. Discussion

Avicennia alba was the most dominant mangrove species across all study sites, which demonstrated strong tolerance to various substrate types and salinity levels. Community structure analysis based on the Importance Value Index (IVI) further confirmed the dominance of Avicennia alba, particularly in locations with muddy substrates and moderate to high salinity levels (15–24‰). The IVI was calculated using the formula *IVI = Relative Density + Relative Frequency + Relative Dominance*. Meanwhile, Relative dominance was determined through the basal area of each tree, which was calculated using the following formula: *Basal Area = (π × DBH²) / (4 × 10.000)* (Mangore et al., 2022).

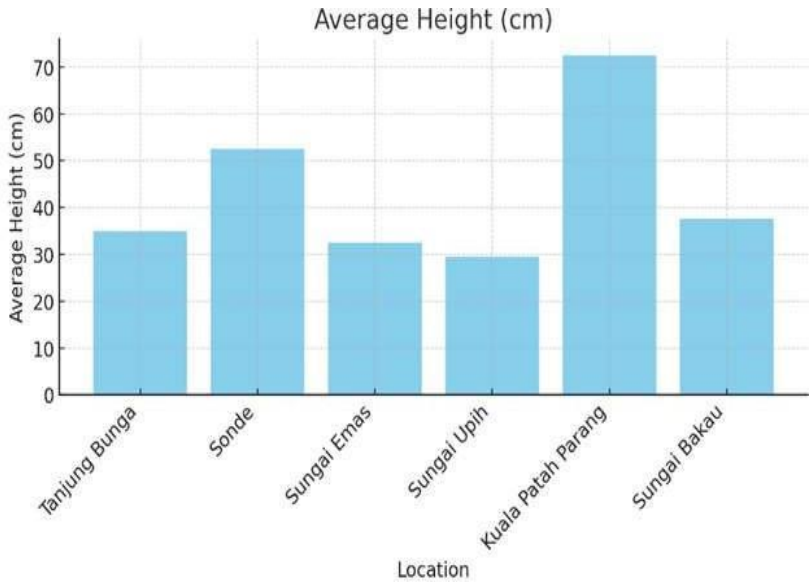


Figure 7. Graph of the average height of mangrove plants in the research area. Based on the graph in

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Figure 7, Kuala Patah Parang demonstrated the best performance in terms of average mangrove height, reaching approximately 72 cm, indicating optimal vertical growth. In contrast, Sungai Upih and Sungai Emas recorded the lowest average heights (<35 cm), suggesting growth constraints likely caused by less suitable substrate conditions or disturbances from human activities. A strong correlation between substrate temperature, soil moisture, and vertical growth sites, with cooler substrates and higher moisture levels, tends to support better plant height development.

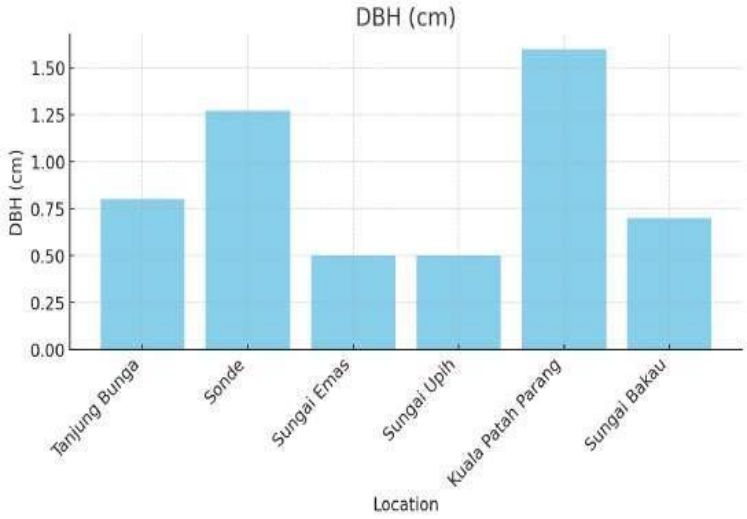


Figure 8. Diameter at Breast Height (DBH) graph of mangrove plants at the research location

DBH (Diameter at Breast Height) reflects the stem's structural health and the plant's relative age, serving as an important indicator in biomass and carbon stock estimations. In this graph, Kuala Patah Parang shows the highest DBH value (around 1.5 cm), followed by Sonde (around 1.3 cm), while the lowest DBH values are observed in Sungai Emas and Sungai Upih (<0.6 cm). The high DBH value in Kuala Patah Parang indicates a more mature vegetation structure, likely resulting from more stable biophysical conditions and natural protection from wave action and abrasion. Conversely, the low DBH value in Sungai Emas may be caused by boat traffic (pompong) disturbances and ongoing coastal abrasion.

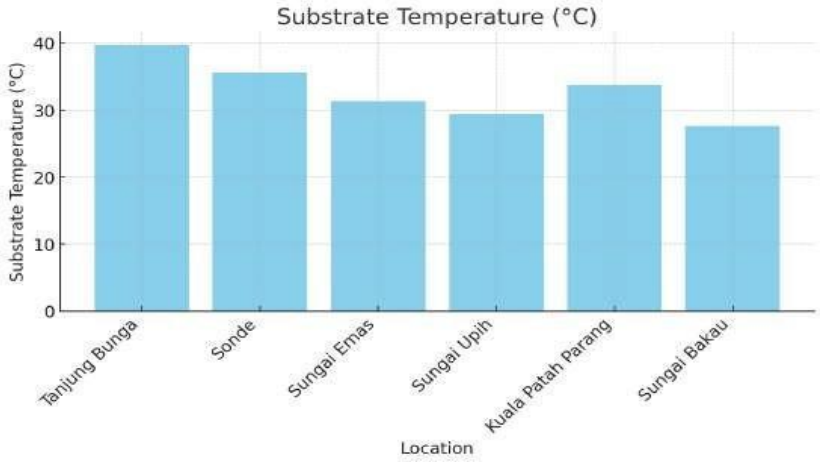


Figure 9. Substrate temperature graph in the research area

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The graph in **Figure 9** shows that Tanjung Bunga recorded the highest substrate temperature (approximately 40°C), followed by Sonde (around 38°C), while the lowest temperature was observed in Sungai Bakau (approximately 28°C). Elevated substrate temperature has been proven to be a significant limiting factor in mangrove regeneration, as it accelerates soil water evaporation, reduces soil moisture, and induces physiological stress in young plants. Empirical evidence suggests that substrate temperatures exceeding 35°C inhibit root metabolism, reduce water uptake, and slow down photosynthesis in newly planted seedlings. This is consistent with field observations in Tanjung Bunga, which recorded the lowest seedling survival rate (<30%).

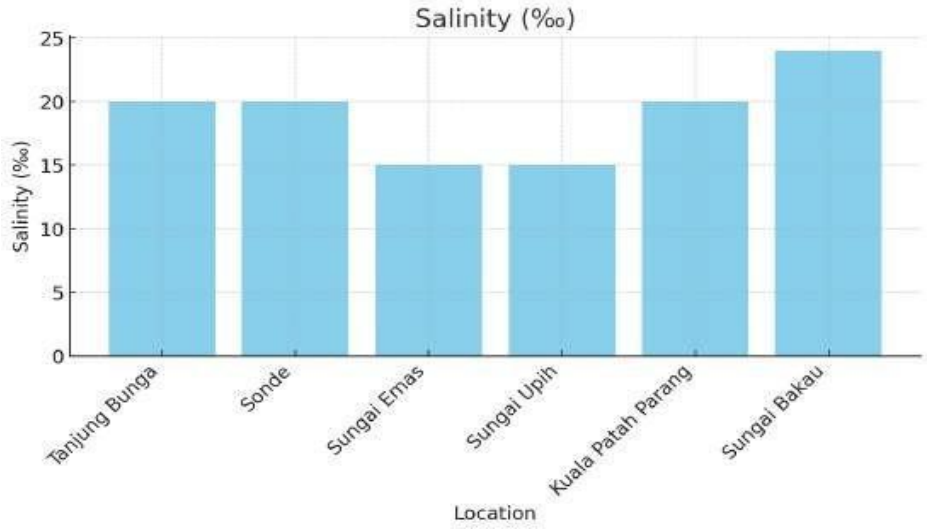


Figure 10. Salinity graph at the research location

The highest salinity was recorded in Sungai Bakau (24‰), while the lowest salinity levels were found in Sungai Emas and Sungai Upih (both at 17‰). Salinity across all locations remains within the optimal tolerance range for *Avicennia alba* (15–25‰); however, its interaction with other environmental parameters can significantly affect growth performance. Although within the acceptable range, high salinity levels in Sungai Bakau may induce osmotic stress if not balanced with adequate substrate moisture and physical protection. Conversely, excessively low salinity may limit the dominance of particular species that rely on specific salinity thresholds to regulate ecological competition.

Mangrove Community Structure and Vegetative Growth Dynamics

Mangroves are unique coastal plant communities adapted to extreme environmental conditions such as high salinity, dynamic tidal flows, and muddy, anaerobic substrates (Kusmana and Rifana, 2023). Avicennia alba is among the most dominant species across nearly all research sites in Riau's coastal areas. Vegetative monitoring from six villages across four regencies, Kepulauan Meranti, Pelalawan, Indragiri Hilir, and Rokan Hilir, indicated that *Avicennia alba* was not only numerically dominant but also ecologically significant based on the Importance Value Index (IVI), which includes parameters of relative density, relative frequency, and relative dominance.

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Mangrove plant heights recorded during monitoring ranged from 20 to 90 cm, with DBH values between 0.5 and 1.6 cm. The site with the best vegetative growth was Kuala Patah Parang Village, Sungai Batang District, Indragiri Hilir Regency, with trees ranging from 55–90 cm and a DBH of 1.6 cm. Despite exposure to boat traffic (pompong), the relatively stable substrate and moderate salinity supported optimal growth. As noted (Soenarto et al., 2025) *Avicennia alba, it* possesses aerial roots and salt-excretion mechanisms, enabling it to thrive under high salinity and low-aeration conditions.

Conversely, the poorest vegetative growth was recorded in Tanjung Bunga and Sungai Bakau villages, with average tree heights of only 25–45 cm and DBH around 0.8 cm. This was closely related to extreme substrate temperatures in Tanjung Bunga (up to 39.9°C) and thick mud layers (lanyau) in Sungai Bakau, which limited root penetration and disrupted gas exchange. As (Rahmi et al., 2025) pointed out, excessively high substrate temperatures can accelerate water evaporation, increase root-zone salinity, and reduce root respiration and photosynthesis in young plants.

Differences in tree height and DBH across sites were also influenced by seedling age at the planting time. Seedlings taller than 40 cm tended to be more vulnerable to environmental stress due to underdeveloped root systems and hardened tissues that limited adaptability. This aligns with (Yona et al., 2018), who emphasized that successful mangrove restoration depends not only on planting techniques and location but also on seedling age and quality.

Substrate and Environmental Biophysics: Key Determining Factors

Biophysical parameters such as substrate temperature, soil moisture, pH, and salinity play critical roles in influencing mangrove growth dynamics. In this study, substrate temperatures ranged from 27.4°C in Sungai Bakau to 39.9°C in Tanjung Bunga. High substrate temperatures, especially above 35°C, negatively affect seedling growth by increasing evaporation and reducing soil moisture (Radja et al., 2023). Soil moisture at sites like Kuala Patah, Parang, and Sungai Emas was recorded at less than 5%, which is far below the optimal range for mangrove root development, which requires semi-saturated conditions for proper respiration.

Salinity across the sites ranged from 15–24‰, which falls within the tolerance range of *Avicennia alba*. However, when combined with extreme temperatures or unstable substrates, high salinity can cause osmotic stress on plant tissues (Sarkar et al., 2023). For instance, Tanjung Bunga's salinity level 20‰ and a near 40°C substrate temperature hindered growth and survival rates. This is consistent with (Suhana, 2018), who explained that high temperatures and salinity interaction can lead to physiological dysfunctions such as reduced turgor pressure and chlorophyll synthesis inhibition.

Regarding pH, locations ranging from neutral to slightly alkaline (pH 7–8.8), such as Sungai Emas and Sungai Upih, exhibited relatively better vegetative growth and regeneration. Soil pH affects the availability of micronutrients and the activity of edaphic microorganisms essential for organic matter mineralization. These findings align with (Rahman and Hadi, 2021), who stated that pH and substrate moisture stability are critical for forming healthy mangrove communities

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Natural Regeneration and Survival Rate

One of the key indicators of mangrove ecosystem dynamics and restoration success is the level of natural regeneration and seedling survival rate. In this study, survival rates varied widely across locations. The highest was observed in Sonde Village at 73.34%, attributed to relatively stable biophysical conditions, appropriate seedling age, and strong community support during planting and maintenance. In contrast, Tanjung Bunga recorded the lowest survival rate at only 27.36%, primarily due to hot, dry substrate conditions (sersai) and the use of older seedlings. The high substrate temperature impaired root resilience against dryness and extreme heat during early growth stages.

Kuala Patah Parang showed a survival rate of 36.57%, hindered by anthropogenic disturbances like small boat (pompong) traffic, which dislodged seedlings via wave action. This site also experienced low soil moisture and micro-erosion (Gijón Mancheño et al., 2024), noting that such hydrodynamic disturbances can lead to up to 40% planting failures, particularly on shorelines lacking natural protection like mature vegetation belts.

Biodiversity within Mangrove Ecosystems

Mangrove ecosystems are essential not only for vegetation but also as habitats for various coastal fauna. Biodiversity monitoring in this study recorded the presence of species such as mudskippers *(Periophthalmus spp.),* small crabs *(Uca spp.),* and clams *(Anadara spp.)* in nearly all studied villages. Sites like Sungai Upih and Sungai Emas recorded the highest biodiversity, with more than three key fauna species within the monitored plots. This biodiversity correlated positively with stable substrate, adequate moisture, and high vegetation density. Conversely, locations under high human pressure, such as Kuala Patah Parang, showed lower faunal diversity. Environmental stress led to microhabitat degradation, particularly for species that rely on mangrove root structures for shelter and foraging. (Mattone and Sheaves, 2024) highlighted that estuarine fauna presence is highly dependent on the structural complexity of vegetation, including root density and plant diversity.

This study confirms the role of mangroves as vital buffers for coastal biodiversity. Ecological imbalance due to vegetation loss leads to declining coastal fauna populations, eventually affecting ecosystem services such as traditional fishing. Thus, increasing vegetation density is a key success indicator in mangrove rehabilitation. This study demonstrates the importance of social structure and community participation in successful mangrove restoration. Villages with active community involvement, such as Sonde and Kuala Patah Parang, showed better vegetative monitoring results than those relying solely on top-down government programs.

Overall, these findings underscore the need for integrated approaches in mangrove management that account for local biophysical conditions, seedling age and quality, and surrounding socio-economic dynamics. This supports Field's recommendation (Friess et al., 2019) that mangrove conservation policies should be designed based on spatial-temporal understanding of ecological pressures and local adaptation, emphasizing the importance of long-term, data-driven monitoring systems to ensure sustainable rehabilitation outcomes.

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4. CONCLUSIONS

The findings of this study confirm that the success of mangrove growth and rehabilitation in the coastal areas of Riau is strongly influenced by the interaction between substrate biophysical conditions, anthropogenic pressures, seedling characteristics, and community involvement. Vegetation monitoring and biophysical observations conducted in six villages during May–June 2024 revealed that *Avicennia alba* is the most dominant and adaptive species, capable of thriving across various salinity levels (15–24‰) and muddy substrates. Sonde Village recorded the highest survival rate at 73.34%, followed by Sungai Upih (65.81%), Sungai Emas (58.32%), Sungai Bakau (57.47%), Kuala Patah Parang (36.57%), and Tanjung Bunga (27.36%). Factors such as substrate temperature and moisture, soil pH, salinity, and physical protection support plant survival and growth. Locations with stable environmental conditions, natural wave protection, and community-based management demonstrated better rehabilitation performance.

Furthermore, mangrove vegetation density is crucial in maintaining coastal biodiversity, supporting ecosystem functions, and local livelihoods. These findings highlight that mangrove rehabilitation strategies should be tailored to local contexts, integrating appropriate species and seedling age selection, physical protection, and continuous biophysical monitoring to ensure ecosystem sustainability. This adaptive and participatory approach is more effective than a uniform, top-down method.

5. RECOMMENDATIONS

Based on the findings of this study, several strategic recommendations are proposed to support the sustainability of mangrove ecosystems in the coastal region of Riau. First, it is essential to implement site-specific and community-based mangrove management, particularly in high-risk areas such as Tanjung Bunga and Sungai Emas, where biophysical stress is high and seedling survival rates are low. Second, biophysical monitoring systems must be enhanced by regularly measuring substrate temperature, salinity, and soil

moisture to enable early detection of ecological changes and guide adaptive rehabilitation strategies. Third, there is a need to strengthen regulatory frameworks and enforcement mechanisms, especially in Indragiri Hilir and Rokan Hilir Regencies, where land-use conversion and weak governance threaten mangrove sustainability. Fourth, mangrove conservation should be integrated into regional development planning, involving multiple stakeholders and supported by long-term ecological monitoring systems. Lastly, selecting ecologically appropriate species, such as Avicennia alba, along with optimizing seedling quality and age, is crucial to improve survival rates and ensure restoration success across various environmental conditions.

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