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Optimal Ratio between Ponds and Mangroves in the Management of Silvofishery in Indramayu Regency

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ABSTRACT

Communities' dependence on aquaculture ponds as their main source of livelihood has resulted in the extensive conversion of mangroves, which then becomes a serious concern for the sustainability of coastal areas in Indramayu Regency, West Java. The economic advantages of aquaculture should be in line with the ecological role of mangroves in achieving sustainable silvofishery management. Despite the fact that different pond-to-mangrove ratios have been suggested in previous research, there is still an absence of quantitative data that takes into consideration all of the three main criteria in decision-making. Thus, the purpose of the study is to determine the most efficient pond-to-mangrove ratio for sustainable development in Indramayu Regency using the Preferred Rating Organization Method for Enrichment Evaluation (PROMETHEE) in a multi-criteria decision analysis (MCDA) approach. We conducted a field survey, interviewing stakeholders, holding focus group discussions and observing the ecological environment to understand various economic, ecological and social indicators. A PROMETHEE II analysis was conducted to rank the pond-to-mangrove ratios according to the established criteria. As a result, the most profitable ratio was identified at 70:30, with the highest net flow value of

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0.1731. Our study indicates that clear and systematic paths to improve silvofishery management decision-making can be achieved by incorporating stakeholder preferences into MCDA. However, the established ratio must take into account the local economic, ecological, and social contexts of the relevant coastal area before being implemented there.

Keywords: Blue Carbon; Coastal Management; Pond–Mangrove; PROMETHEE II; Social Forestry Policy; Sustainability

1. Introduction

Farmers from Indramayu Regency have been using pond farming as their main source of income, but triggering large-scale land degradation and resulting in the less resistance of the coastal ecosystems there to disasters. The purpose of mangrove restoration is not only to restore the ecological function of coastal areas but also help increase the earnings of the local people. One way of improving the financial situation of the coastal residents is to merge the aquaculture industry with mangrove restoration efforts. The scheme is known as “silvofishery”. This mechanism allows obtaining both ecological and economic gains by combining mangrove trees and clean brackish water aquaculture. Nevertheless, the implementation of silvofishery is challenging due to a deficiency in quantitative information on the appropriate ratio between the aquaculture ponds and mangrove areas. Most of the surveyed farmers believe that the ratio between the area of mangroves and the area of the pond ranges from 30% to 50%^[1].

The benefits derived from mangrove forests are immense and highly advantageous from ecological perspectives, including the process of carbon capture, coastal erosion management, and the provision of habitat for shoreline wildlife. Therefore, the loss of mangrove forests for the establishment of traditional ponds may lead to a decline in the effectiveness of these environmental benefits. The implementation of silvofishery is expected to restore these positive impacts, as this method not only boosts fishery productivity but also contributes to environmental improvement. However, there is still no consensus yet on the optimal ratio between ponds and mangroves to maximize both ecological and economic benefits. Recently, the success of silvofishery has been limited by a lack of understanding regarding the optimal ratios and the integration of scientific approaches into decision-making. While farmers’ income from shrimp products is generally considered a key benefit, an integrated aquaculture system involving both mangroves and shrimp presents a

sustainable practice that can preserve mangrove forests and provide long-term benefits to local communities^[2].

The government has initiated social forestry programs to provide legal access for local communities to manage mangrove areas. However, an ongoing challenge remains: balancing economic and environmental interests in the implementation of silvofishery. Some of the key challenges identified in the implementation of silvofishery include: 1) dominance of land use for ponds^[3], 2) vulnerable income^[4], 3) environmental damage and disaster risk^[5], 4) limited community participation^[6], and 5) limited quantitative data to determine the optimal ratio^[7].

More than 90% of the social forestry area on the Indramayu coast is dominated by ponds, while only 2–10% of mangrove cover remains, leading to a significant decline in the ecological functions of the area. Remote sensing and land cover analyses of the social forestry areas in Indramayu Regency indicate an overwhelming dominance of aquaculture land use (~90%), with mangrove forests occupying only a small fraction of the landscape, thereby undermining key ecological functions such as coastal protection, carbon sequestration, and habitat provision^[8]. Furthermore, sustainability assessments highlight the degraded condition of mangroves due to land conversion pressures^[9]. Similarly, in Vietnam, the practice of pond cultivation has significantly eroded the socio-ecological resilience of coastal ecosystems^[10]. The practice of shrimp farming, particularly along Vietnam’s Mekong Delta, has been shown to contribute to the conversion of mangrove forests into ponds, negatively affecting ecosystem services and increasing vulnerability to environmental changes and socio-economic pressures^[11]. Furthermore, land cover change analysis has shown that the accumulation of mangrove conversion into ponds has significantly reduced the area of mangrove forests in many coastal provinces in Vietnam over recent decades^[12]. On a regional scale, the expansion of ponds is identified as a major driver of mangrove loss in Southeast Asia, further exacerbating the socio-ecological vulnerability of coastal areas^[13].

Recent literature suggests that an integrated production system between mangroves and shrimp may help restore this resilience^[11]. While in terms of farmers' income, cultivation of milkfish in ponds remains the main income source on the coast of Indramayu, the business has been affected by sharp fluctuations due to environmental degradation and natural disasters^[14]. Transforming mangrove regions into ponds compromises crucial ecological functions like erosion prevention and disaster risk management. While people have some knowledge about the importance of mangroves, the problem lies in the restoration effort that is impeded by economic, technical, and social difficulties. Moreover, there is still a problem with the limited availability of quantitative information concerning an appropriate pond-to-mangrove ratio. As determining an appropriate pond-to-mangrove ratio is inherently a multi-criteria decision-making issue, this problem may arise as it involves balancing competing objectives such as success in aquaculture, the level of farmers' income, carbon absorption, coastal protection, and social acceptance. Trade-offs are often involved in these objectives, meaning that when maximizing the pond area, it will be possible to get economic gain but reduce ecological functions. Conversely, optimal mangrove coverage will have positive effects in terms of ecosystem services but limit production capacity. Thus, applying the traditional approach based on using only single indicators or fixed ratios is ineffective in this case.

Multi-criteria decision making (MCDA) gives us an approach for adding different, sometimes contradictory factors together into a transparent decision-making approach. One of the MCDA approaches, PROMETHEE II, is especially useful because it gives a full ranking of the alternatives while accounting for stakeholder preferences and allowing for simultaneous assessment of the economic, ecological, and social dimensions. Thus, this method provides us with a more comprehensive basis for determining local pond/mangrove ratios compared to the results that rely solely on ecological or production factors. Although previous research shows that silvofishery is capable of improving ecological performance as well as increasing aquaculture productivity, the findings of these studies are largely incomplete because they investigate the ecological performance of silvofishery, aquaculture productivity, and ecosystem services as single factors without any relation to one another. As a result, there is little information on how to strike a balance between these con-

flicting objectives when establishing pond-to-mangrove ratio. Available recommendations, including the recommended national ratio of 20:80, are predominantly normative and do not consider local socio-economic realities and preferences of stakeholders^[15]. Moreover, empirical evidence suggests that expansion in pond area improves shrimp production, but tightening requirements of mangrove conservation could bring a negative effect on household income, indicating the trade-offs existing between economic goals and environmental goals^[16]. These different results make it clear that figuring out an ideal ratio of ponds to mangroves is not just an ecological or production issue, but rather a multi-criteria decision issue where economic, environmental, and social aspects should be considered at the same time.

This study advances previous research by establishing normative standards through a data-driven, locally contextualized solution to the long-standing debate over pond-mangrove ratios. While silvofishery is a known concept, this research addresses a critical gap in quantitative evidence required to balance economic survival with ecological sustainability in specific socio-ecological contexts.

This study aims to determine the optimal ratio between pond and mangrove areas in Indramayu Regency using the multi-criteria decision analysis (MCDA) approach. This study fills a gap in the literature by utilizing the PROMETHEE II method to assess the various pond-to-mangrove ratios based on multiple sustainability criteria as well as on the preferences of stakeholders in social forestry management in Indramayu Regency. The results are anticipated to offer valuable input for sustainable coastal management that is scientifically sound and contextually applicable.

2. Materials and Methods

2.1. Study Site

This study was conducted across three social forestry areas in the coastal region of Indramayu Regency, West Java Province, Indonesia (**Figure 1**). The specific study locations were: (1) Forest Village Community Institute (LMDH) Karya Wana Tiris, located in Ilir Customs Village, Pasekan District (340.29 ha); (2) Forest Farmers Group (KTH) Babadan Lestari, situated in Babadan Village, Sindang District (313.23 ha); and (3) KTH Hijau Mandiri, located in Karang Anyar Village, Pasekan District (759 ha).

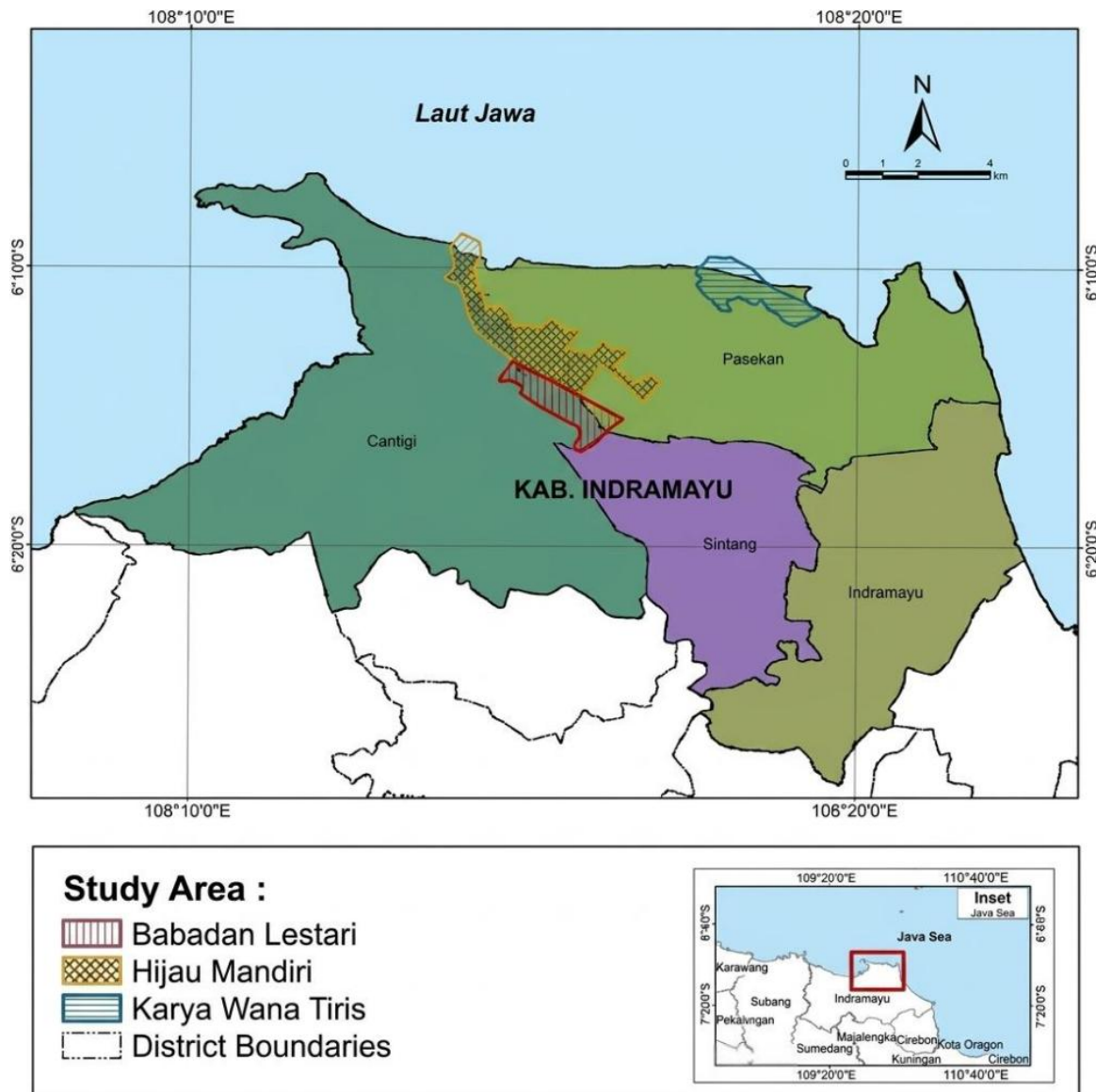


Figure 1. Research locations 108°10'0" E–108°20'0" E and 6°15'0" S–6°20'0" S.

The chosen sites exhibit highly relevant features of pond farming systems and mangrove ecosystems for silvofishery purposes. They differ by their diverse ecological and socio-economic parameters; thus, they provide an all-encompassing background for studying sustainable pond–mangrove ratios.

2.2. Research Design and Analytical Approaches

This study uses the PROMETHEE II approach, which is a multifaceted assessment process that ranks different alternatives. This technique has gained prominence in the fields of economics and operational management in assess-

ing and ranking various alternatives^[17]. The PROMETHEE II methodology was chosen because of its capability to handle management choices that involve many often contradictory criteria like economic viability, sustainability, and social acceptance^[18].

The common configuration observed in the field, as well as initial consultations with the local community and stakeholders. In addition to these three scenarios, we also analyse several other possible alternatives, ranging from 10:90 to 90:10. These alternatives are then chosen by each stakeholder based on their preference. Each alternative was assessed using a set of criteria classified into economic, environmental, and social aspects (**Table 1**).

Table 1. Criteria and indicators used in this research.

Aspects	Criteria	Indicator	Units/Scale	Remarks
Economy	Pond productivity	Fish/shrimp harvest	t/ha/year	Fish/shrimp productivity/ha of pond is based on the results of field measurements and is different for each manager
	Total Ecosystem Value	Total revenue	IDR/ha/year	Total revenue = fish/shrimp productivity × IDR 25 million (fish/shrimp price/ton)
	Operating costs	Total production cost	IDR/ha/year	Total production cost = all costs required for pond management (IDR)
	Net income	Average income of farmers	IDR/ha/year	Average income of farmers = Total revenue – production cost (IDR)
	Mangrove coverage	Percentage of mangrove vegetation area	Percent (%)	(Mangrove cover area/Total pond and mangrove area) × 100%
Environment	Pond coverage	Percentage of pond area	Percent (%)	(Pond area/Total pond and mangrove area) × 100%
	Carbon sequestration	Carbon storage potential	t CO ₂ e/ha	Total biomass × 50% (Standar Nasional Indonesia (SNI) 7724:2011)
	Ecotourism and environmental services	Income from ecotourism and ecosystem services	IDR	-

2.3. Data Collection

Primary data were collected through field surveys, direct observations, biogeophysical measurements, and interviews. The methods used to collect each data are as follows:

2.3.1. Mangrove Cover Measurement

Mangrove cover was assessed using a transect method, with the help of a global positioning system (GPS) for precise location tracking^[19]. The measurement involved determining the extent of mangrove vegetation along designated transects across the study sites.

2.3.2. Carbon Sequestration Potential

The potential for carbon sequestration was estimated using an allometric approach, based on the dominant mangrove vegetation types in the study area. Several sources were used for this calculation, including established methodologies^[20–24].

2.3.3. Socio-Economic Data

We collect socio-economic data through structured interviews and focus group discussions (FGDs) involving local farmers, social forestry managers, and community leaders. These data provided insights into the economic impacts of mangrove degradation, farmers' income, and the social dynamics surrounding the silvofishery area.

2.3.4. Stakeholder Involvement

Decision-making regarding the selection of indicators and scenarios was conducted in a participatory manner. Questionnaire surveys were done for 30 representatives of LMDH/KTH members from the three studied social forestry

areas. Respondents were selected using stratified random sampling, comprising representatives from LMDH/KTH management, village management representatives, elders who were members of LMDH/KTH, and other LMDH/KTH members aged 25–45 years who were literate. This participatory approach was adopted to ensure that the proposed recommendations were locally relevant and socially acceptable^[9].

2.3.5. Weighting and Data Analysis

Stakeholder preferences were systematically converted into criteria weights through a structured, multi-step process during interviews and Focus Group Discussions (FGDs) with 30 respondents representing LMDH/KTH. Determination was made using the following four stages:

First, respondents assessed the relative importance of each economic, environmental, and social indicator using a 5-point Likert scale, where 1 indicates “very low importance” and 5 indicates “very high importance.” Second, to aggregate individual preferences into a representative group value, the scores for each criterion were averaged using the arithmetic mean:

$$S_j = \frac{1}{n} \sum_{i=1}^n s_{ij}$$

where S_j is the aggregate mean score for criterion j , s_{ij} is the score assigned by respondent i , and $n = 30$ is the total number of respondents.

Third, the aggregated scores were normalized to derive the final criteria weight vector (w_j), ensuring that all weights sum to 1 $\sum_{j=1}^k w_j = 1$:

$$w_j = \frac{S_j}{\sum_{m=1}^k S_m}$$

where k represents the total number of evaluation criteria.

Finally, the resulting normalized weights (w_j) were integrated into PROMETHEE software alongside linear preference functions and operational thresholds (indifference q and preference p) to compute the positive (Φ^+), negative (Φ^-), and net (Φ) preference flows for each pond-to-mangrove scenario.

2.3.6. Validity and Reliability

To ensure the validity and reliability of the data:

- Triangulation was applied by comparing findings from quantitative data (such as mangrove cover and carbon sequestration estimates) with qualitative insights obtained from interviews and FGDs.
- Reliability was ensured by pre-testing the interview guides and FGD protocols prior to data collection, and by maintaining consistency in data collection methods throughout the research.

2.3.7. Limitations of the Study

This study has several limitations as follows:

- Temporal Constraints: The remote sensing data used for land use analysis might not capture the most recent changes in land cover, particularly in rapidly changing coastal areas.
- Geographic Constraints: The study is limited to the social forestry areas in Indramayu Regency. Therefore, the findings may not be directly applicable to other coastal

regions with different socio-economic and ecological contexts.

- Sampling Constraints: While 30 farmers were interviewed, the sample size may not fully capture the diversity of aquaculture practices in the region, potentially limiting the socio-economic data's generalizability.
- A formal weight sensitivity analysis was not performed in this study and is recommended for future research to further evaluate the robustness of the proposed pond-to-mangrove ratio under alternative stakeholder preference scenarios, as sensitivity analysis is widely recognized as an important step for assessing ranking stability and minimizing the risk of rank reversal in PROMETHEE II applications^[25,26].

3. Results

3.1. Land Conditions and Mangrove Cover at the Research Site

Spatial analysis of three social forestry locations in Indramayu Regency shows that land use for ponds dominates almost the entire area, with very minimal mangrove cover (**Figure 2**). At LMDH Karya Wana Tiris, the mangrove area is only 14.29 ha (1%), at KTH Babadan Lestari only 6.21 ha (<1%), and at KTH Hijau Mandiri 78.60 ha (6%) of the total area, respectively. In total, only around 7% of the total area (1,412.545 ha) is still covered by mangroves, while the remaining 88% has been converted to ponds (**Table 2**).

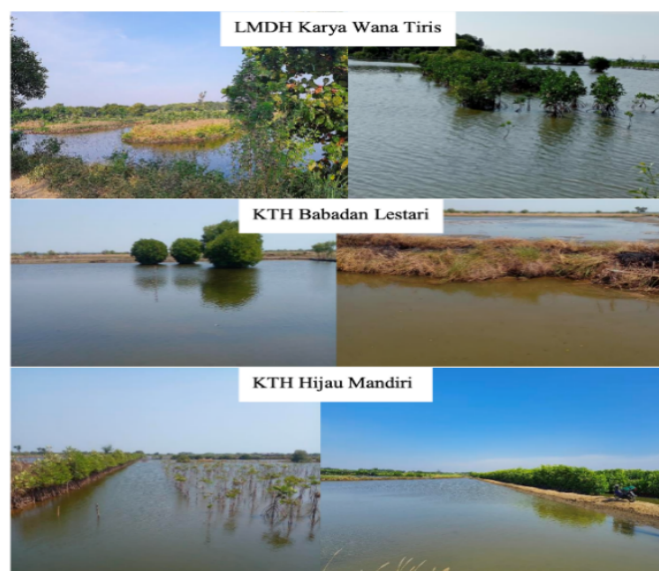


Figure 2. Condition of mangrove ponds in LMDH Karya Wana Tiris, KTH Babadan Lestari, and KTH Hijau Mandiri.

Table 2. Mangrove and pond cover area and pond–mangrove ratio.

Location	Mangrove		Pond		Total (ha)	Ratio Pond:Mangrove
	ha	%	ha	%		
Karya Wana Tiris	14.29	5	252.71	95	268.00	95:5
Babadan Lestari	6.21	2	307.01	98	313.22	98:2
Hijau Mandiri	78.60	10	680.43	90	759.03	90:10
Total/Average	99.10	7	1,240.15	88	1,412.54	88:7

The dominance of land use for ponds has direct implications for the decline in the function of coastal ecosystems. The conversion of mangroves into ponds results in ecological degradation such as a decrease in carbon stocks^[27–30], increased CO₂ emissions^[30,31], increased water pollution^[32], and reduced regional capabilities due to the influence of climate change, such as decreased shrimp production, flash floods and abrasion^[33]. Our field findings also confirm that areas with relatively larger remaining mangrove cover show better resilience to disasters than areas with extreme pond-to-mangrove ratios (98:2).

3.2. Pond Productivity and Community Economic Potential

The low mangrove cover is closely related to the high dependence of the community on conventional ponds. With the increase in the ratio of pond area compared to mangroves,

farmers' net income also tends to increase (**Table 3**). The income of milkfish farmers ranges from IDR 2–5 million per month, with operational costs reaching IDR 5.91 million per harvest. However, the low mangrove cover affects the economic stability of farmers. In extreme weather conditions such as flash flood occurrences, pond productivity decreases drastically, as experienced in 2021. This clearly shows the economic vulnerability of households that depend on ponds for their livelihoods^[34]. The silvofishery system integrates ponds with mangrove trees to generate economic benefits from aquaculture activities and environmental sustainability^[35], improved income stability, easier pond management, and increased the diversity of aquaculture products by enabling combined shrimp, crab, and fish production^[36]. However, mangrove pond cultivation in Subang, West Java, experienced different results, as the increase in pond ratio does not cause significant changes to farmers' income in the mangrove cover range between 19% and 50%^[37].

Table 3. Income value (netto) based on the mangrove pond ratio scenario.

No	LMDH/KTH	Pond and Mangrove Area Ratio	Pond Area (ha)	Total Ecosystem Value (IDR)	Pond Operations (IDR)	Net Income (IDR)
1	Karya Wana Tiris (KWT)	95:5	252.71	7,750,000,000	1,493,416,173	6,256,583,827
		90:10	240.30	7,369,344,983	1,420,064,384	5,949,280,598
		80:20	213.60	6,550,528,873	1,262,279,453	5,288,249,421
		70:30	186.90	5,731,712,764	1,104,494,521	4,627,218,243
		60: 40	160.20	4,912,896,655	946,709,590	3,966,187,066
		50:50	133.50	4,094,080,546	788,924,658	3,305,155,888
		40:60	106.80	3,275,264,437	631,139,726	2,644,124,710
		30:70	80.10	2,456,448,328	473,354,795	1,983,093,533
		20:80	53.40	1,637,632,218	315,569,863	1,322,062,355
		10:90	26.70	818,816,109	157,784,932	661,031,178
		98:2	307.01	9,350,000,000	1,814,288,816	7,535,711,184
		90:10	281.91	8,585,494,451	1,665,942,948	6,919,551,503
2	Bebadan Lestari (BL)	80:20	250.58	7,631,550,6231	1,480,838,176	6,150,712,447
		70:30	219.26	6,677,606,795	1,295,733,404	5,381,873,391
		60:40	187.94	5,723,662,968	1,110,628,632	4,613,034,335
		50:50	156.62	4,769,719,140	925,523,860	3,844,195,280
		40:60	125.29	3,815,775,312	740,419,088	3,075,356,224
		30:70	93.97	2,861,831,484	555,314,316	2,306,517,168
		20:80	62.65	1,907,887,656	370,209,544	1,537,678,1121
		10:90	31.32	953,943,828	185,104,772	768,839,056

Table 3. *Cont.*

No	LMDH/KTH	Pond and Mangrove Area Ratio	Pond Area (ha)	Total Ecosystem Value (IDR)	Pond Operations (IDR)	Net Income (IDR)
3	Hijau Mandiri (HM)	90:10	680.43	21,725,000,000	4,021,038,612	17,703,961,388
		90:10	683.13	21,811,084,335	4,036,971,797	17,774,112,539
		80:20	607.22	19,387,630,520	3,588,419,375	15,799,211,145
		70:30	531.32	16,964,176,705	3,139,866,953	13,824,309,752
		60:40	455.42	14,540,722,890	2,691,314,531	11,849,408,359
		50:50	379.52	12,117,269,075	2,242,762,109	9,874,506,966
		40:60	303.61	9,693,815,260	1,794,209,687	7,899,605,573
		30:70	227.71	7,270,361,445	1,345,657,266	5,924,704,180
		20:80	151.81	4,846,907,630	897,104,844	3,949,802,786
		10:90	75.90	2,423,453,815	448,552,422	1,974,901,393

Note:

1. Total revenue = fish/shrimp productivity × IDR 25 million (fish/shrimp price/ton).
2. Pond Operating Costs = Pond Area × Rp. 5.91 Million.
3. Net income = Total Ecosystem Value – Pond Operating Costs.
4. Fish/shrimp production comes from the results of measurements in the field (t/ha).
5. Assumptions used in calculating total ecosystem value = pond area × fish/shrimp production/ha.
6. The area of the pond is calculated from the ratio of pond area and mangrove area.
7. fish/shrimp production: KWT = 1.22 t/ha, BL = 1.21 t/ha, HM = 1.27 t/ha.

3.3. Development of Ecotourism and Environmental Services

Despite the potential for economic diversification, such as the development of ecotourism and environmental services, adoption at the local level is still limited. At LMDH Karya Wana Tiris, ecotourism development initiatives have started but are still constrained by accessibility, funding, and promotion. Experience from Vietnam's Ca Mau province can be used as a learning example, where beekeeping, ecotourism, and carbon service payments can reduce household dependence on mangrove-shrimp cultivation, and thus play an important role in forest conservation and community prosperity in the province^[38]. In addition, participation in activities such as ecotourism, marine cultural events, and traditional fishing experiences provides a deeper understanding and appreciation of local cultural traditions, potentially strengthening awareness and protection of such cultural heritage^[39]. By exploring and preserving local cultural heritage and encouraging the development and production of traditional cultural and handicraft products, we can not only meet market demand, but also increase the added value of local fishery products.

3.4. Carbon Storage and Ecological Function of Mangrove Ponds

Our field measurements and vegetation analysis show that ponds with mangrove cover between 44% and 80% could store carbon by 40–50 t of CO₂e/ha. This is in line

with findings of Harefa et al.^[40], which stated that increasing vegetative cover in mangrove-pond systems (wanamina) does not reduce fish productivity, but rather increases carbon stocks significantly. This means that the integration of mangroves in aquaculture systems can provide dual benefits: economic and ecological. Meanwhile, the results of the study by Sumarga et al.^[37] confirm that there is no significant difference in production output between ponds with high and low mangrove cover, but the ecological contribution of systems with high cover is much greater. According to Sasmito et al.^[30], mangrove conversion has eliminated 60% of soil carbon stocks and 85% of living biomass carbon stocks in West Papua.

3.5. Optimal Pond–Mangrove Ratio

A study of alternative pond–mangrove ratios across in three farmer groups in Indramayu used the PROMETHEE II approach^[41], a common technique for multi-criteria decision-making (MCDM) problems. Our results showed that the ratio of 70:30 (pond:mangrove) resulted in the highest preference value with $\Phi = 0.1731$, followed by a ratio of 10:90 with $\Phi = 0.1058$ and a ratio of 20:80 with $\Phi = 0.0388$ (Table 4 and Figure 3). The 70:30 ratio is considered the most balanced as it meets the needs of pond productivity and mangrove ecosystem conservation in Indramayu. Here, the 70:30 pond-to-mangrove ratio is chosen as the top-ranked alternative under the baseline weighting structure derived from local stakeholder preferences ($\Phi = 0.1731$). However,

since a formal weight sensitivity analysis was not conducted in this study, the ranking reflects an optimal balance that applies only to the established weighting scenario, rather than a robust optimum verified across all possible preference variations. The 70:30 ratio has also proven to produce the maximum value of net flow ($\Phi = 0.1731$), which means it is the most balanced option among all the solutions assessed. Recent papers on multi-criteria decision analysis have emphasized the advantages of PROMETHEE in tackling complex environmental issues due to its ability to integrate conflicting

criteria and provide clear rankings^[42,43]. Recent research has shown that PROMETHEE II achieves better decision making by allowing decision makers to understand the relative performance of alternative management strategies^[44]. While subsequent studies may further improve the credibility of these results by conducting formal sensitivity or probabilistic uncertainty analyses, the consistency of the results obtained from PROMETHEE II makes it reasonable to assume that a 70:30 ratio is a viable management option in the current decision framework.

Table 4. Results of alternative ranking of pond–mangrove ratio (PROMETHEE II method).

Ratio	Φ Value (Net Flow)	Rank	Interpretation
70:30	0.1731	1	Optimal, economic–ecological balance
10:90	0.1058	2	Conservation focus, low economic benefits
20:80	0.0673	3	Old, less adaptive ratio locally

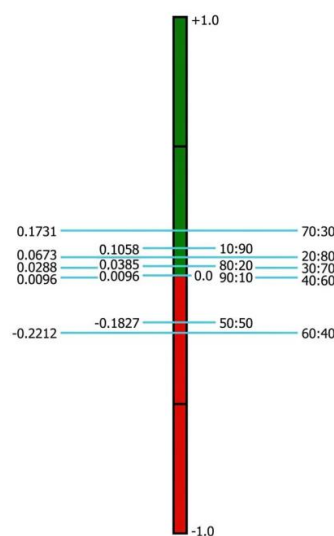


Figure 3. PROMETHEE ranking.

The optimal ratio resulting from this study (70:30) is different from the recommendation applied by Perhutani (20:80) and the study by Nur^[45], which proposed 40:60 or 50:50. Meanwhile, based on the results of research^[38], the best ratio of mangroves and ponds in Ca Mau Province, Vietnam is 60:40, where in this proportion mangroves have shown to play an important role in protecting ecosystems and supporting the economic sustainability of the community. These results show that the optimal ratio is contextual and needs to be adjusted to local biophysical and socioeconomic conditions. In the context of conditions at the study site, the total income from fish and carbon production is observed to be gained at the optimal mangrove pond ratio (70:30) ranging from IDR 6,336,871,200 to IDR 22,076,430,056 depending on the area of the pond and mangrove (Table 5).

Table 5. Income on optimal mangrove pond ratio.

LMDH/KTH	Mangrove Pond Area (ha)	Pond Area (ha)	Mangrove Area (ha)	Milkfish Production (t/Year)	Carbon (t)	Revenue (IDR)
Karya Wana Tiris	267.00	186.90	80.10	230	1,966	6,336,871,200
Bebadan Lestari	313.23	219.26	93.97	267	4,903	8,158,434,312
Hijau Mandiri	759.03	531.32	227.71	680	16,914	22,076,430,056

Note: KTH: Forest farmer group.

4. Discussion

The decline in mangrove cover in the study area may indicate significant degradation of coastal ecosystems. Ponds dominate the land use in the study area, leading to a reduction

in the ecological functions of mangroves, such as protection against coastal erosion and carbon sequestration capacity. This is in accordance with the findings^[37], which revealed that the conversion of mangroves into ponds has a direct impact on the destruction of coastal habitats and increased

water pollution. According to Adame et al. [46], emissions from mangrove loss could reach 2,391 Tg CO₂eq by the end of the century, or 3,392 Tg CO₂eq when considering the sequestration of lost soil carbon. The highest emissions are predicted in Southeast and South Asia (Western Coral Triangle, Sunda Plateau, and Bay of Bengal) due to conversion to aquaculture or agriculture. On the other hand, locations with higher mangrove cover show greater resilience to natural disasters, such as tidal flooding, which is in line with the findings of Menéndez et al. [47], which state that mangroves serve as natural protectors against erosion and storm surge.

Income from pond businesses at the research site shows a high dependence on ponds. However, low net income and high operating costs indicate that the conventional pond system on the site is vulnerable to economic and environmental fluctuations. These findings strengthen the claim that dependence on ponds without proper mangrove conservation can result in the lower socio-economic resilience of coastal communities [34].

We notice ecotourism as another source of income that may improve the community's earnings. Ecotourism here is still a fledgling sector of economic diversification, demonstrating the necessity of strong efforts in advancing its nature-based tourism businesses for improvement of the community's economic resilience. However, one of the most significant problems is the lack of marketing and accessibility of the area, which may limit the possibilities of the ecotourism industry. Nonetheless, ecotourism has produced substantial economic benefits for the region and ensured community involvement and management [48].

Results of carbon measurement and biodiversity assessment show that the system of ponds with mangroves stores a high carbon stock without damaging fish production. This proves that combining fish farming and mangrove conservation is an effective approach. Previous studies have reported that silvofishery systems benefit in twofold by augmenting carbon storage while yielding long-term economic benefits from the fisheries sector. In addition, it has been found that increased area of mangroves leads to enhanced water quality, less sedimentation, and a decrease in chemical pollution from fertilizers and feeds [40]. Water quality plays an important role in enhancing the effectiveness of ponds since it also creates a good environment for the cultured biota [49]. As a result, this ensures stability of the ecosystem and long-term

sustainability of production.

The PROMETHEE II analysis identified the 70:30 pond–mangrove ratio as the preferred scenario, as it obtained the highest net flow value ($\Phi = 0.1731$) among the evaluated alternatives. Consequently, this ratio serves as a model for achieving an appropriate balance among key criteria in the MCDA framework. It provides communities with the ability to enhance their socio-economic status sustainably. However, the optimal utilization of the 70:30 ratio is highly dependent on the provision of effective governmental support, financing for the restoration of mangrove plants, and technical assistance for farmers. As evidenced by previous studies, the role of incentives such as blue carbon financing offered by various policies may ensure successful application of the silvofishery initiative in the long-term perspective [50–52].

Our interview with stakeholders showed that they approved of the 70:30 ratio as socially acceptable; however, using it in practice means that around 30% of the current pond will have to be rehabilitated into mangroves. This means that practical implementation would face financial and institutional problems such as the supply of seedlings, funding of rehabilitation activities, provision of technical expertise, and communication within institutions. Other studies also indicate that any effective blue carbon incentive schemes can motivate conservation activities in mangroves, while misapplied subsidies may further trigger mangrove conversion for aquaculture development [52].

The baseline preference for the 70:30 ratio is inherently tied to the current socio-economic priorities of local stakeholders that emphasize immediate income generation. In the absence of a formal sensitivity analysis, the ranking stability of this ratio, therefore, remains conditional. It cannot be conclusively determined whether the 70:30 ratio would retain its top ranking if stakeholder preferences were to shift toward other ecological conservation criteria (e.g., carbon sequestration and disaster mitigation). The relatively high dependence of local farmers on pond cultivation, with monthly income ranging from IDR 2–5 million, may contribute to the importance assigned to economic criteria in the decision framework. On the other hand, ponds currently dominate the three studied social forestry areas, accounting for approximately 88% of the combined area, leaving the mangrove cover limited to about 7%. These conditions provide an important socio-economic context for interpreting

the stakeholder-derived weights and the resulting preference for the 70:30 scenario. However, without a formal sensitivity analysis, it cannot be determined whether the 70:30 ratio would remain the highest-ranked alternative if greater importance were assigned to ecological criteria such as mangrove cover and carbon-related ecosystem services. Therefore, the 70:30 ratio should be interpreted as the preferred scenario under the weighting structure applied in this study rather than as a universally robust optimum. However, future studies should evaluate alternative weighting schemes to determine the stability of the PROMETHEE II ranking.

Successful mangrove restoration projects require a complete management approach for both fisheries development programs and appropriate social forestry policy, strongly emphasizing the necessity of combining two aspects: ecology and economy in coastal management. This study reveals that a locally based multi-criteria approach will provide more responsive management recommendations compared to standard normative approaches. Furthermore, recent advancements in MCDA practices guarantee the high quality of the recommendations^[26]. In the same way, while PROMETHEE II is a powerful decision-making method in complicated environmental issues, sensitivity analysis is an important complementary method in assessing the impact of different weighting schemes and minimizing the likelihood of rank reversal^[25]. This research shows that the 70:30 ratio of freshwater pond to mangrove yields the maximum net flow value ($\Phi = 0.1731$), and therefore, holds the most balanced trade-off in the economic, environmental, and social criteria used in the proposal. The detailed account of the assessment criteria, stakeholder-based weighting approach, and application of the PROMETHEE II method increases the transparency, reproducibility, and scientific credibility of the formulated proposal.

The broader environmental and socio-economic benefits associated with silvofishery systems, such as improvements in water quality, sediment stabilization, coastal protection, enhanced disaster resilience, blue carbon storage, and long-term community resilience, have been widely reported in previous studies^[50–52]. However, these results had not been directly measured within our study here; hence, the interpretation must be regarded as possible consequences rather than factual conclusions. Further research is therefore necessary to achieve certainty on those goals in the future

by using long-term ecological monitoring along with socio-economic assessment.

The results obtained may also be used to develop policies in the field of mangrove rehabilitation within social forestry projects, particularly through initiating the implementation of the criteria highlighted in this study. Here, the 70:30 ratio could become a benchmark for practitioners in areas similar to the study area. Although the framework applied in the current study may be of great interest to coastal areas around the globe and serve as a framework for various projects in the field of silvofishing, it is essential to acknowledge that these numbers should not be treated as universal. It is important to consider all peculiarities of various coastal areas and be aware of the differences in ecological characteristics, aquaculture, socio-economics, and the stakeholders involved, to ensure the success of the system to be implemented in other regions.

5. Conclusions

The PROMETHEE II analysis identifies the 70:30 pond–mangrove ratio as the most favourable baseline scenario under the specific criteria weights derived from local stakeholders. However, as this study did not include a formal sensitivity analysis, the findings should be interpreted as a context-specific baseline recommendation rather than a universally robust optimum. Future research incorporating probabilistic uncertainty and weight sensitivity analyses is essential to confirm the stability of this ratio under changing policy or environmental priorities. This ratio represents the most favorable trade-off between economic, ecological, and social considerations within the study area. The findings provide a locally contextualized basis for silvofishery planning in the studied social forestry areas. However, potential long-term benefits related to water quality, sedimentation, disaster resilience, blue carbon, and community resilience should be considered as potential implications rather than confirmed outcomes, as these effects were not directly evaluated over the long term in this study. Further longitudinal and sensitivity analyses are recommended to assess the robustness and long-term impacts of the proposed ratio.

Suggestions

The 70:30 pond-to-mangrove ratio serves strictly as a context-specific baseline for Indramayu Regency rather

than a universal policy mandate. Coastal management frameworks must avoid rigid, fixed ratios and instead adopt adaptive configurations tailored to local biophysical conditions and socio-economic dependencies. While the specific numerical ratio is non-generalizable, the participatory MCDA–PROMETHEE II framework provides a transparent, replicable decision-making tool for other coastal social forestry regions. Operationalizing these site-specific balances requires targeted extension services and performance-based incentives—such as blue carbon financing—to offset short-term income trade-offs during mangrove rehabilitation. Finally, future research should combine multi-year longitudinal field monitoring with formal weight sensitivity and probabilistic uncertainty modeling to verify decision stability under shifting market and climate conditions.

Author Contributions

Conceptualization, O.R.; methodology, O.R.; software, R.B.P.; validation, D.R.P.; formal analysis, R.B.P.; investigation, R.B.P.; resources, R.B.P.; data curation, D.R.P.; writing—original draft preparation, O.R., R.B.P., D.R.P.; writing—review and editing, E.I.P.; visualization, S.H.G.; supervision, E.I.P. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

If anyone needs data related to this research, they can contact the author.

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Conflicts of Interest

The authors declare no conflict of interest.

AI Use Statement

During the preparation of this manuscript, the authors used AI solely for language refinement and improvement of grammar and readability. No AI tools were used for data analysis, interpretation, statistical analysis, figure generation, or the generation of scientific findings or conclusions.

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