Aquacultura Indonesiana, 26(2), 2025
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On-line: https://aquacultura.id/index.php/ai/article/view/202

Silvofishery as an Ecosystem-Based Solution for Coastal Rehabilitation and Sustainable Aquaculture: Lessons learn from Brebes, Indonesia

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Submitted: September 8th, 2025; Revised: October 29th, 2025; Accepted: November 8th, 2025; Available Online: December 5th, 2025

DOI: 10.21534/ai.v26i2.202

Abstract

Mangrove degradation in Indonesia has primarily resulted from large-scale conversion to traditional aquaculture ponds with low productivity. To address this, the Integrated Mangrove Aquaculture (IMA) or silvofishery approach has been promoted as an ecosystem-based model that combines ecological restoration and sustainable fish production. This study evaluated the effectiveness of traditional silvofishery ponds in Brebes, Central Java, to assess both ecological recovery and aquaculture performance. Field observations and trials were conducted from February 2024 to February 2025 in 4 ha of silvofishery ponds with mangrove coverage of approximately 50–60%. Water quality parameters, including temperature, salinity, pH, dissolved oxygen (DO), and nutrients, were monitored in situ and in the laboratory. Results showed that DO levels occasionally fell below 2 mg L^{-1} under dense mangrove canopies, contributing to Enterocytozoon hepatopenaei (EHP) infection and mortality of Penaeus monodon. In contrast, Chanos chanos and Litopenaeus vannamei exhibited higher tolerance and achieved moderate productivity under minimal input conditions. Mangrove density was found to enhance the availability of natural food resources; however, excessive mangrove density can result in increased shading and a consequent reduction in photosynthetic oxygen production. The findings suggest that simple interventions such as periodic pond drying, sludge removal, and improved hydrological design can optimize pond function and ecological balance. Overall, silvofishery demonstrates strong potential as an adaptive model for restoring coastal ecosystems while maintaining sustainable aquaculture production in Indonesia.

Keywords: Silvofishery; Integrated Mangrove Aquaculture (IMA); Water Quality; Dissolved Oxygen; Enterocytozoon hepatopenaei (EHP); Coastal Ecosystem Restoration

1. Introduction

Indonesia hosts the largest mangrove ecosystem in the world, representing one of the most diverse mangrove habitats globally (Kusumahadi et al., 2020). Over the past few decades, however, the country has experienced a significant decline in mangrove cover. Ilman et al., (2016) identified land conversion into aquaculture ponds as the primary driver of mangrove loss in Indonesia. This situation raises serious environmental concerns, as mangrove plays vital ecological roles in coastal protection, shoreline stabilization, blue carbon storage, and the provision of critical nursery and feeding habitats for numerous aquatic species that sustain coastal food webs.

According to the Indonesia Shrimp Forum (FUI, 2022), approximately 322,000 hectares of active shrimp ponds were recorded in 2021. Of this area, about 93% are classified as traditional ponds with productivity levels below 300 kg/ha/culture cycle, while only around 7% are semi-intensive or intensive systems with yields ranging from 7–30 tons/ha/culture cycle. The low productivity of traditional aquaculture systems has become a serious concern for the government, as the economic benefits remain disproportionate to the extensive ecological degradation caused by mangrove conversion.

In response to these challenges, an ecosystem-based approach integrating coastal rehabilitation with sustainable aquaculture practices has been widely promoted. This approach, known as Integrated Mangrove Aquaculture (IMA) or silvofishery, aims to restore the ecological function of mangrove ecosystems while maintaining or improving pond productivity. Nevertheless, many mangrove rehabilitation programs in Indonesia have been implemented without concurrent improvements in aquaculture systems, resulting in limited success and weak economic sustainability for local farmers.

To address this issue, the present study was conducted to evaluate the effectiveness of silvofishery practices in traditional ponds as a means of restoring mangrove ecological functions while sustaining aquaculture production. The outcome of this research

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are expected to provide a scientific basis for developing adaptive and sustainable silvofishery models applicable at both local and regional scales.

2. Theory

Silvofishery has developed as an approach that integrates aquaculture with mangrove forest management. The development of silvofishery aims to restore the ecological function of mangrove forests and simultaneously improve fish production. Based on how the mangroves are planted or left in the pond, several types of silvofishery systems have been identified, as shown in Figure 1.

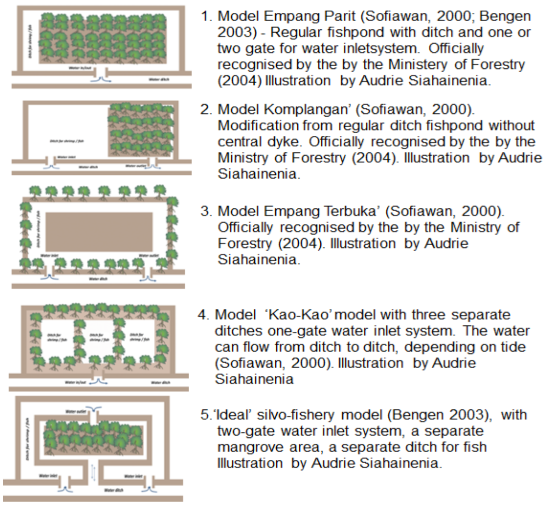

Figure 1. Typical traditional ponds/"silvofishery"

3. Method

3.1. Study Area and Period

This study was conducted in Sawojajar Village, Brebes Regency, Central Java, Indonesia, from February 2024 to February 2025. The study covered approximately 4 ha of traditional ponds.

3.2. Pond Design and Layout

The study ponds were using existing traditional silvofishery ponds with a total area of approximately 4 ha. The trial ponds in this study consisted of two ponds (pond A and B). Each pond was enclosed by dikes and connected to the main canal through a single sluice gate, which functioned as both inlet and outlet for tidal water exchange. The pond interior consisted of two principal zones: a central platform area (plataran) designated as the main culture area, and a peripheral canal (caren) that acted as a drainage channel, a shelter for fish under periods of intense sunlight, and a sediment deposition zone.

Mangrove trees, primarily Rhizophora mucronata, were planted (in 2014) and in designated areas within the platform area (50-60%). The overall pond layout allowed tidal water to enter and exit through the main sluice gate, ensuring water exchange and maintaining ecological connectivity between the pond and surrounding public mangrove waterways (Figure 2).

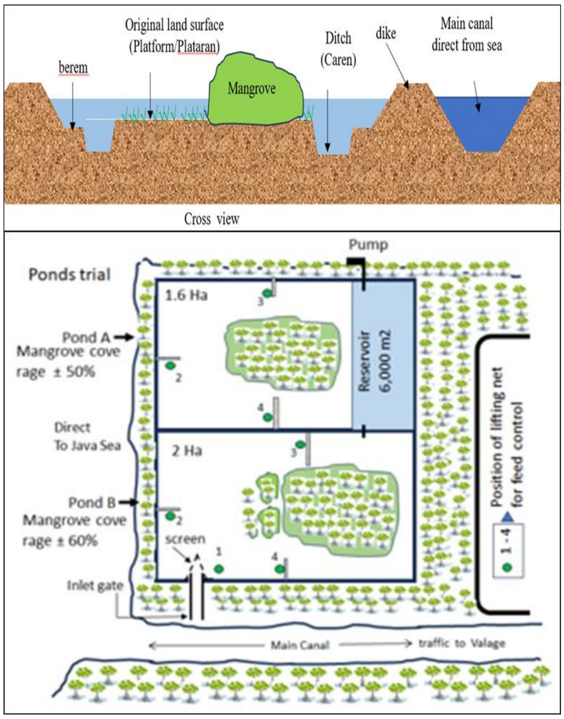

Figure 2. Silvofishery pond layout in Sawojajar, Brebes (Central Java, Indonesia).

3.3. Ponds preparation

Since its construction in 2020, the study pond had not undergone any major maintenance or complete drying prior to this research. The pond bottom accumulated a thick layer of organic-rich sediment, particularly in the caren area, where sludge depth reached 40-50 cm. Before the culture trials, minor rehabilitation was carried out to seal several leakages along the earthen dikes and to re-level the pond bottom to create a gentle slope toward the outlet gate (Figure 3).

Figure 3. Pond preparation, embankment repair, water preparation and pond water disinfection.

Quicklime (CaO) and hydrated lime [Ca(OH)2] were applied evenly across both the central platform (plataran) and canal areas at rates of 2 and 4 tons per pond, respectively, to neutralize acidity and oxidize organic matter. After one week of reaction, the pond was filled with water to a depth of about 10 cm (in platform areas). To eliminate unwanted organisms such as wild fish, eels, and snakes, saponin was applied at a dosage of 75kg per pond, followed by chlorination (10 ppm) after two days. The pond was then filled to 40-50 cm depth and treated with fermented organic fertilizer to stimulate the growth of natural feed organisms such as plankton, periphyton, and benthic organisms.

3.4. Cultivation method

a. Fish stocking

The study was conducted over two culture cycles. The first cycle was from 28 April to 5 August 2024 using milkfish (Chanos chanos) cultured in polyculture with tiger shrimp (Penaeus monodon). The initial stocking densities were 0.1 milk fish fingerling/m2 and 4-5 juvenile shrimps/m2 respectively. Milkfish fingerlings with an average weight of 83 gram each and juvenile shrimp (average 1 gram each after 2 weeks of nursery rearing) were sourced from local farmers. The second cycle (17 August 2024 – 7 February 2025) used milkfish polyculture with white shrimp (Litopenaeus vannamei). The milkfish were smaller (less than 2 gram each), while L. vannamei juvenile averaged 1 gram each after nursery rearing. All post larvae and fingerlings were purchased from local hatcheries and stocked into the same silvofishery pond system.

b. Feed and water management

Throughout both culture cycles, no artificial feed was provided to either fish or shrimp during the first month. From the second month onward, artificial feed was supplied at a low rate of only 5–10% of the feeding amount typically applied in intensive culture systems. The cultured species mainly relied on natural food sources such as plankton, benthic microalgae, and periphyton that developed naturally within the pond ecosystem.

Water was maintained at a depth of approximately 40-50 cm (on plataran area) during the culture period. No complete water exchange was carried out during the first two months; only water replenishment was conducted to compensate for evaporation and seepage losses. From the third month onward, partial water exchange of about 10-15% every 3-4 days (equivalent to 3-5% per day) was performed through the sluice gate during high tide or, when needed, by pumping water from reservoir ponds.

This low-input management approach aimed to maintain water stability and minimize environmental stress, allowing the silvofishery system to function as a semi-natural, self-sustaining pond ecosystem.

3.5. Data Collection

Data was collected to assess both the ecological condition and aquaculture performance of silvofishery ponds:

a. Water Quality

To evaluate water quality as a key factor supporting aquaculture performance, Temperature, salinity, pH and dissolved oxygen (DO) were measured from three representative points within pond area to capture spatial variability of water condition. Those parameters were recorded daily using a portable multiparameter water quality meter that provides simultaneous reading for all parameters. Nutrient parameters (NO3-, NO2-, PO43-, and TAN) were analyzed twice a week to determine nutrient dynamics within the system. The list of water quality parameters and their measurement frequency is summarized in Table 1.

Water quality results were compared with the Indonesian National Standard for aquaculture (SNI 6989.57:2008) and FAO aquaculture water quality guidelines to evaluate suitability for fish and shrimp culture.

Table 1. Water quality parameters

Parameters	Unit	Method	Measurement Frequency
pH	-	Portable multiparameter water quality meter	Every day at all sampling points
Temperature	℃		
DO	ppm		
Salinity	ppt		
TAN	ppm	Colorimetric	Twice a week at one sampling point (mangrove area)
Nitrate (NO_3^-)	ppm		
Nitrite (NO_2^-)	ppm		
Orthophosphate (PO_4^{3-})	ppm		

The abundance of microorganisms serving as natural feed such as plankton and periphyton was analyzed monthly at the Bio-Micro Laboratory, Faculty of Fisheries and Marine Sciences, IPB University, Bogor. This analysis was conducted only during the second research cycle.

b. Aquaculture performance

Fish and shrimp productivity were assessed through direct measurement taken during two culture cycles. For milkfish (Chanos chanos), data collection began with recording the number of individuals stocked and their average weight at the start of the culture period. The measurement was also conducted at harvest to determine average weight and the number of fish harvested. The observed variables included stocking density (individuals per hectare), survival rate (SR) which is calculated as the ratio between the number of fish harvested and the number stocked, and productivity, which is calculated as total harvested weight per hectare per culture cycle.

For tiger shrimp (Penaeus monodon), and white shrimp (Litopenaeus vannamei), data collection began with counting the total number of post larvae stocked in each pond. During culture, shrimp were sampled biweekly to determine average body weight using pooled samples of 50 individuals. At harvest, total biomass and mean individual weight were recorded to calculate survival rate (SR) and productivity (kg/ha/cycle). Mortality events and visible signs of disease were also noted throughout the culture period to evaluate pond health conditions.

4. Results and Discussion

4.1. Results

4.1.1 Water quality dynamics during culture

The pond's long-term lack of physical maintenance, particularly the absence of regular drying and sediment removal, resulted in the accumulation of thick organic sludge exceeding 50 cm in the cairn area (Figure 3). In this study, the sludge was intentionally left undisturbed, and no thinning of the densely planted mangroves in platform area (plataran) was carried out. This setup was designed to observe how sediment thickness and mangrove density influence water quality characteristics and potential constraints on aquaculture performance.

Throughout the culture period, dissolved oxygen (DO) levels fluctuated considerably, with several readings showing critically low concentrations, especially areas coles to mangrove root zones, and within the caren, . In those areas DO occasionally drops to around 1.5 ppm. These low-oxygen conditions were likely caused by reduced photosynthetic activity of phytoplankton due to limited sunlight penetration, restricted water circulation, high rates of organic matter decomposition, and the oxygen demand from mangrove root respiration and benthic microbial activity. (Tables 2 and Table 3).

Table 2. Water quality performance in the trial pond A

Parameters		Cycle 1			Cycle 2			Standard *
		Mangrove area	Platform area	Ditch area	Mangrove area	Platform area	Ditch area	
DO (ppm)	Surface	0,11-5,52 (1,71)	1,49-6,42 (3,95)	1,52-5,70 (3,63)	1,07-6,45 (3,47)	1,81-7,02 (4,16)	1,62-7,18 (3,82)	> 3,0
	Bottom	0,10-4,32 (1,22)	1,15-5,60 (3,69)	0,07-4,52 (2,53)	0,93-6,31 (3,31)	1,74-7,22 (4,11)	0,79-7,13 (3,19)	
pH	Surface	7,4-8,0 (7,6)	7,4-8,0 (7,7)	7,4-8,0 (7,7)	7,3-8,3 (7,9)	7,5-8,3 (7,9)	7,5-8,3 (7,9)	7,5-8,5
Temperature (°C)	Surface	28,6-31,3 (29,6)	28,4-31,4 (29,8)	28,5-31,4 (29,8)	25,4-36,3 (29,4)	25,4-36,7 (29,6)	25,5-36,0 (29,5)	28-32
	Bottom	28,2-31,3 (29,5)	28,7-31,4 (29,8)	28,5-31,7 (29,9)	25,5-36,2 (29,4)	25,5-36,2 (29,6)	20,9-35,6 (29,3)	
Salinity (ppt)		19,9-31,5 (27,3)	18,5-31,5 (27,3)	18,1-31,5 (27,2)	12,7-41,9 (32,9)	12,2-41,7 (33,1)	13,1-41,7 (33,0)	5-40
TAN (ppm)		0,5-1,5 (1,0)	-	-	1,0-2,0 (1,4)	-	-	< 2
NO_2 (ppm)		0,0-0,0 (0,0)	-	-	0,0-0,0 (0,0)	-	-	0,01
NO_3 (ppm)		0,0-0,0 (0,0)	-	-	0,0-0,0 (0,0)	-	-	0,5
PO_4 (ppm)		1,0-4,0 (1,9)	-	-	0,0-5,0 (1,1)	-	-	≥ 0,1

Table 3. Water quality performance in the trial pond B

Parameters		Cycle 1			Cycle 2			Standard *
		Mangrove area	Platform area	Ditch area	Mangrove area	Platform area	Ditch area	
DO (ppm)	Surface	1,66-4,56 (2,94)	2,19-6,92 (4,31)	2,39-5,95 (4,05)	1,55-5,88 (3,32)	2,40-7,96 (4,45)	1,97-7,45 (4,28)	> 3,0
	Bottom	1,53-4,57 (2,87)	2,02-6,28 (4,16)	0,41-5,43 (3,61)	1,50-5,59 (3,27)	2,26-7,99 (4,45)	1,88-7,59 (4,04)	
pH	Surface	7,8-8,3 (8,1)	7,9-8,4 (8,1)	7,9-8,4 (8,1)	7,9-8,4 (8,2)	7,9-8,5 (8,2)	7,9-8,4 (8,2)	7,5-8,5
Temperature (°C)	Surface	26,3-32,1 (28,7)	26,9-31,9 (29,1)	26,7-32,0 (28,9)	25,3-31,5 (29,1)	25,3-33,1 (29,9)	25,5-32,3 (29,5)	28-32
	Bottom	26,3-32,3 (28,7)	26,7-32,0 (29,1)	26,6-31,8 (28,9)	25,4-31,5 (29,1)	25,3-32,3 (29,6)	25,4-31,9 (29,2)	
Salinity (ppt)		23,1-34,2 (29,0)	22,0-34,2 (28,9)	22,3-34,2 (29,0)	17,8-44,0 (33,0)	18,0-44,1 (32,8)	18,2-43,8 (32,9)	5-40
TAN (ppm)		0,5-1,5 (1,1)	-	-	1,0-1,5 (1,4)	-	-	< 2
NO_2 (ppm)		0,0-0,2 (0,0)	-	-	0,0-0,0 (0,0)	-	-	0,01
NO_3 (ppm)		0,0-0,0 (0,0)	-	-	0,0-0,0 (0,0)	-	-	0,5
PO_4 (ppm)		0,0-5,0 (1,4)	-	-	0,0-4,0 (1,3)	-	-	≥ 0,1

*Standard set by Dept. of Marine Affair and Fisheries Decree No. 75/PERMEN-KP/2016

Natural feed such as phytoplankton and zooplankton grow and develop very well, as presented in Table 4. In addition, there are probiotic bacteria found in mangrove roots which can be seen in Table 5 below.

Table 4. The abundance of plankton

Class	Genus	Total abundance (cells/m^3)
Bacillariophyceae	12	2.622.600
Cyanophyceae	1	8.035.200
Dinophyceae	4	706.800
Protozoa	4	601.400
Crustacea	1	15.500
Nematoda	1	3.100

Table 5. Probiotic bacteria found in mangrove roots

Phylum	Family	Genus
Firmicutes	Bacillaceae	Bacillus
	Enterococcaceae	Enterococcus
	Lactobacillaceae	Lactobacillus
	Streptococcaceae	Streptococcus

These findings demonstrate that while the integration of mangroves enhanced nutrient recycling and natural feed production, excessive sediment accumulation and dense vegetation coverage constrained oxygen dynamics, creating a trade-off between ecological restoration and aquaculture productivity.

4.1.2. Aquaculture performance and productivity

Cycle 1: Milkfish and Tiger Shrimp Polyculture.

The first culture cycle (April–August 2024) involved milkfish (Chanos chanos) and tiger shrimp (Penaeus monodon) cultured together under a low-input silvofishery system. The overall pond productivity ranged from 248 to 1,104 kg/ha/cycle (Table 4), depending on the relative abundance of fish and shrimp.

Table 4. Silvofishery pond production with polyculture system (fish and shrimp)

Items	Cycle 1				Cycle 2			
	Pond A		Pond B		Pond A		Pond B	
	Milkfish	Tiger shrimp	Milkfish	Tiger shrimp	Milkfish	White shrimp	Milkfish	White shrimp
Pond area (m^2)	20.000		14.000		20.000		14.000	
Stocking								
Date	28 Apr 24	29 Apr 24	28 Apr 24	28 Apr 24	7 Sep 24	17 Aug 24	7 Sep 24	19 Oct 24
Total stocking (ind/pond)	2.145	112.828	1.260	62.625	1.090	95.890	2.725	106.778
Stocking density (ind/m^2)	0,11	5,6	0,1	4,5	0,1	5	0,2	7,6
Average weight (g/ind)	83	0,5	83	0,5	2	0,5	2	0,5
Harvest								
Date	5 Aug 24	7 June 24	15 Aug 24	7 June 24	7 Feb 25	29 Oct 25	7 Feb 25	7 Feb 25
Cultivation period (days)	100	mass mortality and considered exhausted at 50 days due to EHP	110	mass mortality and considered exhausted at 50 days due to EHP	153	mass mortality and considered exhausted at 73 days due to EHP	153	111
Production (kg)	634		496		275		717	829
Amount (fishtail)	1.394		1.033		916		2.044	42.711
MBW (g/ind)	455		480		300		351	19,4
Survival Rate (%)	65		82		84		75	40
Total production (kg/pond)	634	-	496	-	275	-	1.546	
Productivity (kg/ha/cycle)	317	-	248	-	196	-	1.104	
Productivity (kg/ha/year)	772	-	603	-	393	-	2.687	
Feed (kg)	50	10	50	10	25	10	266	266
Total feed (kg)	60		60		35		532	
Total FCR	0,08		0,12		0,13		0,34	

During the culture period, persistent low dissolved oxygen (DO) levels occasionally below 2 ppm were recorded, particularly in the caren and mangrove-dense areas (Table 2 and Table 3). These hypoxic conditions coincided with significant shrimp mortality beginning in the third week of culture. Laboratory analysis conducted at PT. Central Proteina Prima confirmed the presence of Enterocytozoon hepatopenaei (EHP) infection in affected shrimp. Mortality continued until no shrimp remained by day 50. Penaeus Monodon is a benthic species with limited mobility, making it difficult to escape from poor water quality conditions, particularly low oxygen levels. The optimal dissolved oxygen concentration for shrimp growth is greater than 4.0 ppm, while concentrations below 2.0 ppm are considered lethal (Widigdo 2013).

In contrast, milkfish showed no visible signs of stress and grew normally throughout the 100-day cycle. The survival rate (SR) reached 65% in Pond A and 82% in Pond B, with final average body weights of 455 g (Pond A) and 480 g (Pond B), from an initial mean of 83 g/ind. Consequently, total milkfish production reached 317 kg/ha/cycle (Pond A) and 248 kg/ha/cycle (Pond B), equivalent to 603–772 kg/ha/year when annualized. These results indicate that milkfish was considerably more tolerant of fluctuating environmental conditions than tiger shrimp under the existing pond design and water quality setting.

Cycle 2: Milkfish and White Shrimp Polyculture.

In this cycle, white shrimp (Litopenaeus vannamei) replaced P. monodon as the secondary species. Shrimp in Pond A again suffered heavy mortality from EHP and were completely lost by day 73. In contrast, L. vannamei in Pond B remained healthy, reaching an average body weight of 19.4 g at day 111, with an estimated SR of 40% and total production of 829 kg/ha/cycle.

Milkfish continued to perform consistently in both ponds, with final average body weights of 300 g (Pond A) and 315 g (Pond B) after 153 days, from an initial mean of about 1 g/ind. The estimated milkfish yields were 275 kg (Pond A) and 644 kg (Pond B), resulting in total production (fish + shrimp) of 1,472 kg/ha/cycle in Pond B and 275 kg/ha/cycle in Pond A.

4.2. Discussion

This field experiment in Brebes was conducted to closely simulate the aquaculture practices commonly applied by local farmers, aiming to identify key ecological and technical constraints within silvofishery ponds. The results confirmed that while most physicochemical parameters such as pH, salinity, and temperature remained within optimal ranges, dissolved oxygen (DO) concentrations frequently dropped below 2 ppm beneath dense mangrove canopies. Such hypoxic conditions are known to be critical thresholds for shrimp survival and were closely associated with mortality of Penaeus monodon, worsened by Enterocytozoon hepatopenaei (EHP) infections. In contrast, Chanos chanos and Litopenaeus vannamei exhibited better adaptation due to higher mobility and broader tolerance to environmental fluctuations.

Enterocytozoon hepatopenaei (EHP) is a disease caused by the microsporidia parasite that currently poses a very challenging threat (Amelia et al., 2020). EHP can damage the digestive and immune systems of shrimp, making them susceptible to other diseases and adverse environmental conditions that can ultimately lead to death. Factors of water quality such as temperature, salinity, and oxygen levels significantly affect shrimp health and the dynamics of EHP infection (Utami et al., 2025). This is in line with the results found in the field, that DO values of less than 2 ppm combined with positive EHP results can cause mass mortality of shrimp in DOC 50 and 73 days.

The presence of a thick layer of organic-rich sediments (> 50 cm) that had accumulated over several years was identified as another key constraint. Limited pond drying and continuous organic deposition from mangrove litter fostered anaerobic conditions that supported microbial proliferation, including EHP spores. Similar patterns have been reported by Widigdo et al., (2024) indicating that disease persistence in silvofishery ponds is closely linked to poor pond bottom oxidation. Although the accumulated organic substrate enhanced the growth of beneficial microbial communities such as Bacillus and Lactobacillus, the imbalance between aerobic and anaerobic processes created ecological instability that ultimately compromised shrimp health.

The findings above gave rise to the idea of organizing or regulating mangrove planting in mangrove rehabilitation activities in traditional with low productivity and in greenbelt areas. The mangrove arrangement aims to increase aquaculture production by improving water quality in areas with mangrove plants. Two general configurations of silvofishery systems can be distinguished under Indonesian coastal conditions: (1) "open-system silvofishery" or greenbelt "silvofishery" (Figure 4), which reconnects degraded aquaculture areas to natural tidal regimes, allowing free water exchange and supporting both fisheries and mangrove regeneration; and (2) traditional pond or "closed silvofishery", where mangrove trees are planted within pond embankments and platform areas (plataran) (Figure 5). The Brebes study site represents the latter configuration, characterized by limited hydrological exchange and high organic accumulation. Lessons from this study indicate that while traditional silvofishery effectively restores mangrove cover, its ecological function remains suboptimal unless hydrological design is improved to mimic the natural flushing processes found in open systems.

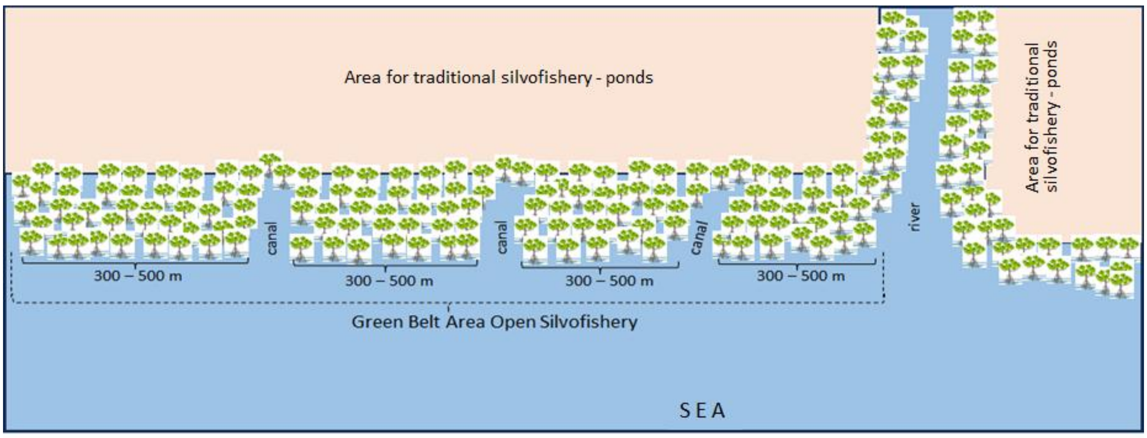

Figure 4. Open-system or greenbelt silvofishery

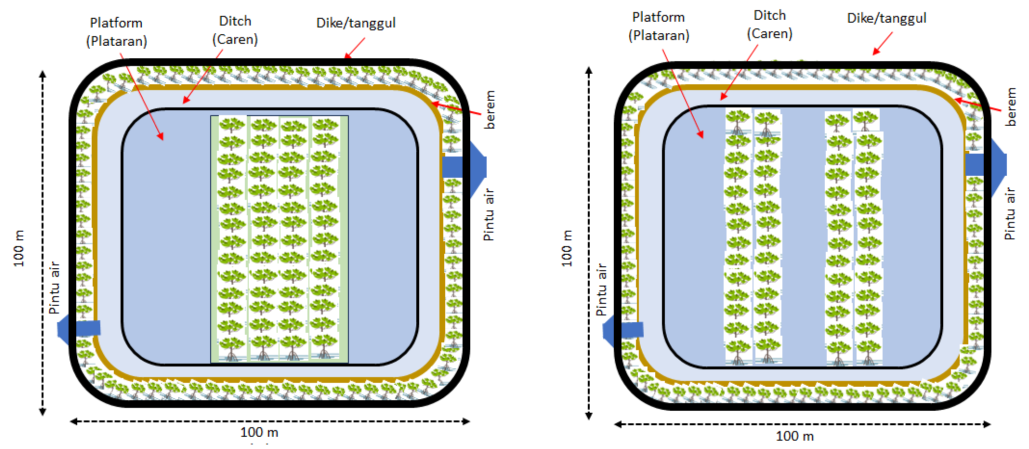

Figure 5. Example of traditional pond or closed silvofishery

From a design and management perspective, optimizing the balance between mangrove coverage, sediment management, and pond hydrodynamics is critical for sustaining ecological and aquaculture functions. Key recommendations include periodic pond drying and sludge removal to reduce organic buildup, thinning mangrove canopy cover around 50–60% to allow sufficient light penetration and water movement, and installing at least two well positioned sluice gates combined with gently sloped drainage canals (0.5-1%) to enhance tidal exchange. These adjustments align with the principles of Integrated Mangrove Aquaculture (IMA), which emphasize ecological harmony and resilience rather than production intensification. Consequently, silvofishery ponds, when properly designed and managed, can serve as adaptive coastal systems that simultaneously rehabilitate mangrove ecosystems and sustain local livelihoods.

4. Conclusion

This study confirms that simple rehabilitation measures such as proper pond drying, sludge removal, and limited water exchange (5% every 3–4 days) can significantly improve the productivity of fish and environmental stability of traditional silvofishery ponds. Moderate mangrove coverage (around 50–60%) supports stable water quality and provides ecological benefits through natural feed and substrate enrichment. However, excessive shading and organic accumulation beneath dense mangrove stands led to hypoxic conditions (<2 ppm DO) and disease outbreaks such as Enterocytozoon hepatopenaei (EHP), resulting in the failure of Penaeus monodon culture.

In contrast, Chanos chanos and Litopenaeus vannamei demonstrated greater adaptability to semi-natural, low-input conditions, achieving moderate yields and minimum artificial feed. These findings highlight the importance of improving pond design, particularly hydrological exchange, drainage slope, and mangrove planting arrangements, to optimize both ecological functions and aquaculture productivity.

Overall, this study demonstrates that integrating aquaculture practices with mangrove rehabilitation through an Integrated Mangrove Aquaculture (IMA) approach provides a viable and scalable model for sustainable coastal management. The findings confirm that silvofishery effectively supports both ecological restoration of mangrove ecosystems and sustained aquaculture productivity, offering an adaptive solution for restoring degraded coastal areas while maintaining local livelihoods. This research also has practical implications for silvofishery management and mangrove rehabilitation policies.

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