

# Land suitability assessment for mangrove-based silvofishery in North Sumatra, Indonesia

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<sup>2</sup>Department of Forestry, Faculty of Forestry, Universitas Sumatera Utara. Kampus 2 USU Bekala, Simalingkar A, Pancur Batu, Deli Serdang 20353, North Sumatra, Indonesia. Tel./fax.: +62-61-8220605, \*email: m.basyuni@usu.ac.id

<sup>3</sup>Center of Excellence for Mangrove, Universitas Sumatera Utara. Jl. Dr. T. Mansur No. 9, Medan 20155, North Sumatra, Indonesia

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**Abstract.** *Risdayanti, Basyuni M, Aththorick TA. 2026. Land suitability assessment for mangrove-based silvofishery in North Sumatra, Indonesia. Asian J For 10 (1): r100130. <https://doi.org/10.13057/asianjfor/r100130>. Silvofishery integrates mangrove conservation with brackish-water aquaculture and is increasingly promoted as a sustainable alternative to conventional pond systems in Indonesia. However, site-specific evaluations of biophysical land suitability remain limited. This study aimed to assess land suitability for mangrove-based silvofishery in Pasar Rawa Village, Langkat District, North Sumatra, Indonesia, by integrating vegetation structure, soil characteristics, water quality parameters, and a weighted scoring land-evaluation approach. Mangrove vegetation was surveyed using three perpendicular transects with 21 nested plots (10×10 m trees; 5×5 m saplings; 1×1 m seedlings). Soil (0-30 cm) and water samples were collected from the inlet, outlet, and pond interior compartments. Five mangrove species were recorded, dominated by *Rhizophora apiculata* and *Sonneratia alba*. Total densities reached 257.1 ind/ha (trees), 3,219.1 ind/ha (saplings), and 833.3 ind/ha (seedlings), indicating active regeneration. Water quality showed a mean temperature of 28.6°C, salinity of 15.0 ppt, pH of 6.5, and dissolved oxygen of 8.7 mg/L, within acceptable ranges for silvofishery. Soil analysis revealed moderately acidic conditions as the primary limiting factor. The weighted scoring system yielded a suitability index of 75.75%, classifying the area as Highly Suitable (S1). Acidic soil pH and suboptimal stand density were identified as manageable constraints. These findings provide a practical decision-support framework for restoration-based silvofishery planning and support evidence that maintaining mangrove cover does not compromise aquaculture productivity.*

**Keywords:** Land suitability, mangrove, silvofishery, *wanamina*, weighted scoring

## INTRODUCTION

Mangrove ecosystems occupy dynamic intertidal zones characterized by tidal inundation, salinity gradients, and anaerobic soils, supporting specialized halophytic vegetation and high primary productivity (Alongi 2020; Ramadhani et al. 2024; Purwoko et al. 2026). Beyond shoreline stabilization and nutrient cycling, mangroves contribute significantly to carbon sequestration, fisheries productivity, and coastal resilience (Mehvar et al. 2018; Duke et al. 2019; Kurniawati et al. 2022; Nur et al. 2022; Koedaryanto et al. 2024). Their function as nursery, feeding, and spawning grounds makes mangroves essential for sustaining coastal fisheries.

Globally, mangroves are under continuous pressure from land-use conversion, particularly aquaculture expansion (Friess et al. 2019; Goldberg et al. 2020). Indonesia hosts the world's largest mangrove extent, yet conversion to aquaculture remains a primary driver of degradation (Basyuni et al. 2022; Sumarga et al. 2022). National mangrove loss has been strongly associated with brackish-water pond expansion, resulting in hydrological disruption and declining ecosystem services (Basyuni et al. 2018; Sumarga et al. 2022). These changes reduce carbon

storage capacity and weaken natural coastal protection functions (Mehvar et al. 2018; Goldberg et al. 2020).

Hydrological restoration studies in North Kalimantan, Indonesia, demonstrate that restoring tidal connectivity significantly improves regeneration and ecological stability (Basyuni et al. 2025). Proper water exchange is therefore fundamental not only for ecological recovery but also for sustainable aquaculture systems (Primavera and Esteban 2008). In North Sumatra, rapid expansion of brackish-water aquaculture has contributed significantly to mangrove loss, resulting in declining ecosystem services, increased coastal vulnerability, and reduced water quality and fisheries productivity (Basyuni et al. 2018). In response to these challenges, silvofishery (*wanamina*) has been promoted as a management approach that integrates mangrove conservation with aquaculture production (Sumarga et al. 2024). In contrast to fully cleared pond systems, integrated mangrove-aquaculture designs preserve mangrove vegetation within pond landscapes, which contributes to sediment retention, organic matter processing, and improved environmental regulation (Walton et al. 2006; Bosma and Verdegem 2011).

Previous studies have shown that silvofishery systems can enhance ecological functions, stabilize pond environments, and improve long-term productivity

compared with conventional aquaculture practices that involve complete mangrove clearing (Ariadi et al. 2023). However, the success of silvofishery is highly dependent on land suitability, particularly water quality, soil characteristics, and mangrove vegetation structure, which directly influence nutrient dynamics, organism survival, and ecological stability within pond systems (Musa et al. 2020; Soeprpto et al. 2023). Potential acid sulfate soils commonly found in former mangrove areas may oxidize when exposed to air, producing sulfuric acid and mobilizing toxic elements such as iron and aluminum, which can severely constrain aquaculture productivity if not properly mitigated (Dent and Pons 1995; Sammut et al. 1996). Furthermore, salinity levels that fall outside species-specific tolerance ranges can disrupt osmoregulatory processes, leading to physiological stress, reduced growth performance, and increased mortality in cultured organisms (Boyd 2015; Food and Agriculture Organization (FAO) 2020). Vegetation density and species composition further influence sediment dynamics, organic matter input, and ecological buffering capacity (Duke et al. 2019; Alongi 2020).

Pasar Rawa Village, located in Gebang Sub-district, Langkat District, North Sumatra, Indonesia, represents a coastal area with potential for silvofishery development. Although the mangrove ecosystem in this area previously experienced degradation due to activities such as charcoal production, recent improvements in management under the Forest Management Unit (KPH) and the Village Forest Management Institution (LPHD) have created opportunities for restoration-based utilization. Local communities remain highly dependent on fisheries-based livelihoods, particularly traditional brackish-water ponds adjacent to

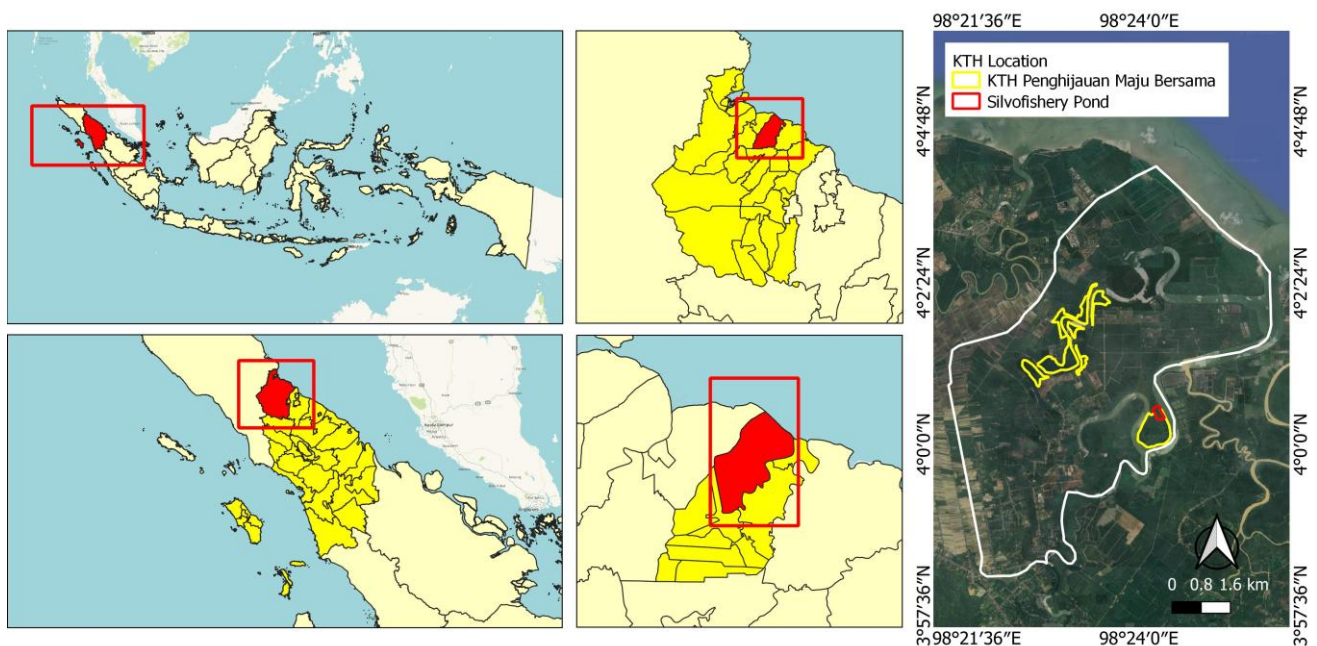
mangrove areas, highlighting the need for integrated and sustainable management approaches.

Despite the growing promotion of silvofishery as a sustainable alternative to conventional aquaculture, most existing studies focus on ecosystem services, carbon storage, or production performance, while providing limited insight into land-suitability constraints that determine where silvofishery can be effectively implemented. In particular, site-specific evaluations that integrate mangrove vegetation structure, soil properties, and water quality to identify biophysical limiting factors at the local management scale remain scarce, especially in rehabilitated mangrove areas. Therefore, this study aims to assess land suitability for mangrove-based silvofishery in Pasar Rawa Village by integrating vegetation, soil, and water quality parameters using a weighted scoring approach. This research contributes to silvofishery planning by explicitly identifying key limiting factors and suitability classes, providing a practical decision-support basis for sustainable mangrove management and coastal aquaculture development.

## MATERIALS AND METHODS

### Study area

This study was conducted in silvofishery pond areas located in Pasar Rawa Village, Gebang Sub-district, Langkat District, North Sumatra Province, Indonesia. Based on its geographical location, Pasar Rawa is located in the northern  $4^{\circ}00'77.5''$  north (N) and  $98^{\circ}40'36.7''$  east (E) of Sumatra Province, which is directly adjacent to the Malacca Strait (Figure 1).



**Figure 1.** The study site was located within the KTH Penghijauan Maju Bersama in Pasar Rawa Village, Gebang Sub-district, Langkat District, North Sumatra, Indonesia

The total area of the silvofishery pond covers 7 hectares, consisting of 6 hectares of ponds with mangrove cover, namely pond compartments that still maintain mangrove vegetation both within the pond area and along the pond embankments, and 1 hectare of ponds without mangrove cover, which was used as a comparison. This compartmentalization was intended to evaluate differences in biophysical conditions between pond systems integrated with mangroves and pond systems without mangrove cover. Sampling points for vegetation, water quality, and soil were purposively placed within each compartment. The placement of these sampling points was designed to ensure that each measured parameter represented the specific conditions of each pond compartment. Fieldwork was conducted from April to May 2025 and included the collection of vegetation, water quality, and soil property data. Soil analysis was carried out at the Laboratory of the Indonesian Oil Palm Research Center, Medan.

### Mangrove vegetation sampling

Mangrove vegetation was analyzed using the quadrant transect method (Fachrul 2008). The determination of observation sites in the Pasar Rawa mangrove area was carried out using a purposive sampling method by selecting representative locations from each zone, considering the feasibility of sampling in accordance with the research objectives. Observations were conducted at the seedling, sapling, and tree levels. A total of three transects were established perpendicular to the shoreline with an inter-transect distance of approximately 25 m. Along each transect, seven observation plots were placed. The plot sizes used were 10×10 m for the tree level, 5×5 m for the sapling level, and 1×1 m for the seedling level. The total number of observation plots for each growth stage was 21 plots, with a total sampled area of 6000 m<sup>2</sup>. Mangrove individuals were classified as trees (DBH≥10 cm), saplings (DBH<10 cm and height>1.5 m), and seedlings (height≤1.5 m). Tree diameter was calculated from the stem circumference measured at a height of 1.3 m above ground level using the formula  $DBH = \text{circumference}/\pi$ . For trees with multiple stems, measurements were taken for each main stem.

### Water sampling

Water quality measurements were conducted at three sampling points within the same pond, representing different pond zones: the inlet (water entry point), the middle section of the pond (interior), and the outlet (water discharge point). Data collection was carried out during high tide (rising tide), with measurements taken between 09:00 and 10:00 Western Indonesian Time (WIB). The water quality parameters measured included temperature, salinity, pH, and Dissolved Oxygen (DO). Salinity measurement was done by using a hand refractometer by taking water samples and storing them in a prism, then observing and recording values on the salinity scale. The temperature measurement was done by using a thermometer, which was placed directly into the water and then reading and recording the temperature values on the thermometer scale. pH measurement was done by using a

pH meter, which was done by pressing the on button to turn on the device and dipping the electrode into the water, then waiting until the value that comes out on the monitor was stable, after which the value was observed as the pH value at the observation location. Dissolved oxygen measurement was done by using a DO meter that was directly immersed in the water, after which the DO value was read and recorded from the instrument. Each parameter was measured in triplicate at each sampling point (inlet, middle section, and outlet) within the same pond compartment, and the average values were used for subsequent analysis.

### Soil sampling

Soil samples were collected only from the surface layer (0-30 cm) (FAO 2019) using a soil auger at each sampling point, as this layer represents the primary root zone influencing mangrove growth and pond soil interactions. Deeper soil horizons were not sampled; therefore, potential acid sulfate conditions discussed in this study are interpreted based solely on surface soil characteristics and existing literature, rather than direct subsoil verification. At each sampling point, three sub-samples were collected and composited into one representative sample. The soil samples were stored in sealed containers, properly labeled, and transported to the Oil Palm Research Center (PPKS) Laboratory in Medan for analysis. Laboratory analyses included measurements of soil pH, soil texture (sand, silt, and clay), and organic matter content. All analytical procedures followed standard soil laboratory methods.

### Data analysis

#### *Mangrove density*

The data analysis used to calculate density refers to the method proposed by Bengen et al. (2022) as follows:

**Species Density (Di)**, is the number of individuals of a species within a unit area.

$$D_i = \frac{n_i}{A} \quad [1]$$

Where:

Di: Species density (ind/ha)

Ni: Total number of individuals of the species

A: Total plot area (m<sup>2</sup>)

To express density in individuals per hectare (ind/ha), values initially obtained in ind/m<sup>2</sup> were multiplied by 10,000 (1 ha = 10,000 m<sup>2</sup>).

**Total Density**, is the total number of mangrove individuals within a unit area, expressed as follows:

$$\text{Total density} = \frac{\sum n}{A} \quad [2]$$

Where:

∑n: Total number of individuals of all species

A: Sampling area (m<sup>2</sup>)

#### *Water quality analysis*

Water quality parameter data at each observation point were collected directly in the field (in situ). The data were processed using Microsoft Excel and classified in tabulated form. The results were then compared with the quality standards of the Government Regulation of the Republic of Indonesia No. 22 of 2021 concerning the Implementation

of Environmental Protection and Management, Appendix VIII on Seawater Quality Standards.

#### Soil quality analysis

Soil quality analysis was conducted on four main parameters: soil texture, soil pH, organic carbon (C-organic), and total nitrogen. Soil texture was determined using the hydrometer method to identify the percentage of sand, silt, and clay fractions, which were then classified based on the USDA soil texture triangle. Soil pH was analyzed using a pH meter under two conditions, pH H<sub>2</sub>O and pH KCl, to determine active and potential acidity levels. Organic carbon content was measured using the wet oxidation method with K<sub>2</sub>Cr<sub>2</sub>O<sub>7</sub> solution and subsequently analyzed with a spectrophotometer at a wavelength of 561 nm. Meanwhile, total nitrogen analysis was carried out using the indophenol blue spectrophotometric method at a wavelength of 636 nm (Balai Penelitian Tanah 2005).

#### Land suitability of silvofishery

Land suitability assessment was conducted individually for each mangrove-based pond compartment. Vegetation, soil, and water quality parameters measured in each compartment were scored separately and then combined using a weighted method to determine the final suitability class (S1, S2, or N). The non-mangrove pond was used as an environmental comparison and was not included in the suitability scoring calculation.

The primary data, secondary data, and laboratory analysis results obtained were compiled and then used in the analysis stage. The collected data were analyzed using weighting and scoring methods. Furthermore, the results of the field analysis were assigned scores according to land suitability classes (scores: 1-4), which were then multiplied by their respective weights and summed. The total score was divided by four and multiplied by 100% (Karim et al.

2012). The final value obtained from this calculation was matched with the corresponding class categories to determine the level of land suitability. Based on this analysis, the potential and land suitability of mangrove-based silvofishery in North Sumatra, Indonesia.

To clarify the criteria for the assessment of mangrove-based silvofishery land suitability, the details are presented in Table 1. Based on the score values of each parameter, an assessment was conducted to determine whether the land is suitable for mangrove-based silvofishery land suitability using the following formula (Karim et al. 2012):

$$\text{Feasibility value} = \frac{\sum \text{value}}{\text{high score}} \times 100\% \quad [3]$$

So that the determination of categories is obtained based on the percentage of the suitability interval, as seen in Table 2.

**Table 2.** Intervals of suitability values based on suitability categories

Category	Suitability interval (%)
Highly suitable (S1)	75-100
Suitable (S2)	50-75
Suitable conditions (S3)	25-50
Not suitable (N)	0-25

Note: Score 4: Highly suitable class, the land does not have a significant limiting factor for sustainable use; Score 3: Moderately suitable class, the land has limiting factors that are somewhat significant for sustainable use and may reduce productivity; Score 2: Marginally suitable class, the land has severe limiting factors for sustainable use, and reduces productivity; Score 1: Not suitable class, the land has very severe and permanent limiting factors that may prevent its utilization

**Table 1.** Matrix of land suitability levels for mangrove-based silvofishery

Parameters	S1 (Score 4)	S2 (Score 3)	S3 (Score 2)	N (Score 1)	Weight	score	value
Soil quality							
Soil texture	Sandy clay. Sandy clay loam. Clay loam. Silty clay. Silty clay loam	Loamy sand. Sandy loam. Loam. Silty loam	Clay. silt	Sand	0.13		
pH	7.5-8.5	6.5-7.4	5.5-6.4	<5.5 or >8.5	0.12		
C-Organic (%)	<6.0	6.0-12.0	12.1-15.0	>15.0	0.08		
Total nitrogen (%)	>0.5	0.38-0.5	0.25-0.37	<0.25	0.07		
Water quality							
Salinity (ppt)	15.0-30.0	30.1-35.0; 10-15	35.1-50.0; 5.0-10.0	>50.0-<5	0.08		
pH	7.5-8.5	8.6-9.5; 6.5-7.5	9.6-11.0; 5.5-6.5	>11.0; <5.0	0.12		
Temperature (°C)	26.0-32.0	20.1-25.0	15.0-20.0	>32.0; <15.0	0.14		
DO (mg/L)	>4.0	3.1-4.0	2.1-3.0	<2.0	0.18		
Mangrove density (ind/m <sup>2</sup> )	>15-20	>10-15; >20	5-10	<5	0.250		

Source: Karim et al. (2012) and Yulianda (2019)

## RESULTS AND DISCUSSION

### Mangrove vegetation density

Five mangrove species from three families were identified in the study area: *Rhizophora apiculata*, *Rhizophora stylosa*, *Sonneratia alba*, *Sonneratia caseolaris*, and *Xylocarpus granatum*. Vegetation density was assessed at three growth levels: tree, sapling, and seedling (Table 3).

At the tree level, total density reached 257.1 ind/ha, comprising four species, with *S. alba* exhibiting the highest density (114.3 ind/ha). At the sapling level, total density was markedly higher at 3,219.1 ind/ha and was dominated by *R. apiculata* (2,571.4 ind/ha). Seedling observations recorded only *R. apiculata*, with a density of 833.3 ind/ha. Overall, the vegetation structure indicates the dominance of *Rhizophora* and *Sonneratia* species across different growth stages.

Mangrove density is widely used as an indicator of stand structure, regeneration capacity, and ecosystem condition. Five mangrove species belonging to three families were recorded in the study area (*R. apiculata*, *R. stylosa*, *S. alba*, *S. caseolaris*, and *X. granatum*), a level of species richness commonly reported for Indonesian mangrove ecosystems and considered representative of relatively intact mangrove stands (Kusmana 2017; Duke et al. 2019).

The observed sapling density (>3,000 ind/ha) falls within the dense regeneration category, which is generally interpreted as a healthy regeneration condition in mangrove forests (Kusmana et al. 2003; Bengen 2004). High sapling abundance indicates effective recruitment and survival at early growth stages, which is essential for sustaining stand structure over time. The dominance of *S. alba* at the tree level signifies its adaptation to intertidal zones frequently inundated by seawater and sandy substrate conditions (Setyadi et al. 2021), whereas the high density of *R. apiculata* at the sapling level reflects its broad tolerance to salinity fluctuations and anoxic sediments typical of pond mangrove environments (Alongi 2020).

The presence of *R. apiculata* as the sole species at the seedling level may be attributed to several factors. First, *Rhizophora* species produce large, viviparous propagules that have higher establishment success on soft muddy substrates compared with smaller, non-viviparous propagules (Bengen 2004). Second, site conditions within the study area, characterized by fine sediments and frequent tidal inundation, favor *Rhizophora* establishment over other genera. Third, seasonal variation may have influenced seedling composition, as propagule availability and recruitment success vary temporally. Finally, the use of purposive sampling may have limited the detection of less abundant seedlings of other species. These factors should be considered when interpreting seedling composition.

Overall, the vegetation structure from seedling to tree level indicates a stable and regenerating mangrove ecosystem. Dense mangrove stands also influence the availability of habitat for fisheries resources, including mud crabs, whose abundance is positively correlated with mangrove density and substrate quality (Putri et al. 2022).

These findings reinforce the suitability of the area for integrated silvofishery, particularly the empang-parit model, which integrates mangrove conservation and aquatic ecosystem management while increasing the economic benefits for fishers (Hilmi et al. 2021).

### Water physico-chemical properties

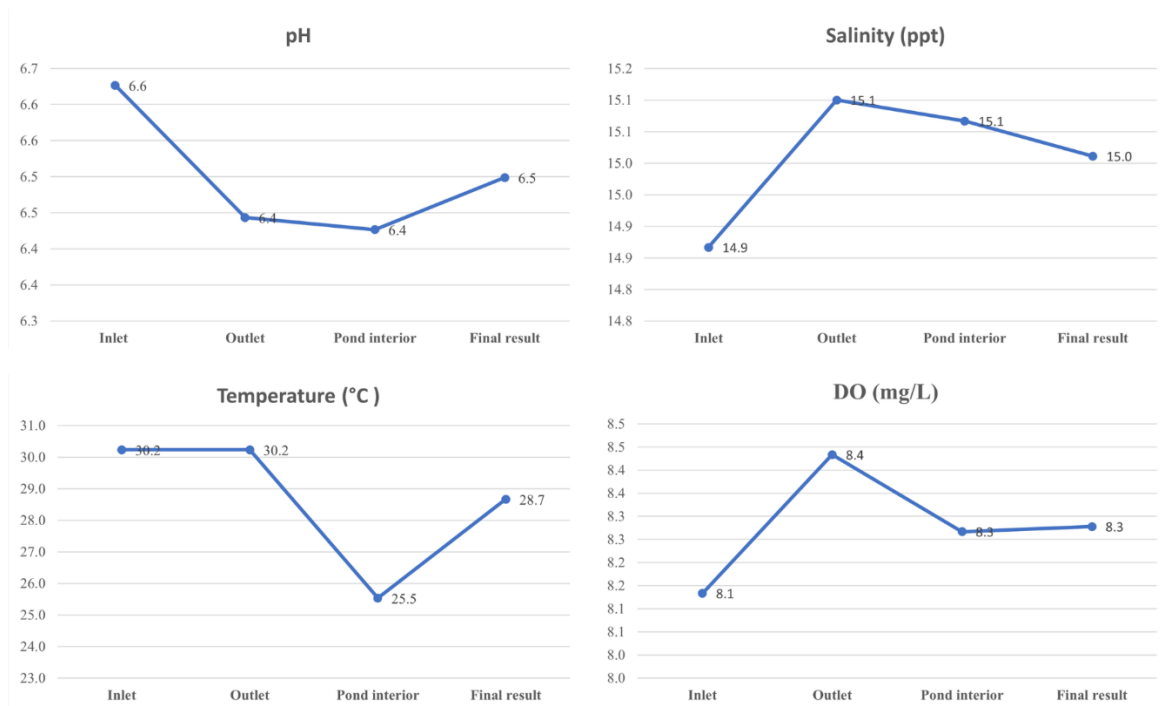
Water quality is a major limiting factor in silvofishery cultivation, as fluctuations in its parameters directly affect biota metabolism and ecosystem productivity. The suitability of mangrove ponds can be evaluated based on water quality aspects. An area suitable for aquaculture activities is characterized by salinity values ranging from 15.0-30.0 ppt, temperatures of 26.0-32.0°C, pH values of 7.5-8.5, and Dissolved Oxygen (DO) levels of >4.0ppm. Based on field observations, the physical and chemical characteristics of the water at the research site are presented in Figure 2.

The water pH values at all sampling points showed an average of 6.50. Salinity averaged 15.0 ppt, water temperature averaged 28.7°C, and Dissolved Oxygen (DO) concentration averaged an average of 8.3 mg/L. Overall, all observation points exhibited water quality values that were within or close to the quality standard thresholds for brackish-water aquaculture, with pH being the only parameter slightly below the optimal range.

The recorded water pH value of 6.5 is slightly lower than the optimal range for aquaculture activities (7.0-8.5) as stipulated in Government Regulation No. 22 of 2021. This mildly acidic condition is presumed to result from the decomposition of mangrove litter, respiration of organic matter, and tidal flushing patterns (Boyd and Tucker 2014). Nevertheless, this pH level remains within the tolerance limits for many brackish-water species (Siahainenia et al. 2026). Management measures such as liming are therefore recommended to neutralize soil acidity and stabilize water chemistry, a common practice in brackish-water pond management (Boyd 1995).

**Table 3.** Number and density of mangrove species at the tree, sapling, and seedling level

Level	Species	No. individuals	Species density (ind/ha)
Tree	<i>Rhizophora apiculata</i> Blume	16	76.2
	<i>Sonneratia alba</i> Sm.	24	114.3
	<i>Sonneratia caseolaris</i> (L.) Engl.	6	28.6
	<i>Xylocarpus granatum</i> J.Koenig	8	38.1
	Total	54	257.1
Sapling	<i>Rhizophora apiculata</i> Blume	135	2,571.4
	<i>Rhizophora stylosa</i> Griffith	7	133.3
	<i>Sonneratia alba</i> Sm.	26	495.2
	<i>Sonneratia caseolaris</i> (L.) Engl.	1	19.1
	Total	169	3,219.1
Seedling	<i>Rhizophora apiculata</i> Blume	7	833.3
	Total	7	833.3



**Figure 2.** Water quality at the silvofishery pond

The average salinity of 15.0 ppt indicates brackish-water conditions that are suitable for the development of mangrove-based silvofishery. Salinity variation is influenced by tidal exchange, freshwater inputs, and hydrological circulation patterns (Noor et al. 1999). This salinity range falls within the tolerance limits of mangrove species and major cultured organisms such as *Rhizophora*, *Sonneratia*, shrimp, milkfish, and mud crabs (Dewi 2020). Such conditions support the hydrological characteristics required for the sustainability of silvofishery systems.

The average water temperature of 28.7°C falls within the optimal range for aquaculture activities (28.0-32.0°C) according to Government Regulation No. 22 of 2021. Slightly lower temperatures in the inner pond areas may be influenced by shading effects, reduced water exchange, or deeper pond morphology. Temperature strongly affects oxygen dynamics and biochemical processes; therefore, maintaining optimal thermal conditions is essential to sustain productivity (Matatula et al. 2019).

The average dissolved oxygen concentration of 8.3 mg/L exceeds the minimum threshold (>5 mg/L) required for aquaculture activities, indicating that the water quality is still relatively good (Musa et al. 2025). High DO values indicate good water circulation, adequate photosynthetic activity, and low levels of organic pollution (Boyd and Tucker 2014). Favorable DO conditions support growth, feeding activity, metabolism, and survival of cultured organisms such as shrimp, fish, and crabs (National Technical Advisory Committee (NTAC) 1968; Pescod 1973). Overall, the measured water quality parameters reflect environmental conditions that support silvofishery

development, with pH being the only parameter requiring corrective management actions.

### Soil physical and chemical properties

Soil samples collected from the three sampling points showed an average pH value of 5.4, which is classified as acidic (Figure 3). The organic carbon content had an average value of 6.6%, while total nitrogen (N-total) averaged 0.2%, falling into the low to moderate category. Soil texture analysis indicated that all sampling points had a sandy loam texture.

Soil pH averaged 5.4, classified as acidic based on Soil Research Institute criteria (Balai Penelitian Tanah 2005). Acidic mangrove soils are common due to sulfate reduction, organic matter decomposition, and accumulation of litter (Boyd 1990). Acidic soils can lower water pH, reduce nutrient availability, and increase the toxicity of metals such as Al and Fe (Hakim et al. 1986). The values observed are comparable to those reported in other Indonesian mangrove ecosystems (Yanti et al. 2021).

C-organic average value (6.6%) falls into the “very high” category (>5%). High organic carbon is typical of mangrove soils due to high litter input, anaerobic decomposition, and accumulation of detritus (Juliyanto et al. 2023). High organic C supports soil fertility, and enhances functions as an energy source for soil microorganisms to grow and develop (Sombo et al. 2024). Although high organic carbon generally benefits pond ecosystems, excessive organic matter may increase oxygen demand during decomposition and warrants monitoring (Boyd et al. 2002).

N-total averaged 0.2%, categorized as low to moderate. Nitrogen levels in mangrove sediments depend on sedimentation rates, organic input, microbial activity, and stand age (Wijayanti 2022). Moderate nitrogen levels at the outlet point may be influenced by organic residues from aquaculture feed and biotic activity. Adequate nitrogen is essential for mangrove productivity and supports primary production within silvofishery ponds.

In addition to the soil quality parameters described above, soil texture also influences overall soil quality. The soil texture fractions showed a dominant sand content with an average value of 59.8%, followed by silt at 30.3% and clay at 9.9% (Table 4). Based on the USDA classification, all sampling points were classified as sandy loam.

All sampling points exhibited sandy loam textures, consistent with typical mangrove-associated substrates composed of sand, silt, and clay mixtures transported through tidal action (Soerianegara 1971). Sandy loam soil provides balanced drainage, aeration, and moderate water retention, making it suitable for aquaculture pond bottoms (Hillel 2013; Hendrajat et al. 2018). This substrate type supports mangrove species such as *Rhizophora* and *Sonneratia*, which thrive in muddy to sandy-mud substrates (Bengen 2004). Overall, soil properties indicate favorable environmental conditions for silvofishery, although acidic pH and variable nitrogen levels require periodic management.

### Land suitability assessment

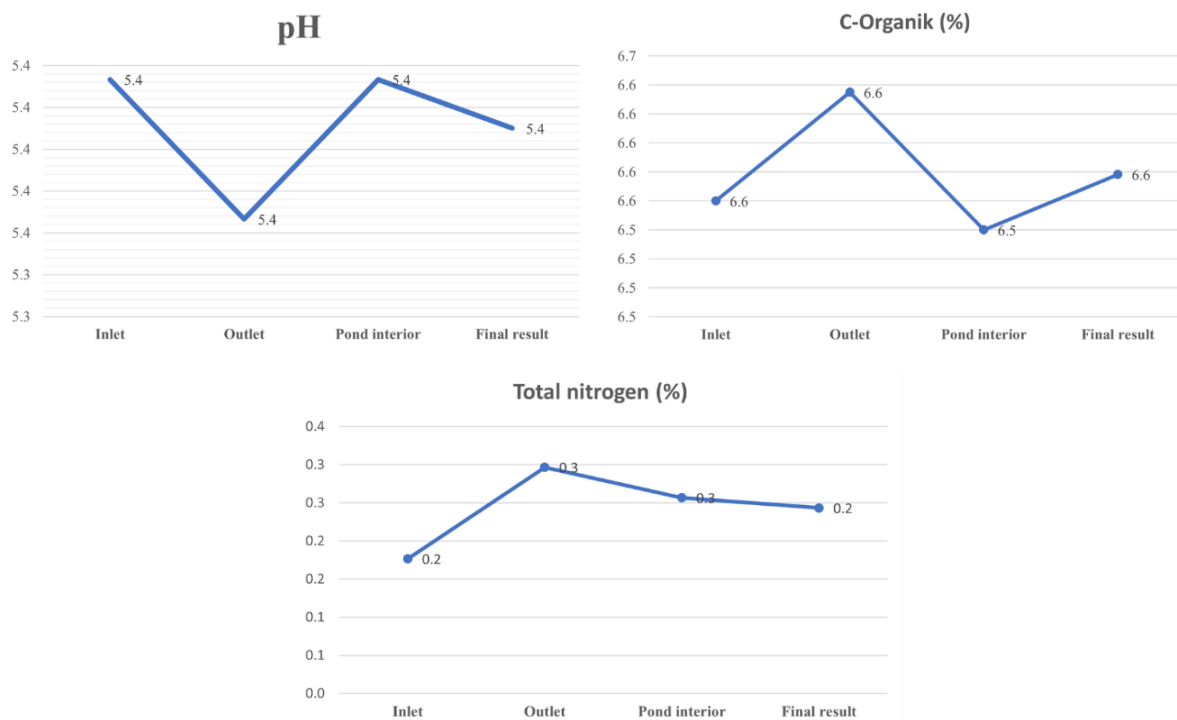
This study demonstrates that the mangrove ecosystem in Pasar Rawa Village is classified as Highly Suitable (S1), with a final land suitability value of 75.75%, as derived

from the integrated biophysical assessment presented in Table 5. The suitability classification reflects the combined influence of vegetation structure, soil characteristics, and water quality parameters, each contributing differently to the overall score.

Based on the results of the land suitability analysis presented in Table 5, the research site shows a feasibility level of 75.75%, which classifies it into the Highly Suitable (S1) category. This value reflects environmental conditions that are generally highly supportive of mangrove-based silvofishery land suitability, although several limiting factors still need to be considered. The dominance of water quality parameters that achieved the maximum score (score 4), such as salinity (15.0 ppt), temperature (28.7°C), and dissolved oxygen/DO (8.3 mg/L), indicates that the aquatic environment at the site falls within the optimal range for mangrove biota metabolism and osmoregulation. This finding is consistent with the statement of Kathiresan and Bingham (2001), who noted that the stability of water physicochemical parameters, particularly salinity, is a key factor determining mangrove zonation and survival in coastal areas.

**Table 4.** Soil texture analysis results

Texture	Units	Mean $\pm$ SD
Sand	%	59.8 $\pm$ 8.9
Silt	%	30.3 $\pm$ 6.4
Clay	%	9.9 $\pm$ 2.7
Texture class		Sandy loam



**Figure 3.** Soil quality at silvofishery pond

**Table 5.** Land suitability value of silvofishery at the research site

Component	Parameters	Field measurement results	Suitability Class	Score	Weight	Value
Vegetation	Mangrove density (ind/100 m <sup>2</sup> )	2.57	N	1	0.250	0.250
Soil	Texture	Sandy loam	S2	3	0.13	0.39
	pH	5.4	N	1	0.12	0.12
	C-Organik (%)	6.6	S2	3	0.08	0.24
	Total nitrogen (%)	0.2	N	1	0.07	0.07
Water	Salinity (ppt)	15.0	S1	4	0.08	0.32
	pH	6.5	S2	3	0.12	0.36
	Temperature (°C)	28.7	S1	4	0.14	0.56
	DO (mg/L)	8.3	S1	4	0.18	0.72
Total						3.03
Final Suitability Value						75.75%

However, several parameters were identified as limiting factors. Soil pH (5.4) and total nitrogen content (0.2%) received low scores, reflecting acidic and nutrient-poor soil conditions that may constrain productivity. Acidic soil conditions can also affect the availability of macronutrients and increase the solubility of heavy metals, which are toxic to root systems. Nevertheless, the sandy loam soil texture provides good mechanical support and aeration for root development, in accordance with Noor et al. (1999), who stated that substrates composed of mixed sand and clay are highly ideal for the colonization of species such as *S. alba*. Another significant limiting factor is the low density of existing mangroves (2.57 ind/100 m<sup>2</sup>), indicating that although the land is physically and chemically suitable, current mangrove stand density remains very sparse and requires rehabilitation efforts or enrichment planting.

Overall, the final value of 75.75% demonstrates that the land has substantial potential for development as a silvofishery area, provided that management interventions are implemented to improve soil pH conditions and accelerate vegetation restoration. In accordance with the standards of the Ministry of Environment (Kementerian Lingkungan Hidup 2004), areas with water quality characteristics similar to those at the research site possess high carrying capacity for primary productivity in coastal environments, thereby indicating a high likelihood of success for future rehabilitation activities (Basyuni et al. 2022).

Although mangrove silvofishery has been widely promoted as a sustainable alternative to conventional aquaculture, most existing studies emphasize ecosystem service valuation, carbon storage, or production performance without explicitly assessing land suitability constraints at the local management scale. Recent works, including ecosystem service quantification in silvofishery systems and carbon-fishery synergies, have demonstrated the multifunctional benefits of mangrove-integrated aquaculture (Sumarga et al. 2024); however, they provide limited guidance on where and under what biophysical conditions silvofishery can be optimally implemented (Friess et al. 2019; Sumarga et al. 2022).

This study offers a novel contribution by conducting a site-specific land suitability evaluation for silvofishery

development in a community-managed mangrove area, integrating mangrove vegetation structure, soil characteristics, and water quality parameters using a weighted scoring approach. Unlike previous studies that focus on ecosystem service outcomes or production trade-offs, this research emphasizes pre-implementation suitability assessment as a decision-support tool for sustainable mangrove forestry and aquaculture planning (Sumarga et al. 2022), yet its application in silvofishery planning remains limited.

By identifying key limiting factors, particularly soil acidity, and mapping suitability classes within the mangrove area of Pasar Rawa Village, this study provides practical, forestry-oriented evidence to support ecosystem-based coastal management. The findings bridge the gap between mangrove conservation science and applied silvofishery planning, thereby strengthening the role of land suitability analysis in sustainable mangrove utilization strategies in Indonesia and comparable tropical coastal regions (Friess et al. 2019).

### Practical implications

Hydrological connectivity should be prioritized in silvofishery management to maintain sediment dynamics, prevent acid sulfate soil oxidation, and enhance natural mangrove regeneration. Empirical evidence from hydrological restoration in North Kalimantan demonstrates that restoring tidal exchange significantly improves soil conditions and accelerates vegetation recovery in previously degraded pond landscapes (Basyuni et al. 2025). Therefore, maintaining functional inlet-outlet systems is essential for long-term silvofishery sustainability. Globally, ecological mangrove restoration frameworks emphasize hydrology as the primary driver of long-term system resilience (Friess et al. 2019).

Optimization of mangrove stand density is recommended to balance ecological integrity and aquaculture productivity. Research in integrated mangrove-fish pond systems in West Jawa, Indonesia, indicates that high mangrove cover does not reduce fish yields while significantly increasing aboveground carbon storage (Sumarga et al. 2022). This finding supports the adoption of density-based management strategies that maintain

structural complexity without compromising economic returns.

Soil acidity management should be incorporated into operational guidelines for silvofishery development. Acid sulfate soils are a common legacy issue in converted pond systems, and controlled tidal flushing combined with organic matter enrichment has been shown to gradually stabilize soil pH and improve biogeochemical functioning (Basyuni et al. 2025). Regular monitoring of soil pH and redox potential is therefore recommended as part of adaptive management.

The weighted land suitability scoring framework applied in this study can serve as a practical decision-support tool for coastal planners and local governments. Multi-criteria ecosystem service assessments demonstrate that silvofishery systems simultaneously generate carbon storage, fisheries income, biodiversity habitat, and climate mitigation benefits (Sumarga et al. 2024). Integrating such biophysical and ecosystem service indicators strengthens evidence-based planning and aligns with sustainable coastal development objectives. Promoting silvofishery as a restoration-compatible aquaculture model contributes to Indonesia's broader mangrove rehabilitation agenda. Integrated systems that maintain mangrove cover while sustaining aquaculture production provide a scalable pathway for balancing conservation and livelihood outcomes.

### Study limitations and away forward

This study presents a site-specific biophysical land suitability assessment; however, several limitations should be acknowledged. First, field data were collected during a single sampling period, which may not fully capture seasonal variability in salinity, dissolved oxygen, and sediment dynamics. Mangrove-aquaculture systems are strongly influenced by monsoonal cycles and tidal amplitude fluctuations, which can affect water quality and regeneration patterns (Friess et al. 2019). Multi-season monitoring would provide a more comprehensive understanding of temporal variability. Second, the suitability index relied on a weighted scoring framework, which inherently involves a degree of subjectivity in parameter weighting. Although the weighting scheme was based on ecosystem-function prioritization and previous silvofishery assessments (Sumarga et al. 2024), alternative weighting configurations could yield slightly different classifications. Future studies may incorporate sensitivity analysis or Analytic Hierarchy Process (AHP) approaches to improve transparency and robustness.

Third, the study focused primarily on biophysical parameters (vegetation, soil, and water quality) and did not integrate socio-economic variables such as household income, market accessibility, or governance structures. Evidence from integrated mangrove-aquaculture systems suggests that long-term sustainability is strongly influenced by institutional and community-based management factors (McSherry et al. 2023). Therefore, a comprehensive sustainability assessment should combine ecological and socio-economic dimensions. Fourth, soil analysis was limited to the 0-30 cm depth interval. In former pond

systems, deeper sediment layers may contain oxidizable sulfides that influence long-term acidity dynamics (Wang et al. 2025). Future research incorporating deeper sediment cores and redox profiling would improve the understanding of subsoil constraints.

Finally, this study did not quantify ecosystem service outcomes such as carbon stock, fisheries yield performance, or economic returns. Previous research demonstrates that silvofishery systems can enhance carbon storage while maintaining aquaculture productivity (Sumarga et al. 2022); however, such outcomes were not directly measured here. Incorporating carbon accounting and production data would strengthen the applied relevance of the suitability framework.

Despite these limitations, the integrated vegetation-soil-water assessment provides a robust baseline for evidence-based silvofishery planning and can serve as a foundation for longitudinal and multidisciplinary research. Future research should incorporate socio-economic indicators, stakeholder engagement analysis, and long-term ecological monitoring to strengthen sustainability evaluations. Expanding the framework to include carbon stock assessment and production performance metrics would further enhance its contribution to ecosystem-based coastal management and national mangrove rehabilitation strategies.

In conclusion, this study demonstrates that the mangrove ecosystem in Pasar Rawa Village is classified as Highly Suitable (S1) for mangrove-based silvofishery, with a land suitability value of 75.75%. This classification is primarily supported by favorable water quality conditions, including salinity (15.0 ppt), temperature (28.7°C), and dissolved oxygen (8.7 mg/L), as well as suitable soil texture (sandy loam) and evidence of active mangrove regeneration dominated by *Rhizophora* and *Sonneratia*. However, soil acidity (pH 5.4) and low mangrove stand density (2.57 ind/100 m<sup>2</sup>) were identified as key limiting factors that may constrain long-term system productivity and ecological stability. These findings indicate that while the site is highly suitable, targeted management interventions, particularly soil amelioration and vegetation enrichment, are required to optimize system performance. This study is limited by its single-season sampling design and the focus on surface soil properties, which may not fully capture temporal variability and subsoil constraints. Future research should incorporate multi-season monitoring, deeper soil profiling, and socio-economic variables to provide a more comprehensive assessment of silvofishery sustainability. Overall, the integrated evaluation of vegetation, soil, and water parameters provides a robust, site-specific decision-support framework for sustainable silvofishery development, contributing to the alignment of ecological conservation and aquaculture productivity in mangrove landscapes.

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