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| **Literature Review**

A Silvofishery Model for Enhancing Blue Carbon and Sustainable Aquaculture in Indramayu's Coastal Region

Belinda Calista Tansy*, Giovani Rahadian Arif
Forestry Engineering Program, School of Life Sciences and Technology, Institut Teknologi Bandung, Indonesia

Correspondence Email: Belindatansy21@gmail.com

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Abstract: Indramayu Regency is one of Indonesia's regions with significant blue carbon potential, where it is mostly found in its mangrove ecosystems. However, ecosystem degradation brought on by the conversion of land into ponds has reduced this blue carbon potential. This study aimed to design an integrated mangrove-aquaculture (silvofishery) and estimating its potential as blue cabon component for CO_2 emission absorption. Methods used included spatial analysis to determine zoning design, a literature review of silvofishery models and mangrove species to choose the best type and model, and a dynamic system model simulation of CO_2 absorption. The study resulted in design of a silvofishery scheme using 'empang parit' model that optimizes the ponds long-term ecological and economic value. *Rhizophora mucronata* used as the species planted in this design that are divided into three zones: (1) Protected Forest Zone (ZHL) covering 7,700.15 ha (mangrove-to-pond (MT) ratio 80:20, planting distance 1x1 m); (Abrasion-Accretion Protection Zone (ZAA) covering 1,592.73 ha (MT ratio 80:20, planting distance 1x2 m); and (3) Optimal Silvofishery Zone (ZWO) covering 13,626.94 ha (MT ratio 60:40, planting distance 2x2 m). According to simulation results, the design area's CO_2 absorption in year 35 reached 671.17 tons/ha in ZHL, 332.62 tons/ha in ZAA, and 141.57 tons/ha in ZWO, with total absorption reaching 7.86 millions tons CO_2 for entire design area. The 'empang parit' silvofishery design in the coastal region of Indramayu has the potential to raise the region's capacity to absorb CO_2 by more than 217 thousand tons annually while preserving ponds economic value.

Keywords: Silvofishery; CO_2 Emission; Blue Carbon; Indramayu Regency

1. INTRODUCTION

Through the Enhanced Nationally Determined Contribution, which aims to reduce greenhouse gas (GHG) emissions by 31.89% unconditionally and 43.20% with international support, Indonesia has reinforced its commitment to mitigating climate change (Ermgassen et al., 2020; Twidyawati et al., 2021 Heriamsal & Amin, 2024). According to Indonesia's First Biennial Update Report (BUR), total GHG emissions in 2019 reached 1.845 GtCO2e, with the Land Use Change and Forestry (LUCF) sector contributing up to 50.13% from total GHG emissions (Roy et al., 2024; Stankovic et al., 2023; Pratama & Ryabtsev, 2025). In response, Indonesia's government, through the Forestry and Other Land Use (FOLU) Net Sink 2030 strategy, aims to reduce emissions by as much as 140 MtCO2e by reducing deforestation, forest restoration, managing peatland, and law enforcement (Sidik et al., 2023; Murdiyarso et al., 2023; Dalimunte et al., 2025).

To meet the climate goals, coastal ecosystems are just as vital as other forest ecosystems (Monuki et al., 2021; Finkl & Makowski, 2021; Tuholske et al., 2021). Mangrove ecosystems offer critical carbon sequestration services as part of the blue carbon ecosystems sector (Lovelock et al., 2022; Palit et al., 2022; Sari & Aliyu,

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2025). However, development puts these ecosystems under pressure, particularly in Indramayu Regency, which is one of the largest aquaculture regions on the northern coast of West Java. With 22,918 hectares of ponds and an annual pond production of 318,590.66 tons, Indramayu has become a key location for the aquaculture revitalization program launched by the Ministry of Marine Affairs and Fisheries (Press Release No. SP.264/SJ.5/VI/2025) as the program targets 2,875 hectares in Indramayu (Garsetiasih et al., 2021; Sukaesih et al., 2021). The Decree of the Minister of Forestry No. 274/MENLHK/SETJEN/KUM.1/5/2025 allocating more than 20,000 hectares of coastal area for aquaculture raises concerns over mangrove degradation, reduced carbon sequestration, and biodiversity loss (Novianti et al., 2022; Zahra et al., 2022; Nurdin et al., 2021).

Another problem is a coal-fired power plant in Indramayu Regency, the sixth-largest in Java, which released 3.98 MtCO2e in 2024, thereby increasing the environmental burden on the area. The pressures from aquaculture expansion, mangrove ecosystem loss, and energy sector emissions all put ecosystem resilience and climate goals at risk (Hapsari et al., 2022; Nur & Hilmi, 2021). Integrated mangrove-aquaculture systems, also known as silvofishery, are being promoted more to balance production and conservation. However, existing studies on silvofishery systems in Indonesia have predominantly focused on improving aquaculture productivity or on static carbon stock assessments, with limited integration of spatially explicit design and long-term carbon sequestration modeling. Moreover, few studies have explicitly linked silvofishery-based mangrove management to national climate mitigation frameworks such as Indonesia's Enhanced NDC and FOLU Net Sink 2030 targets.

This study addresses these gaps by proposing a spatially zoned silvofishery design and employing a dynamic system model to estimate long-term CO_2 absorption, providing a policy-relevant assessment of silvofishery as a blue carbon-based climate mitigation strategy. Therefore, this study aims to develop an integrated silvofishery design for the coastal area of Indramayu Regency and to estimate its long-term potential as a blue carbon component for CO_2 emission absorption.

2. RESEARCH METHODS

This study was conducted in the coastal area of Indramayu Regency, West Java Province, Indonesia, which is located along the northern coast of Java Island between 107°52´–108°36´ E and 6°15´–6°40´ S. Indramayu Regency was selected as the study area due to its extensive aquaculture ponds, significant mangrove degradation resulting from land conversion, and its strategic role in national aquaculture revitalization and climate mitigation programs. The region also faces increasing environmental pressure from coastal erosion and greenhouse gas emissions, making it a relevant location for developing and evaluating a silvofishery-based mangrove ecosystem design.

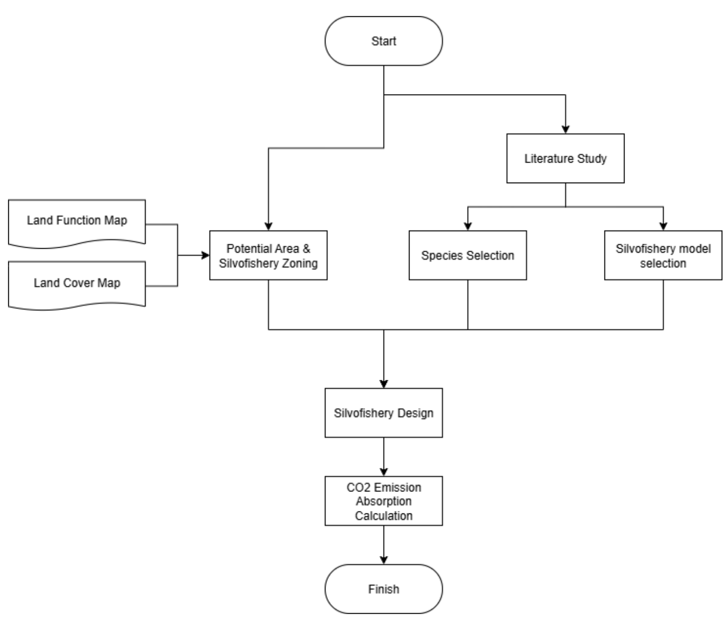

Figure 1. Research Flowchart (Source: Data Processing Results, 2025)

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a. Determination of Potential Areas and Design Zoning

The determination of the potential area and design zoning was based on integrating data on land cover (particularly existing pond-cover conditions), location, status, and function, as well as the mitigation of land-cover changes caused by ocean waves. Each zone will have a different formation from the others. The study area is located in Indramayu Regency, West Java, with a focus on the northern coastal region. Indramayu Regency is located between 107°52´–108°36´ E and 6°15´–6°40´ S, as shown in Figure 2.

Figure 2. Map of Study Area (Source: Google Earth, 2025)

b. Selection of Silvofishery Model and Plant Species Used

The silvofishery model selection was based on a model that optimizes both ecological and economic functions. A literature review of silvofishery types and models is used to select the optimal model for the design (Perwitasari, 2021; Poedjirahajoe, 2019). For the mangrove species used in the design, selection is based on the site's biophysical and ecological conditions, as well as vegetation characteristics. The choice of mangrove species is based on those that can influence the formation of new sediment and protect the design area from abrasion. Furthermore, the vegetation must have a rapid growth rate and be well adapted to the area, which will affect the improvement of mangrove ecosystem quality and carbon emission absorption.

c. Estimating Carbon Emission Absorption

Mangrove ecosystems are highly effective at absorbing and storing carbon. With this design, it is expected that the mangrove ecosystem's capacity to sequester carbon will increase gradually. The increase in carbon emission absorption was estimated using a dynamic system model in STELLA 9.0.2. The model used parameterized characteristics such as wood density and average diameter increment. In line with Indonesia's regulation (PP No.27 tahun 2025) on the Protection and Management of Mangrove Ecosystems, a 50% survival

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rate was presumed, which is the minimum requirement for mangrove ecosystem rehabilitation. In accordance with Indonesia's net-zero emissions target by 2060, this model was run over a 35-year period. This timeframe was selected to assess how the silvofishery design contributed to Indonesia's goal of reducing carbon emissions. The carbon estimation calculation follows the Indonesian National Standard (SNI 7724:2019) for measuring and calculating carbon stocks in forest carbon stock estimation. Carbon emission calculation involves calculating biomass and then converting the biomass value to carbon stored. Mangrove biomass was estimated using allometric equations, as shown in Table 1.

Table 1. Allometric equation for several mangrove species in Java

Species	Above-ground Biomass (AGB) (kg)	Below-ground Biomass (BGB) (kg)
Avicennia marina	$B = 0.308 \times dbh^{2.11}$ *(1)*	$B = 1.28 \times dbh^{1.17}$ *(2)*
Bruguiera gymnorrhiza	$B = 0.186 \times dbh^{2.31}$ *(3)*	$B = 0.199 \times \rho^{0.899} \times dbh^{2.22}$ *(4)*
Ceriops tagal	$B = 0.251 \times \rho \times dbh^{2.46}$ *(5)*	$B = 0.199 \times \rho^{0.899} \times dbh^{2.22}$ *(4)*
Rhizophora apiculata	$B = 0.235 \times dbh^{2.42}$ *(6)*	$B = 0.00698 \times dbh^{2.61}$ *(7)*
Rhizophora mucronata	$B = 0.235 \times dbh^{2.42}$ *(6)*	$B = 0.199 \times \rho^{0.899} \times dbh^{2.22}$ *(4)*
Sonneratia alba	$B = 0.251 \times \rho \times dbh^{2.46}$ *(5)*	$B = 0.199 \times \rho^{0.899} \times dbh^{2.22}$ *(4)*
Xylocarpus granatum	$B = 0.251 \times \rho \times dbh^{2.46}$ *(5)*	$B = 0.199 \times \rho^{0.899} \times dbh^{2.22}$ *(4)*

(Source: Henri, et. al. 2024)

The carbon content value of biomass is calculated using the following equation (SNI 7724:2019):

$$CB = \frac{B \times \%C_{organik}}{1000}$$

CB = Carbon content (ton)
B = Biomass (kg)
$\%C_{organik}$ = Percentage of carbon content (% C organic = 0.47)

The amount of CO_2 absorbed by the plants is calculated by converting the carbon content to CO_2. Mathematically, the molar mass of CO_2 is 44 g/mol, since the atomic masses of carbon (C) and oxygen (O) are 12 and 16 g/mol, respectively. To convert the mass of carbon to the equivalent mass of CO_2, the ratio 44/12 (approximately 3.67) is used. This means that one kilogram of carbon is equivalent to approximately 3.67 kg of CO_2.

3. RESULTS AND DISCUSSION

a. Silvofishery Design and Zoning Outcomes

Based on existing silvofishery models, the 'empang parit' model is chosen for the design. The 'empang parit' model can utilize mangrove forests by constructing ponds in the form of enclosed ponds or water channels, as shown in Figure 3. The commodities that can be cultivated in these ponds include shrimp and milkfish, which are common commodities grown in the design area. According to Poedjirahajoe (2019), the animals farmed in the 'empang parit' system can form a symbiosis with the vegetation. This offers advantages

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in both ecological and economic terms, as ponds employing the 'empang parit' method have been shown to enhance aquaculture yields, particularly for milkfish and several shrimp species.

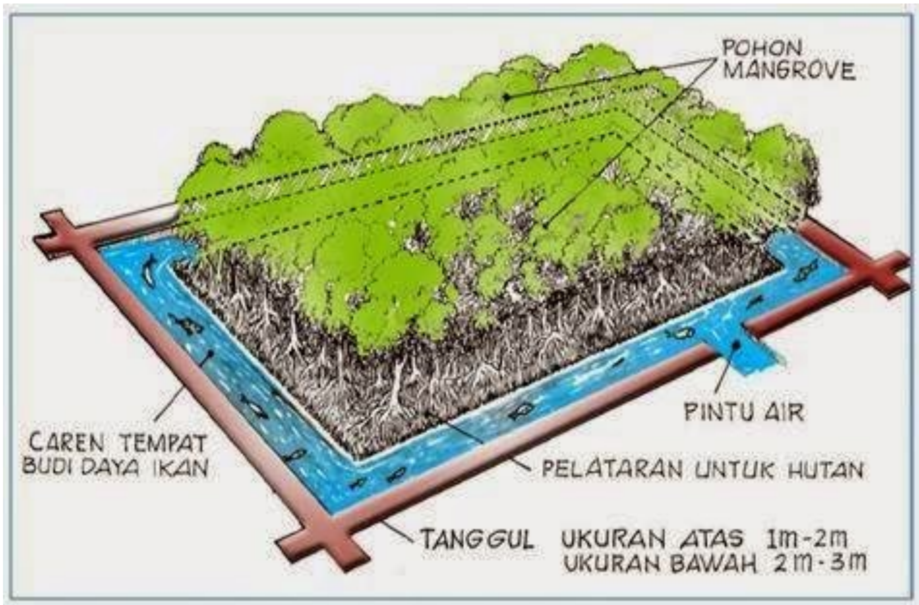

Figure 3. Empang parit' Silvofishery Model (Source: biodiversityru4.com)

In Indonesia, mangrove diversity is high, with an estimated 202 species. There are 89 tree species, five palm species, 19 liana species, 44 herbaceous species, 44 epiphyte species, and one fern species among them (Badu et al., 2022). The mangrove species selected for the design are based on those found in Java, particularly in Indramayu Regency. The species options are listed in Table 2 below.

Table 2. Mangrove Species in Java

Species	Characteristics
Acanthus ilicifolius	Herbaceous type, leaves with sharp serrations (like thistles), height reaches 2 meters.
Acrostichum aureum	Fern type, shiny green leaves 1-3 meters long, height reaches 4 meters.
Avicennia marina	Horizontal roots, erect pneumatophores, smooth greenish-grey bark, elliptical or oval leaves, height reaches 30 meters.
Avicennia alba	Horizontal roots, pneumatophores, bark has small grey protrusions, elliptic-lanceolate leaves, height reaches 25 meters.
Bruguiera gymnorrhiza	Buttress roots and plank roots (as pneumatophores), bark has lenticels, grey-black, elliptical leaves, height reaches 15 meters.
Ceriops tagal	Stilt roots, smooth grey bark, elliptical leaves, height reaches 25 meters.
Excoecaria agallocha	Pneumatophores, grey bark, elliptical leaves with pointed tips, toxic sap, height reaches 15 meters.
Rhizophora apiculata	Red stilt roots, aerial roots emerge from branches, grey bark, elliptical leaves with pointed tips, height reaches 30 meters.
Rhizophora mucronata	Stilt roots, aerial roots emerge from branches, blackish-grey bark, broad elliptical leaves with pointed tips, height reaches 27 meters.
Sonneratia alba	Pneumatophores, fissured grey-brown bark, oval leaves with rounded tips, height reaches 20 meters.
Xylocarpus granatum	Plank roots that form fissures, light brown bark, elliptical leaves with rounded tips, height reaches 20 meters.

(Source: Muzaki, et al., 2019; Brahmin, 2020)

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Rhizophora mucronata was chosen as the species for the silvofishery design. The *Rhizophora mucronata* species has stilt roots that can improve soil structure (Wibisono, 2015). Extracts from *Rhizophora mucronata* leaves have been shown to enhance the growth of pond-cultured animals (Syakirin et al., 2023). The compounds found in *Rhizophora mucronata* that are beneficial for growth, appetite enhancement, and immunity improvement of cultivated animals include flavonoids, alkaloids, terpenoids, and saponins. Additionally, *Rhizophora mucronata* is a mangrove species that thrives in wetlands. The growth and characteristic parameters of *Rhizophora mucronata*, which were subsequently used as the basis for generating the dynamic system, are presented in Table 3.

Table 3. Parameterization of *Rhizophora mucronata* Species Characteristics

Parameter	Value	Reference
Diameter increment (cm/year)	0.356	Kesuma, et al. 2016
Wood density (g/cm^3)	0.98	Henri, et. al. 2024

Based on the spatial analysis, the design area's zoning was determined as illustrated in **Figure 4**. The design area is divided into three (3) zones, consisting of:

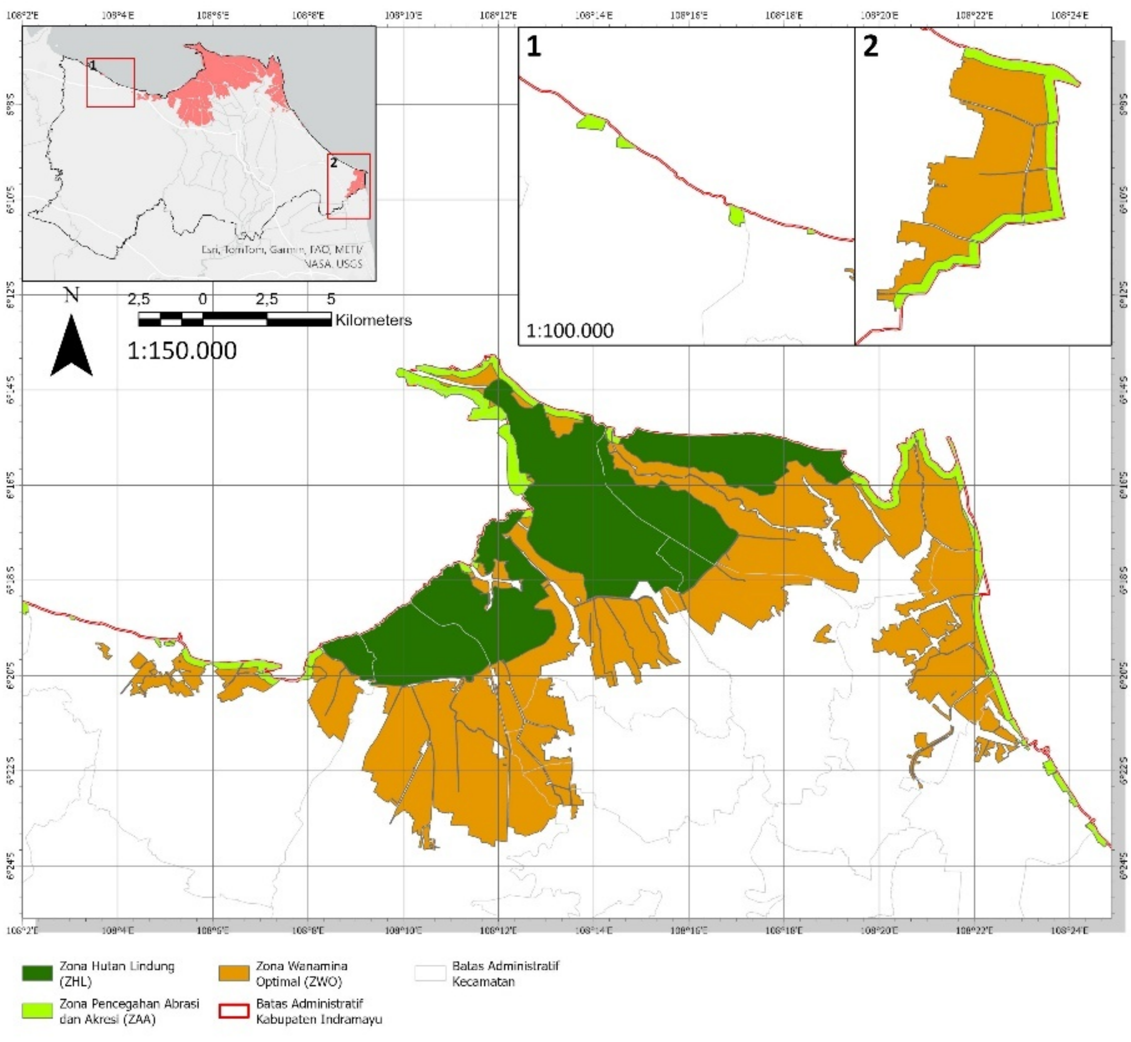

Figure 4. Design Area Map (Source: Data Processing Results, 2025)

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b. Protected Forest Zones (ZHL)

ZHL is a zone established in traditional pond areas, designated for the actual function of a protected forest. This zone covers 7,700.15 hectares within the study area. Protected forest, as defined in Indonesia's Government Regulation (PP No.23 Tahun 2021) on Forestry Management, is a forest area that functions as a life support system protector to control erosion, regulate water management, prevent floods, stop seawater intrusion, and preserve soil fertility. Silvofishery can be a solution for utilizing protected forests because, in addition to providing regulatory ecosystem services, including carbon sequestration, it also offers the ecosystem service of producing commodities raised in pond areas. The design in ZHL implemented uses the 'empang parit' silvofishery model with a mangrove-to-pond (MT) ratio of 80:20. The design also uses a planting spacing of 1 x 1 m to maximize the presence of mangrove vegetation and minimize future human intervention.

c. Abrasion-Accretion Protection Zone (ZAA)

The design implemented in ZAA is intended to mitigate land-cover changes caused by ocean waves by developing a mangrove ecosystem that extends up to 250 meters from the shoreline to serve as a wavebreak. ZAA covers 1,592.73 hectares within the study area. To optimize vegetation's ability to break waves, the 'empang parit' silvofishery model with a high mangrove percentage is needed. This led to the selection of silvofishery with an 80:20 MT ratio and 1 x 2 meters planting distance. This strategy is used to maintain the pond's economic value while maximizing its ecological function.

d. Optimal Silvofishery Zone (ZWO)

In sustainable management, the ecosystem's economic value is just as crucial as its ecological value. This led to the ZWO zone design, which aims to preserve the area's sustainability while optimizing economic value. This zone covers 13,626.94 hectares. 'Empang parit' silvofishery model with MT ratio of 60:40 and a plant spacing of 2 x 2 m was chosen. According to research by Amrial et al. (2015), a 60:40 silvofishery ratio, if appropriately managed, represents a balance between economic and ecological conditions that can preserve the mangrove ecosystem while enhancing community welfare. While this zone is primarily intended for monetary value and day-to-day use, the other two zones, with an 80:20 ratio, can be used as research, development, and demonstration facilities.

e. CO_2 Absorption Potential of the Silvofishery Design

Compared with other silvofishery implementations reported in the literature, the present study provides a more comprehensive assessment of the long-term carbon sequestration potential, integrated with explicit spatial zoning. Previous research in Indonesia has mainly focused on productivity or ecosystem characteristics of silvofishery ponds, such as carbon stock and species diversity in mangrove-fish pond systems (e.g., in Tanjung Rejo, Deli Serdang, where higher mangrove coverage resulted in greater carbon deposits of 40–50 t C ha^{-1} $year^{-1}$) and on the benefits of silvofishery for water quality and fish productivity in Brebes Regency silvofishery ponds (Novida et al., 2025; Basyuni et al., 2022). Other studies have explored silvofishery as a sustainable aquaculture approach, improving environmental parameters and fish growth in integrated systems (Andriani & Wulandari, 2025).

However, these studies did not combine dynamic, long-term carbon modeling with policy-relevant climate mitigation goals. In contrast, the current research develops a dynamic system model to project CO_2 absorption over 35 years. It aligns the findings with national mitigation frameworks such as Indonesia's FOLU Net Sink 2030 target, demonstrating how spatially optimized silvofishery designs can contribute to both ecosystem service provision and climate objectives. This integration of long-term sequestration projections with zonation outcomes distinguishes the present study from prior work and underscores its novelty and policy relevance. Based on the developed dynamic system, annual CO_2 absorption was found to increase with the growth of mangrove plants in each zone, as shown in Figure 5.

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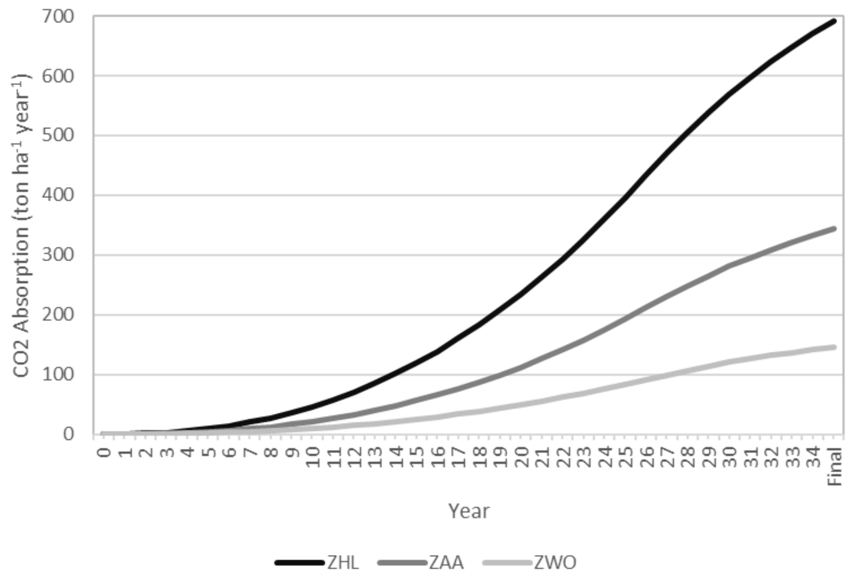

Figure 5. CO_2 absorption estimation per ha per year (Source: Data Processing Results, 2025)

By the year 35, ZHL can absorb up to 671.17 tons of CO_2/ha annually, ZAA up to 332.52 tons /ha, and ZWO up to 141.57 tons /ha. Compared with the other zones, ZHL has the highest annual CO_2 absorption per hectare. This is influenced by the number of mangrove individuals per hectare in this zone because of the high mangrove proportion and denser planting spacing. This result is consistent with the ZHL's primary purpose of maximizing carbon-emission absorption ecosystem services. When compared to research conducted by Henri et. al. (2024), CO_2 absorption in natural mangrove ecosystems can absorb up to 413.02 tons of CO_2 per hectare. This shows that the dynamic system model used can provide a pretty representative projection of the CO_2 emission absorption potential within the mangrove ecosystem. The estimated total CO_2 emission absorption is 7,863,293 tons, as shown in Figure 6. Averaging more than 217 thousand tons of CO_2 absorbed per year indicates that Indramayu Regency's pond area has excellent potential as a CO2-absorbing agent through silvofishery.

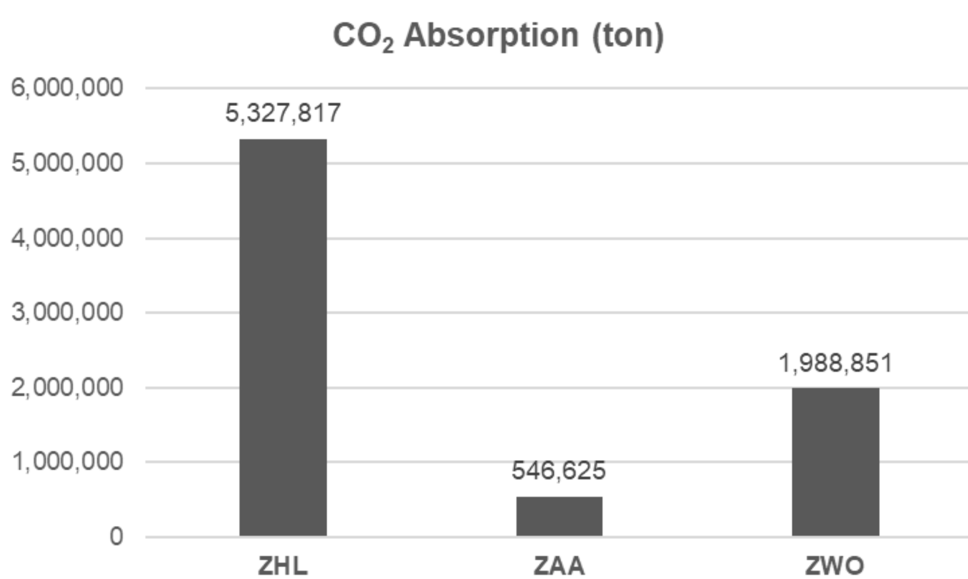

Figure 6. Estimation of total CO_2 absorption for each zone (Source: Data Processing Results, 2025)

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However, several considerations must be noted when using this model, particularly because estimation errors in the developed dynamic system model may accumulate over long horizons. This is primarily because the current model does not fully account for competitive interactions among individual mangrove plants and the subsequent effects of this competition on their growth. Despite the promising results, several limitations of the applied dynamic system model should be acknowledged. The model assumes a constant growth rate and survival probability for mangrove vegetation over the simulation period. In contrast, in reality, mangrove growth is influenced by interplant competition, nutrient availability, hydrodynamic conditions, and management practices.

The current model does not explicitly incorporate competitive interactions between individual mangrove trees, which may lead to overestimation of biomass accumulation and CO_2 absorption over long-term projections. In addition, external disturbances such as extreme weather events, sea-level rise, and changes in pond management intensity were not explicitly simulated, which may affect the robustness of long-term estimates. The results of the dynamic system model are also influenced by several key assumptions that affect the projected CO_2 absorption outcomes. One critical assumption is that a constant 50% mangrove survival rate is applied throughout the 35-year simulation period, in accordance with national mangrove rehabilitation standards. Variations in survival rates due to site-specific environmental conditions, management intensity, or disturbance events could substantially alter trajectories of biomass accumulation and carbon sequestration. Higher survival rates would increase projected CO_2 absorption, while lower survival rates could significantly reduce long-term sequestration potential.

Another critical assumption concerns the use of a fixed diameter increment and a constant wood density for *Rhizophora mucronata*. In practice, growth rates may vary spatially and temporally due to nutrient availability, salinity gradients, hydrodynamic conditions, and competition among individual trees. The assumption of uniform growth parameters may therefore result in simplified projections that do not fully capture natural variability. Consequently, the estimated CO_2 absorption values should be interpreted as potential outcomes under optimal, controlled management conditions rather than as precise predictions. Although a formal sensitivity analysis was not conducted in this study, the discussion of these assumptions highlights that survival rate, growth parameters, and planting density are the most influential factors controlling long-term CO_2 sequestration in silvofishery systems. Future modeling efforts should incorporate sensitivity or scenario-based analyses to quantify the relative influence of these parameters and improve the robustness of policy-relevant carbon estimates.

Beyond biophysical and modeling considerations, the successful implementation of silvofishery systems is strongly influenced by socioeconomic conditions and stakeholder involvement. In coastal regions such as Indramayu Regency, traditional pond owners and local communities are key actors whose livelihoods depend on aquaculture productivity. The adoption of silvofishery designs may be constrained by land tenure arrangements, perceived risks to short-term pond yields, and additional labor or management requirements associated with mangrove maintenance. Without clear economic incentives and institutional support, stakeholders may be reluctant to modify existing pond management practices.

Effective stakeholder engagement is therefore essential to ensure the feasibility and long-term sustainability of silvofishery implementation. Participatory planning approaches involving local communities, pond owners, government agencies, and non-governmental organizations can facilitate knowledge exchange, increase local acceptance, and align ecological objectives with economic priorities. Previous studies have shown that community-based mangrove management and co-management arrangements can enhance compliance, reduce conflicts, and improve restoration outcomes in coastal areas. Integrating such participatory frameworks into silvofishery planning would strengthen the applicability of the proposed design beyond its biophysical performance.

From a policy perspective, the implementation of silvofishery systems may benefit from incentive-based mechanisms, such as carbon financing, ecosystem service payments, or support programs for sustainable aquaculture. Linking silvofishery-based carbon sequestration to emerging blue carbon markets or national climate finance instruments could provide additional economic motivation for local stakeholders. These socioeconomic and governance considerations highlight that the effectiveness of silvofishery as a climate mitigation strategy depends not only on its technical.

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4. CONCLUSION

This study demonstrates that the 'empang parit' silvofishery design using *Rhizophora mucronata* is an effective approach for integrating mangrove ecosystem restoration and aquaculture activities in the coastal area of Indramayu Regency. The results indicate that a zoning-based silvofishery design can simultaneously support ecological functions and maintain the economic value of traditional ponds. The key findings show that the proposed silvofishery design significantly enhances carbon sequestration capacity. The dynamic system simulation estimates an average CO_2 absorption of more than 217 thousand tons per year, with a cumulative sequestration potential of approximately 7.86 million tons of CO_2 by year 35. These results highlight the potential role of spatially optimized silvofishery systems as a blue-carbon-based climate-mitigation strategy in coastal regions.

Based on these findings, future research is recommended to incorporate interplant growth competition and ecological interactions into dynamic carbon models to improve the accuracy of long-term emission-absorption estimates. In addition, comprehensive socioeconomic analyses should be conducted to assess community acceptance, economic feasibility, and governance aspects of silvofishery implementation. Such improvements are essential to ensure that silvofishery designs contribute not only to the sustainability of mangrove ecosystems but also to the long-term well-being of coastal communities.

5. AUTHOR CONTRIBUTIONS

BCT conducted the literature review and provided the data for Table 2; GRA wrote the manuscript and performed all spatial and model analyses. All authors reviewed the final manuscript.

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