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Analysis of mangrove vegetation diversity in Pematang Kuala Village, Teluk Mengkudu Sub-district, Serdang Bedagai Regency, North Sumatra

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ABSTRACT

Mangrove ecosystems are important in ecological, economic, and social aspects, especially for coastal communities. However, damage to mangrove ecosystems due to land-use changes for purposes such as settlements and fish ponds can threaten their sustainability. This study aims to analyze the potential of the mangrove ecosystem, apply the *kao-kao* model in silvofishery pond management, and analyze the potential of mangroves in increasing the income of the community in Pematang Kuala Village, Teluk Mengkudu Sub-district, Serdang Bedagai District, North Sumatra Province. The methods used include field surveys for vegetation analysis and interviews with Kelompok Usaha Bersama (KUB) Nelayan Sepakat members. Vegetation analysis was conducted in three zones: utilization zone I, II, and the protection zone. Each zone consisted of 5 plots, totaling 15 plots. Interviews were conducted with 27 respondents. The study results showed that the mangrove ecosystem in Pematang Kuala Village is dominated by *Avicennia marina* and *Rhizophora mangle,* with an important value index of 300 in both utilization and protection zones. In the protection zone, the Shannon-Wiener diversity index was 0.95, indicating a low level of diversity. Based on the *kao-kao* system model, it was observed that the productivity of fish ponds and fishermen's catch increased. Community income has significantly increased over the last five years, with an average net income of IDR 19,550,000 every six months. The presence of mangroves also provides indirect benefits as a coastal protector from abrasion, with an estimated economic value of IDR 247,950,000 per year.

Keywords: Coastal, Coastal Economy, Kao-kao Pond Model, Mangrove, Silvofishery

1. Introduction

Mangroves are a component of coastal ecosystems that play an important role ecologically, economically, socially, and environmentally, and are also key in climate change mitigation strategies [1]. Mangrove degradation has reached up to 70%, primarily due to a lack of awareness regarding the economic importance of mangroves and land conversion into aquaculture ponds [2,3]. Mangrove ecosystems are important in increasing the income of communities living in mangrove areas [4]. However, local communities often neglect mangrove conservation, leading to the degradation of the mangrove ecosystem [5].

The mangrove ecosystem plays a vital physical role in preventing seawater intrusion, serving as a windbreaker, wave buffer, and a natural barrier against coastal erosion, tsunamis, and storms. Ecologically, it functions as a feeding, spawning, and nursery ground for various marine organisms. In addition, mangroves also hold important social functions, such as serving as platforms for education, ecotourism, and cultural identity [6]. Mangroves are widely recognized as one of the ecosystems most capable of absorbing and storing carbon faster than many other tree species [7]. Carbon storage in mangrove ecosystems is found in the aboveground and belowground biomass, making them crucial in the global effort to address climate change [8].

As a village located in a coastal area, most residents in Hamlet V, Pematang Kuala Village, work as fishermen and fish pond operators. One of the main challenges faced by the coastal community is the declining fish catch. Previous studies have revealed that the low number of fish and other marine organisms caught is closely related to the community's lack of awareness and concern regarding mangrove conservation [9]. In addition, the degradation of mangrove ecosystems has reduced the availability of natural food sources for fish and other marine organisms. This degradation affects marine biodiversity and alters the ecological balance, leading to increased erosion and sedimentation that further disrupt coastal ecosystems [10]. These conditions highlight the importance of maintaining the ecological integrity of mangrove ecosystems through efforts such as vegetation diversity assessment and monitoring [11].

Although the mangrove ecosystem in Pematang Kuala Village remains in relatively good condition, comprehensive data on its vegetation diversity are still lacking. Understanding the composition and diversity of mangrove species is essential, as it indicates ecological resilience, habitat quality, and the long-term sustainability of coastal ecosystems. Therefore, this study specifically aims to analyze the vegetation diversity of mangrove forests in Pematang Kuala Village, Teluk Mengkudu Subdistrict, Serdang Bedagai Regency, North Sumatra Province. The findings are expected to serve as a scientific basis for planning future conservation and rehabilitation efforts, while also strengthening biodiversity protection and the ecological functions that support the livelihoods of local coastal communities.

2. Method

2.1. Time and location

This research was conducted from September to December 2024 in the mangrove forest area of Dusun V Pematang Kuala Village, Teluk Mengkudu Sub-district, Deli Serdang Regency, North Sumatra, with an area of approximately 54.2 Ha of mangrove forest. Geographically, Pematang Kuala Village is located at 3°31'23.1 "N 99°11'30.6 "E with an area of 2.93 Km^2 consisting of five hamlets. The research site was selected based on its representative characteristics as a typical coastal mangrove-based community and the unique application of the Kao-Kao silvofishery model. Integrating these socio-ecological features makes it scientifically suitable for studying mangrove multifunctionality. The location was selected due to its unique integration of traditional pond management and ongoing mangrove rehabilitation, representing a typical yet under-researched coastal community in North Sumatra. The research location map can be seen in Figure 1.

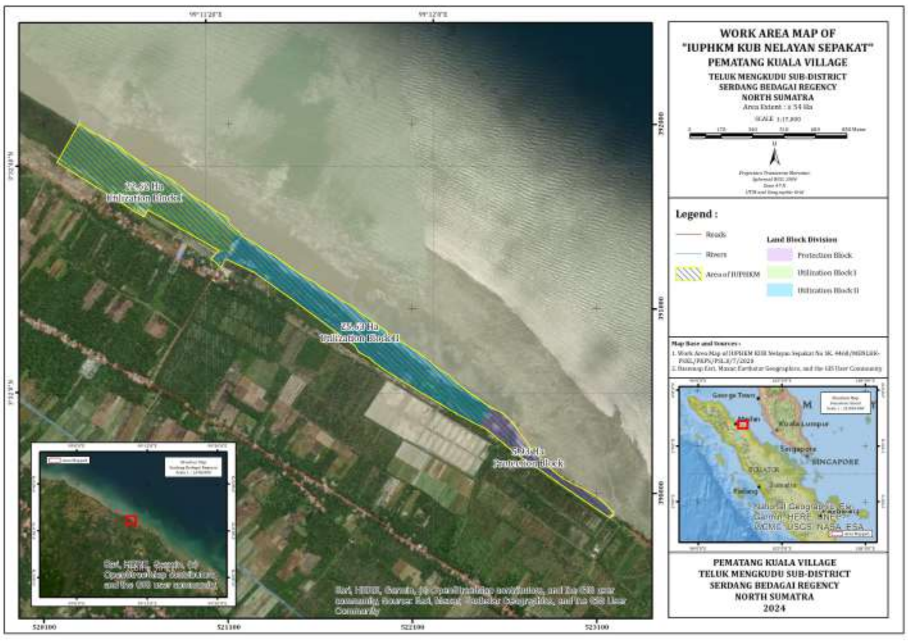


Figure 1. Research location map.

2.2. Tools and Materials

The tools and materials required in this study can be seen in Table 1.

Table 1. Research tools and materials

No	Activity	Tools and materials	Function
1	Vegetation analysis	*Avenza maps*	To determine the sampling plot.
		Planet application	To determine the type of mangrove vegetation species.
		Rafia rope	To make measurement plots.
		Tape measure	To measure tree diameter.
		Haga hypsometer	To measure tree height.
		Stationery	To record data in the field.
		Phiband	To measure the area of the plot.
2	Application of *kao-kao*	Laptop	model Laptop for making *kao-kao* model design.
3	Interview respondents related to community income.	*Interview guide*	As an interview guide that contains questions.
		Camera	For documentation of activities.
		Stationery	To fill in the questionnaire.

2.3. Research Procedure

The procedure carried out in this study is divided into three parts, namely:

2.3.1. Vegetation analysis

The procedures carried out are as follows:

2.3.1.1. Determination of Lines and Plots

- The research line was placed perpendicular to the shoreline to ensure that all zones in the mangrove ecosystem were represented.

- The lane placement system was implemented using the Systematic Strip Sampling with Random Start method. The first strip was determined randomly, while subsequent strips were placed systematically with a distance of 141.42 meters.

2.3.1.2. Zone Division

- The research site was divided into three zones, namely:
a) Utilization Zone 1
b) Utilization Zone 2
c) Protection Zone
- In each zone, vegetation was measured using 10 m x 10 m measuring plots categorized into tree categories.

2.3.1.3. Determination of Measurement Plots

- In each lane, five measuring plots measuring 10 m x 10 m were placed with a distance between plots of 141.42 meters.

- Measurements were only taken at the tree level, i.e., individuals with a trunk diameter ≥ 10 cm.

- The measuring plots were placed systematically according to the predetermined research scheme.

2.3.1.4. Measurement of Vegetation Parameters

- Each mangrove within the 10 m x 10 m plot was identified and measured for diameter.
- Data collected include:
a) Type of mangrove species
b) Number of individuals per species
c) Stem diameter (DBH ≥ 10 cm)

d) Density and frequency of each species

2.3.1.5. Data Analysis
- The data obtained were analyzed to calculate:

a) Species density per zone
b) Species frequency
c) Index of Important Value (INP)
- The results of the analysis were used to describe the composition and structure of mangrove vegetation in each zone.

2.3.2. Kao-kao model

2.3.2.1. Basic Development Model:
a) The Kao-Kao model was developed based on the wisdom of local pond communities who have long integrated mangroves into the fisheries system.

b) The design model is based on field observations and participatory mapping using the Avenza Maps application and GPS surveys.

2.3.2.2. Effectiveness Measurement Model:
a) Measurements were made of the increase in pond productivity with indicators of harvest volume (kg) and net income (Rp) during two harvest periods (2020–2024).

b) Productivity was compared with the period before the model was implemented.

2.3.2.3. Socio-Economic Validation:
a) In-depth interviews were conducted with the Joint Business Group (KUB) of Fishermen. Agree to provide direct benefits (income) and changes in pond management.

b) The interview results were validated with secondary data from forest farming group reports and village catch records.

2.3.2.4. Ecological Validation:
a) The growth of mangrove stems (height and diameter) along the embankment pond was assessed.

b) Direct observation was conducted on air clarity, odor, and the presence of small marine biota (phytoplankton and young shrimp) as indicators of the quality of the pond ecosystem.

2.3.2.5. Data Analysis Technique:
a) Data analysis was conducted using a quantitative approach (production, income) and a qualitative approach (thematic analysis of interviews).

b) Triangulation was conducted to ensure data validity between field observations, interviews, and documentation.

2.3.3. Direct and indirect benefits

2.3.3.1. Direct benefits, such as an increase in the silvofishery farmer's income
The procedure is as follows:

a) Prepared Interview guide
b) Seeking respondents who earn a living as a pond entrepreneur
c) Interviews were conducted, and the results were recorded
d) Documentation was conducted

2.3.3.2. Indirect benefits as an abrasion barrier
The procedures carried out are as follows:

a) An interview guide was prepared
b) Respondents who felt the benefits of mangrove forests as abrasion barriers were sought.
c) Interviewed and analyzed the value of the benefits with the replacement cost method.

2.4. Data analysis

2.4.1. Vegetation Analysis
In the vegetation analysis research, the following formula was used:

For the tree level is

$$IVI = KR + FR + DR \text{ [12]} \quad (1)$$

Description: KR = Relative Density; FR = Relative Frequency; DR = Relative Dominance; IVI = Important Value Index

The calculation is done with the following formula:

$$\text{Density (K) (ind/ha)} = \frac{\sum Individuals\ of\ a\ species}{Sample\ plot\ area} \quad (2)$$

$$\text{Relative Density (KR)(\%)} = \frac{\text{K of a species}}{\text{K of all species}} x\ 100\% \quad (3)$$

$$\text{Frequency (F)} = \frac{(\sum\text{Sub-plots found of a species})}{(\sum\text{All sample sub-plots})} x\ 100\% \quad (4)$$

$$\text{Relative Frequency (FR) (\%)} = \frac{\text{F of a species}}{\text{F of all species}} x\ 100\% \quad (5)$$

$$\text{Dominance (D) (m2/ha)} = \frac{\text{Area of basal area of a species}}{\text{Area of sample plots}} \quad (6)$$

$$\text{LBD} = \frac{1}{4}\pi \text{ x } D^2 \quad (7)$$

$$\text{Relative Dominance (DR) (\%)} = \frac{\text{D of a species}}{\text{D of all species}} x\ 100\% \quad (8)$$

$$\text{Tree Volume (V)} = \text{LBD x Tbc x f; (f = 0.7)} \quad (9)$$

$$\text{Shannon} - \text{Wiener Diversity Index (H')} = -\sum(\frac{ni}{n}.\ln(\frac{ni}{n}) \quad (10)$$

Description: H' = Shannon-Wiener Diversity Index; ni = Number of individuals of the nth species; n = Total number of individuals

Criteria: H' < 1 = Low diversity; 1 < H' < 3 = Medium diversity; H' > 3 = High diversity

$$\text{Species Evenness Index (E)} = \frac{H'}{\ln(S)} \quad (11)$$

Description: E = Species Evenness Index; H' = Species Diversity Index; S = Number of species

Criteria: E < 0.3 = Low evenness; 0.3 < E < 0.6 = Medium evenness; E > 0.6 = High evenness

$$\text{Menhinick Richness Index (R)} = \text{S}/\sqrt{\text{n}} \quad (12)$$

Description: R = Menhinick's Richness Index; S = Number of species; n = Total number of individuals

Criteria: R < 2.5 = Poor diversity; 2.5 < R < 4.0 = Moderate diversity; R > 4.0 = Good diversity

2.4.2. Kao-kao Model Analysis

The results of the vegetation analysis data were integrated with the field survey to review the land area suitable for applying the kao-kao model. Then the width of the mounds was determined with a distance between mounds of 1-2 m, and mangroves were planted along the edges of the mounds with a spacing of 1 m.

2.4.3. Analysis of Direct and Indirect Benefits

2.4.3.1. Income analysis of silvofishery farming communities

To determine the income of silvofishery pond entrepreneurs, a quantitative data analysis by calculating the difference between revenue and business costs are formulated as follows:

$$\prod = \text{TR} - \text{TC} \tag{13}$$

Description: ∏ = Business income (Rp); TR = Business revenue (Rp); TC = Total business cost (Rp)

2.4.3.2. Analysis of indirect benefits as an abrasion barrier

The cost of building a breakwater is calculated based on the price per cubic meter and the number of cubic meters required per meter of building length.

$$\text{B meter} = \text{V per meter x H per cubic meter} \tag{14}$$

Description: B meter = Cost of breakwater per meter length (Rp/m); V per meter = Volume of material per meter length (m^3); H per cubic meter = Material price per cubic meter (Rp/m^3)

The total construction cost for the entire coastline with abrasion impact is calculated as follows.

$$\text{B total} = \text{B meter x L shore} \tag{15}$$

Description: B total = Total cost of building a breakwater (Rp); L shore = Length of coastline affected by abrasion (m)

Data analysis was carried out after all data were collected, then analyzed using qualitative descriptive methods and quantitative data analysis. Qualitative descriptive analysis is used to identify various forms of utilization carried out by the community [13]. Furthermore, quantitative data analysis was carried out to calculate the costs and income of fishermen and pond entrepreneurs, by calculating the difference between revenue and business costs, formulated as follows:

2.5. Data collection method

Data collection in this study involved three main aspects: vegetation structure, Kao-Kao model application, and community economic benefits. Vegetation analysis was conducted using systematic strip sampling to collect data on species composition and structural parameters in three zones. Kao-Kao model assessment involved direct field observation and participatory design with local practitioners to document model layout, management practices, and ecological integration. Respondent interviews were conducted and selected using purposive sampling, targeting community members actively engaged in pond farming and fishing. Selection criteria included a minimum of 5 years of residence and active participation in mangrove-based livelihood activities. This approach ensured relevance and statistical reliability for a qualitative-descriptive analysis. To avoid redundancy, detailed procedures for vegetation analysis and Kao-Kao model development are only described in their respective subsections. Primary interview data was triangulated using village records, group activity documentation, and field verification to ensure validity.

3. Results and Discussion

3.1. Mangrove Vegetation Structure and Diversity

Table 2. Tree Importance Value Index in Utilization Zone I, Pematang Kuala Mangrove Area

No.	Species	Scientific Name	D (ind/ha)	RD (%)	F	RF (%)	Do (m²/ha)	RDo (%)	Volume (m³)	IVI (%)
1	White mangrove	*Avicennia marina*	360	100	100	100	5.13	100	5.28	300
	Total		360	100	100	100	5.13	100	5.28	300

Table 3. Tree Importance Value Index in Utilization Zone II, Pematang Kuala Mangrove Area

No.	Species	Scientific Name	D (ind/ha)	RD (%)	F	RF (%)	Do (m²/ha)	RDo (%)	Volume (m³)	IVI (%)
1	White mangrove	*Avicennia marina*	320	100	60	100	0.01	100	9.85	300
	Total		320	100	60	100	0,01	100	9.85	300

Table 4. Tree Importance Value Index in Protection Zone, Pematang Kuala Mangrove Area

No.	Species	Scientific Name	D (ind/ha)	RD (%)	F	RF (%)	Do (m²/ha)	RDo (%)	Volume (m³)	IVI (%)
1	White pidada	*Avicennia marina*	160	66.5	80	44.4	0.02	15.3	1.76	126.3
2	Sea hibiscus	*Hibiscus tiliaceus*	60	24.9	60	33.3	0.02	20.4	0.22	78.7
3	White teruntum	*Lumnitzera racemosa*	0.32	0.13	20	11.1	0.008	5.58	0.01	16.8
4	Large red mangrove	*Rhizophora mangle*	20	8.32	20	11.1	0.084	58.6	0.08	78.03
	Total		240.3	100	180	100	0.143	100	2.095	300

Table 5. Biodiversity Indices in Utilization Zone I

No.	Species	Scientific Name	ni	ni/N	ln(ni/N)	ni/N* ln(ni/N)
1.	White mangrove	*Avicennia marina*	18	1	0	0
Total			18	1	0	0
Shannon-Wiener Index						0
Evenness Index						0
Species Richness Index						0.23

Table 6. Biodiversity Indices in Utilization Zone II

No.	Species	Scientific Name	ni	ni/N	ln(ni/N)	ni/N* ln(ni/N)
1.	White mangrove	*Avicennia marina*	16	1	0	0
Total			16	1	0	0
Shannon-Wiener Index						0
Evenness Index						0

Species Richness Index	0.25

Table 7. Biodiversity Indices in Protection Zone

No.	Species	Scientific Name	ni	ni/N	ln(ni/N)	ni/N* ln(ni/N)
1.	White mangrove	*Avicennia marina*	8	0.57	-0.55	0.31
2.	Sea hibiscus	*Hibiscus tiliaceus*	3	0.21	-1.54	0.33
3.	White teruntum	*Lumnitzera racemosa*	2	0.14	-1.94	0.27
4.	Large red mangrove	*Rhizophora mangle*	1	0.07	-2.63	0.02
Total			14	1	-6.12	0.95
Shannon-Wiener Index						0.95
Evenness Index						0.68
Species Richness Index						1.06

The vegetation analysis was conducted in three zones: Utilization Zone I, Utilization Zone II, and Protection Zone. Each zone contained five 10 m × 10 m plots, sampled using the Systematic Strip Sampling with Random Start method. The analysis revealed that A. marina dominates all zones, though with varying levels of biodiversity and structural composition.

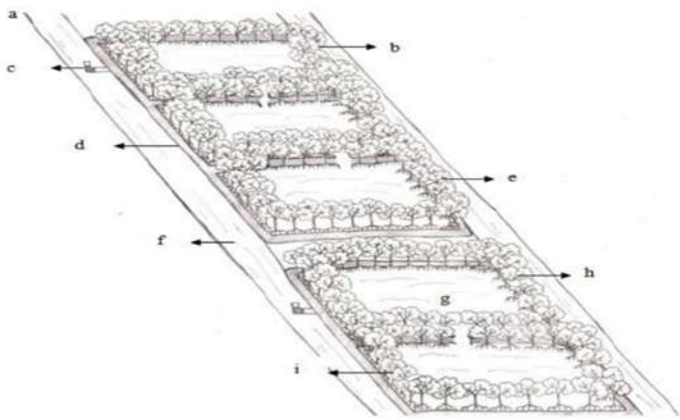
In Utilization Zone I, A. marina recorded a 360 individuals/ha density and dominated entirely with an Important Value Index (IVI) of 300%. No other species were found, leading to a Shannon-Wiener Index (H') of 0.00, an Evenness Index (E) of 0.00, and a Species Richness Index (R) of only 0.23. These findings reflect extremely low biodiversity, indicating monoculture dominance. Such conditions are ecologically fragile and sensitive to environmental disturbances [14].

Similar results were found in Utilization Zone II, where *A. marina* maintained its dominance with a slightly lower density of 320 individuals/ha, but still achieved an IVI of 300%. Biodiversity indices remained at zero (H' = 0.00, E = 0.00), although species richness increased marginally to R = 0.25.

The results indicate that the Protection Zone supports significantly higher structural complexity and species diversity than the Utilization Zones. This is reflected in the presence of four species—*A. marina*, *Hibiscus tiliaceus, Lumnitzera racemosa,* and *Rhizophora mangle*—along with ecological index values that surpass those of the other zones (H' = 0.95, E = 0.68, R = 1.06). These values suggest a healthier and more resilient mangrove ecosystem, where natural regeneration and species coexistence are actively occurring. In contrast, the Utilization Zones are characterized by monoculture dominance of *A. marina*, reflected by zero values in the Shannon-Wiener and Evenness indices, which point to extremely low biodiversity. Species-poor mangrove stands are more vulnerable to environmental changes and offer fewer ecosystem services than biodiverse systems.

Several factors contribute to the ecological success observed in the Protection Zone. First, strict protection measures and the absence of extractive activities have minimized disturbances, allowing the ecosystem to recover its natural dynamics. Second, community engagement through participatory monitoring and co-management practices has enhanced ecological stewardship and local compliance, which are key to maintaining conservation effectiveness. Moreover, the site's intact hydrology and substrate conditions likely facilitate seed dispersal and the successful recruitment of multiple species.

3.2. Kao-Kao Model Implementation in Silvofishery



Description / Legend:
a. Reservoir
b. Rhizophora mangle
c. PVC pipe (or "paralon pipe")
d. Raised bed (or simply "bed")
e. Avicennia marina
f. Water gate (or "sluice gate")
g. Fish/shrimp pond (or simply "pond")
h. Lumnitzera racemosa

Figure 2. Kao-kao Silvofishery Model in Pematang Kuala Village, Teluk Mengkudu Sub-district, Serdang Bedagai Regency

The Kao-Kao model was developed to integrate aquaculture practices with mangrove rehabilitation. It incorporates silvofishery principles where shrimp and crab ponds are embedded within mangrove vegetation zones. As depicted in Figure 2, the model comprises structured pond ridges (paralon) flanked by mangrove belts planted with Rhizophora mangle and A. marina. These are supported by water inlet and outlet systems, drainage, and sedimentation control mechanisms.

Field surveys confirmed that the Kao-Kao model contributed to improved pond water quality through natural filtration, reduced sedimentation, and improved nutrient cycling. These improvements support the hypothesis that integrating ecological engineering in mangrove areas can simultaneously enhance environmental quality and fishpond productivity [9].

3.3. Economic Impact of Mangrove-Based Silvofishery

3.3.1. Aquaculture Income Analysis

Table 8. Shrimp and Mangrove Crab Seed Requirements in One Pond Over 6 months (First Harvest)

No	Cost Type	Price (Rp)	Number of Seedlings	Cost (Rp)
1	Land Management	700,000	-	700,000
2	Labor	2,000,000	-	2,000,000
3	Feed	1,200,000	-	1,200,000
4	Shrimp Seedlings	60	20,000	1,200,000
5	Mangrove Crab Seedlings	1,500	500	750,000
	Total			5.850.000

Table 9. Production Yield from One Pond Over 6 months (First Harvest)

No	Type	Price per kg (Rp)	Quantity (Kg)	Total Price (Rp)
1	Shrimp	80,000	245	19,600,000
2	Mangrove Crab	40,000	145	5,800,000
	Total			25,400,000

A six-month production cycle analysis of shrimp and mud crab farming revealed a net profit of IDR 19,550,000 per pond in 2024, compared to IDR 9,500,000 in 2020. The production cost in one cycle amounted to IDR 5,850,000 (Table 8), while revenue reached IDR 25,400,000 from selling 245 kg of shrimp and 145 kg of crab (Table 9). This economic uplift indicates the efficacy of the Kao-Kao system in increasing productivity by optimizing the ecological functions of mangroves, such as natural feed availability and water stability.

Table 10. Pond Farmers' Income Over the 2020–2024 Period

No	Year	First Harvest Income (Rp)	Second Harvest Income (Rp)
1	2020	9,500,000	10,000,000
2	2021	10,200,000	10,350,000
3	2022	11,550,000	11,950,000
4	2023	14,100,000	15,350,000
5	2024	19,250,000	19,550,000

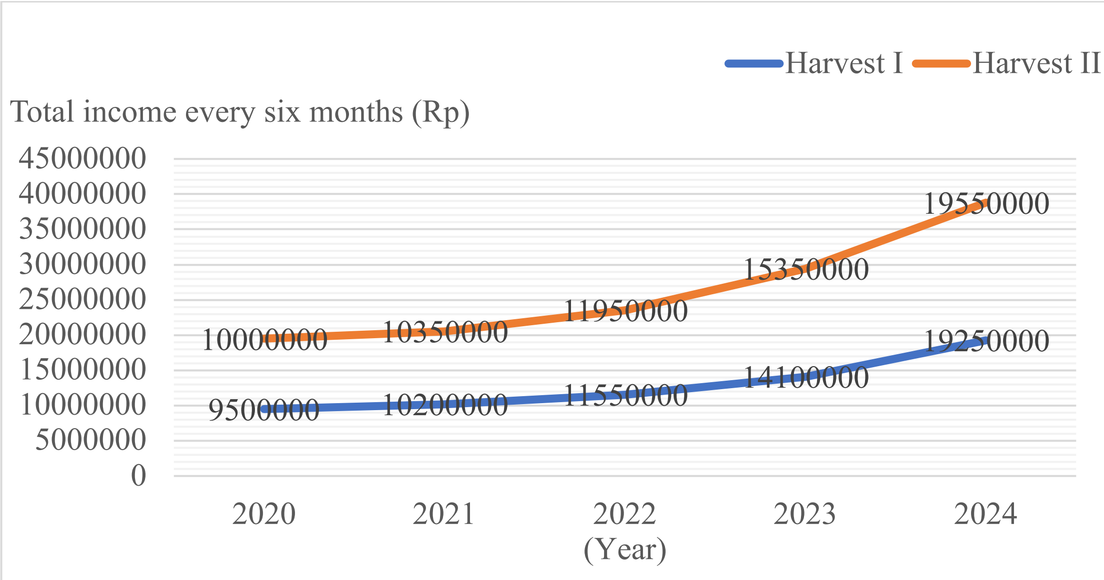


Figure 3. Pond Farmers' Income Over the 2020–2024 Period

Data from Table 10 illustrates a five-year trend of increasing income for silvofishery farmers. This sustained growth supports the notion that integrating mangrove preservation in aquaculture enhances long-term economic viability and reduces dependency on artificial inputs [15].

3.3.2. Fishermen's Daily Catch and Income

Table 11. Fishermen's Daily Catch (day)

No	Catch Type (per day)	Quantity (Kg)	Unit Price (Rp)	Total (Rp)
1	Gulama fish / Croaker	2 kg	7,000	14,000
2	Sangge fish / Threadfin	2 kg	30,000	60,000
3	Tonguefish	2 kg	35,000	70,000
4	Cuttlefish	2 kg	30,000	60,000
5	Yellowtail scad	3 kg	20,000	60,000
6	Mangrove crab	1 kg	40,000	40,000
7	Selapis shrimp	1.5 kg	80,000	120,000
8	Swallow shrimp	1 kg	50,000	50,000
	Total			474,000

Apart from pond farmers, traditional fishermen also experienced positive impacts. As shown in Table 11, the average daily income reached IDR 474,000, derived from various species including gulama, senangin, kepiting bakau, and udang selapis. Interviews revealed that restored mangrove root systems offered a safer habitat for juvenile fish and crustaceans, increasing capture yields over time [16]. These results align with the theory that mangrove ecosystems serve as nurseries and feeding grounds critical for marine biodiversity sustainability.

3.4. Indirect Ecosystem Services: Coastal Protection

Mangroves provide significant protection against coastal erosion, acting as natural wave breakers. Using the replacement cost method, the study estimated the economic value of mangrove protection at IDR 247,950,000 per year. This figure is based on the cost of constructing breakwater structures (IDR 2,850,000 per meter), multiplied by the length of the protected coastline (870 meters), with a 10-year structure lifespan. Thus, the existence of mangrove ecosystems avoids capital expenditures of nearly IDR 2.5 billion [13].

This economic valuation illustrates that mangrove conservation offers direct monetary benefits and substitutes for large-scale infrastructure investments. These findings reinforce previous studies on the financial viability of ecosystem-based adaptation (EbA) strategies in coastal areas [6].

3.5. Hypothesis Evaluation

Based on the introduction, the primary hypothesis posited that the preservation and sustainable utilization of mangrove ecosystems via structured silvofishery would enhance ecological integrity and community livelihoods. The results of this study validate this hypothesis. Significant improvements were found in:

- Species diversity and evenness in protected zones,
- Pond productivity and aquaculture income,
- Capture fishery yields, and
- Economic valuation of non-market ecosystem services.

Thus, integrating ecological restoration into local economic systems—like the Kao-Kao model—emerges as a viable approach to achieving Sustainable Development Goals (SDGs), particularly poverty alleviation, climate adaptation, and marine conservation.

4. Conclusions

The vegetation analysis conducted across three zones, two utilization zones and one protection zone, revealed that *Avicennia marina* dominated all zones, with an Importance Value Index (IVI) of 300 in the utilization zones, and remained the primary species in the protection zone. The Shannon-Wiener diversity index (H') in the utilization zones was 0.00, while in the protection zone it reached 0.95, indicating a significant difference in vegetation structure and diversity among the zones. The monoculture dominance in the utilization zones suggests an ecologically vulnerable condition. In contrast, the higher diversity observed in the protection zone reflects a more stable and resilient ecosystem with potential for natural regeneration. Although this study focused on vegetation analysis, the results correlate with field data on increasing community income. Zones with greater vegetation diversity have supported the success of the Kao-kao silvofishery model, which has demonstrably improved pond productivity and fishery yields. The average net income of pond farmers reached IDR 19,550,000 per harvest cycle, while traditional fishers earned an average of IDR 474,000 per day. These findings affirm that mangrove vegetation diversity plays a critical role in maintaining ecological sustainability and enhancing the economic well-being of coastal communities. Therefore, mangrove conservation and rehabilitation efforts should consider vegetation diversity as a key foundation for sustainable ecosystem management planning.

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