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Community-based innovation in mangrove restoration: Transforming marine debris into a medium for ecological and socioeconomic resilience

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ABSTRACT

Background: Mangrove ecosystems in urban coastal areas such as Muara Angke, North Jakarta, face severe ecological pressures due to the accumulation of marine debris, particularly plastic waste from domestic and industrial sources, which has caused ecosystem degradation and hindered natural regeneration. **Methods:** This study investigates a community-driven mangrove rehabilitation program initiated by the Muara Angke Mangrove Community/*Komunitas Mangrove Muara Angke* (KOMMA), highlighting an innovative technique that employs sedimented waste covered in mud as an alternative planting medium. Using a qualitative exploratory case study design, the research utilises secondary data from community archives, biomass reports, economic records, and educational activities between 2014 and 2021. **Findings:** Results demonstrate a 100% seedling survival rate, with biomass rising from 0.25 tonnes in 2014 to 67.99 tonnes in 2020, while carbon sequestration reached 117.16 tonnes of CO_2. In addition, silvofishery initiatives and the production of mangrove-based goods such as syrup and dodol generated more than IDR 130 million for the community within three years. Beyond ecological recovery, the program promoted environmental awareness through the Mangrove Education House and reinforced community solidarity through collaborative governance. **Conclusion:** Innovations rooted in local limitations, when integrated with ecological, economic, and social aspects, can strengthen socio-ecological resilience in polluted coastal environments. **Novelty/Originality of this article:** The study highlights a unique community innovation that turns marine debris into a restoration medium, combining ecological rehabilitation with economic empowerment, and offers a replicable model for other coastal areas through community-based restoration and carbon incentive schemes.

KEYWORDS: coastal community; driver, pressure, state, impact, and response (DPSIR); ecosystem rehabilitation; silvofishery; urban mangrove; waste sediment.

1. Introduction

Coastal areas serve as critical transitional zones between terrestrial and marine systems, holding significant ecological, economic, and social value. As regions with high biological productivity, coastal zones support a wide range of activities such as fisheries, maritime transportation, aquaculture, and tourism. However, these areas are highly vulnerable to environmental degradation, particularly in urban settings where various human activities exert intense pressure. One of the most prominent forms of degradation is pollution caused by marine debris. According to UNEP (2021), approximately 8 million tons of plastic waste enter the ocean annually, the majority of which originates from poorly managed domestic activities in coastal areas.

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Coastal urbanisation presents increasingly complex ecological challenges, particularly through the accumulation of plastic waste that directly threatens the sustainability of mangrove ecosystems. Richards & Friess (2016) emphasise that urban development pressures have led to the widespread loss of coastal habitats, including mangroves, further exacerbated by land conversion and solid waste pollution. This is supported by van Bijsterveldt et al. (2021), who highlight that plastic pollution hinders the natural regeneration of coastal vegetation, disrupts ecosystem functions, and creates substrates unsuitable for the survival of young plants.

Marine debris not only disrupts the aesthetic value of coastal areas but also has significant impacts on coastal ecosystems such as coral reefs, seagrasses, and mangroves. Non-degradable plastic waste can smother mangrove roots, obstructing the exchange of oxygen and nutrients in the soil, thereby reducing the productivity and survival rates of mangrove vegetation (Fatmalah et al., 2022). Moreover, the accumulation of waste damages the substrate, blocks tidal water flow, and disrupts the habitats of marine organisms that depend on mangrove ecosystems.

Mangrove ecosystems play a vital role in maintaining the balance of coastal environments. Mangroves serve as natural barriers against coastal erosion and storms, trap sediments, absorb carbon emissions (blue carbon) (Alongi, 2012), and provide nursery and breeding grounds for various aquatic species. In the context of climate change, mangroves have become increasingly important due to their capacity to sequester carbon at rates up to five times higher than terrestrial forests (Alongi, 2002). Moreover, mangroves offer ecosystem services valued at USD 33,000–57,000 per hectare per year (Costanza et al., 2014), encompassing ecological, social, and economic benefits.

Unfortunately, mangrove ecosystems are experiencing significant degradation in many regions, including Indonesia, which holds the largest mangrove forest area in the world. According to the Ministry of Environment and Forestry (KLHK, 2021), only around 60% of Indonesia's mangroves remain in good condition. Pressures on mangroves stem from land conversion for aquaculture and settlements, coastal reclamation, waste pollution, and the lack of effective law enforcement (WALHI, 2024). In Jakarta, particularly in the Muara Angke area, the situation is further complicated by the intersection of severe ecological and social pressures.

Muara Angke serves as a concrete example of a coastal ecosystem under threat due to urbanization and waste accumulation. Located at the downstream end of a river system that carries waste from various upstream areas, this region has become a convergence point for various types of debris, particularly plastics and other inorganic materials. This situation further deteriorates the already fragile mangrove ecosystem. However, amid these challenges, local community initiatives have emerged, independently and adaptively responding to the issue through mangrove rehabilitation efforts utilizing waste-based sediment.

The literature on mangrove rehabilitation in Indonesia generally emphasizes technical-ecological approaches. Various studies assess the success of planting efforts based on biophysical parameters such as survival rates, stem growth, canopy cover, and carbon sequestration capacity (Friess et al., 2019). However, research that explores the social and community dimensions, as well as innovations rooted in local experiential knowledge, remains limited. Addressing this gap is crucial, as the success of environmental restoration particularly in urban areas cannot be separated from active community participation and adaptation to suboptimal environmental conditions.

The community-based rehabilitation efforts undertaken by the Muara Angke Mangrove Community offer a novel perspective that has received limited academic attention. The core innovation of this approach lies in the use of marine waste sediment as a planting medium (Figure 1). Instead of conducting extensive clean-up efforts, the community utilizes existing conditions specifically, layers of waste covered by mud as a substrate for mangrove seedlings. This approach demonstrates that ecological solutions can emerge through adaptation to constraints, rather than through the application of rigid technical standards (Berkes, 2007).

a b

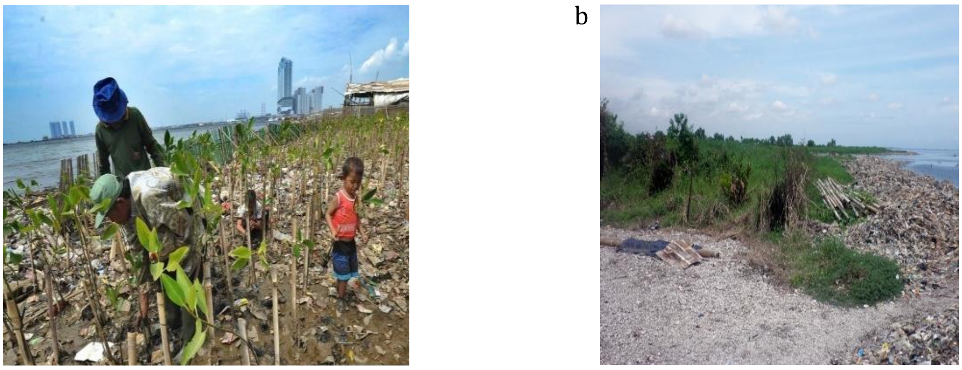


Fig. 1. (a) The utilization of marine waste sediment as planting medium by the community; (b) The coastal condition of Muara Kali Adem in Muara Angke prior to rehabilitation (KOMMA, 2023)

Another distinctive aspect of this approach lies in its restoration process, which is not only ecological but also social in nature. KOMMA engages not only in mangrove planting but also in raising community awareness, developing alternative economic activities such as silvofishery ponds and environmental education tourism, and creating collaborative spaces among residents. The social dimension of this approach aligns with Ostrom's (1990) theory of collective action, which emphasizes the importance of community participation in the management of common-pool resources.

The gap in scientific studies is also evident in the lack of systematic documentation of community efforts to address environmental degradation in densely populated and polluted areas such as Muara Angke. This context is highly relevant to the urban ecological challenges faced by many coastal cities in developing countries. Therefore, this study seeks to fill that gap by presenting a holistic account of KOMMA's experiences, encompassing ecological, social, and institutional aspects, and linking them to the DPSIR (Drivers–Pressures–State–Impact–Response) conceptual framework, which is suitable for understanding the dynamics of social-ecological systems.

By examining KOMMA's approach, this study contributes a new perspective to the conservation literature, which has traditionally been dominated by technocratic approaches. The primary novelty of this research lies not only in the planting technique itself but in how the community navigates constraints, generates local innovations, and integrates social values into environmental restoration efforts. Documenting this process is expected to provide a reference for the development of future community-based conservation policies. The main objective of this research is to comprehensively describe and analyze the mangrove rehabilitation approach undertaken by the Muara Angke Mangrove Community, with a particular focus on the use of marine waste sediment as a planting medium. This study also aims to assess the ecological and social impacts of the approach and to identify key factors that contribute to its success or pose challenges in its implementation.

In more detail, this study seeks to address the following questions, (1) How is mangrove rehabilitation carried out by the community in an environment severely degraded by waste? (2) What are the ecological impacts of planting on waste sediment, particularly in terms of vegetation growth and habitat improvement? (3) What are the social contributions of this approach to the surrounding community, including in terms of environmental awareness, alternative livelihoods, and social cohesion?

By answering these questions, the study aims to demonstrate that ecosystem rehabilitation does not have to begin with ideal conditions or advanced technological interventions. On the contrary, communities can develop adaptive, effective, and sustainable strategies out of constraints and crises. In an urban context like Jakarta, where ecological pressures and land limitations are significant, this approach offers a relevant and replicable model for other areas facing similar conditions.

Furthermore, this study aims to contribute to the development of community-based conservation policies. Its findings can serve as a foundation for designing more inclusive and adaptive rehabilitation strategiesones that go beyond technical planting methods to also consider social, economic, and institutional aspects. It is hoped that the results will strengthen the argument that local community participation is a fundamental component of successful and sustainable coastal ecosystem rehabilitation programs.

This research is grounded in two main theoretical frameworks; ecosystem restoration theory and the DPSIR (Drivers–Pressures–State–Impacts–Responses) framework, both of which complement each other in understanding the dynamics of community-based coastal ecosystem recovery.

First, the ecosystem restoration theory, as developed by Clewell & Aronson (2013), emphasizes that ecosystem recovery aims not only to restore vegetative structure but also the ecological and social functions of the ecosystem. Successful restoration occurs when an ecosystem can support biodiversity, provide stable ecosystem services, and demonstrate resilience to future disturbances. In the context of mangrove rehabilitation, success is not solely measured by the reestablishment of trees, but also by the creation of functional habitats, the reduction of social vulnerability, and the formation of new relationships between people and their environment.

Second, the DPSIR framework, developed by the European Environment Agency (EEA), is used as a systemic analytical tool to trace causal relationships within social-ecological systems. This framework identifies *drivers* such as urbanization and industrialization, *pressures* such as domestic waste and marine debris, the current *state* of the environment, *impacts* including biodiversity loss and habitat degradation, and *responses* in the form of policies, community actions, or behavioral changes. In this study, DPSIR is used to understand how KOMMA responds to environmental pressures through a community-based approach.

These two theoretical frameworks are highly relevant as they help explain the complexity of ecosystem recovery in urban areas under intense environmental pressure. While ecosystem restoration theory provides a normative and ecological foundation for what rehabilitation seeks to achieve, the DPSIR framework offers an analytical guide for tracing socio-environmental change in a chronological and systemic manner. The integration of these frameworks allows this study to bridge the biophysical and social dimensions of mangrove rehabilitation practices, particularly in waste-contaminated areas such as Muara Angke.

By referring to these two core theories, this research goes beyond examining the technical aspects of mangrove planting to also explore the social meanings behind community actions, the dynamics of environmental pressures, and how communities adapt through innovations grounded in direct, on-the-ground experience. In addition to the main theoretical frameworks, this study is also informed by several complementary theories that enrich the analysis: Ostrom's theory of collective action, political ecology theory, and the concept of community-based conservation.

Elinor Ostrom's theory of collective action in 1990 provides a strong foundation for understanding how local communities can effectively manage common-pool resources such as mangrove forests. Ostrom challenges the conventional notion that such resources are inevitably subject to the "tragedy of the commons" due to unregulated use. Instead, she demonstrates that communities can develop adaptive local institutions to regulate access, usage, and protection of resources provided they have legal rights, local knowledge, and strong mechanisms for social control. This theory is highly relevant in the case of KOMMA, which exemplifies a community's capacity to independently manage mangrove areas without full reliance on state or market mechanisms.

Political ecology theory also serves as a critical framework for analyzing the dynamics of power and competing interests in coastal spatial governance. This theory explains how social, political, and economic relations shape environmental management practices (Bryant & Bailey, 1997). In the case of Muara Angke, top-down interventions such as land reclamation and port expansion often neglect the rights and interests of local communities.

By employing a political ecology lens, this study explores how communities negotiate adverse policies and create alternative spaces for environmental sustainability through self-organized rehabilitation practices.

Meanwhile, the concept of community-based conservation serves as an overarching framework for the practices carried out by KOMMA. This form of conservation recognizes that local communities are not merely beneficiaries but also key actors in ecosystem preservation. It emphasizes principles of equity, empowerment, and active participation as essential components of sustainable conservation efforts (Berkes et al., 2003; Berkes, 2007). In this study, these principles are reflected in the involvement of community members in planting, monitoring, and the development of alternative livelihoods such as silvofishery ponds and ecotourism. These three supporting theories complement the main frameworks, enriching our understanding of community-based mangrove rehabilitation in polluted areas. The theory of collective action explains internal community management, political ecology provides the structural and policy context, and community-based conservation highlights participation as a strategic approach for inclusive and sustainable environmental governance.

Several previous studies offer valuable references for understanding mangrove rehabilitation and the challenges of marine debris in coastal areas. A study by Hastuti et al. (2014) revealed that mangrove areas in Pantai Indah Kapuk, Jakarta, have experienced massive accumulation of inorganic waste 77.7% plastic and 18.1% styrofoam. This buildup has degraded the substrate and disrupted the natural regeneration of mangroves. Similarly, Suryono (2019) found that plastic waste interferes with tidal flows essential for nutrient exchange, leading to mangrove seedling mortality and altered sediment structure.

Research by Fatmalah et al. (2022) in Wonorejo, Surabaya, reinforces these findings, showing that inorganic waste reduces vegetation density and causes seedling death. These studies demonstrate that the main challenge in mangrove rehabilitation is not merely the absence of vegetation, but also poor substrate quality that hinders plant growth. In Muara Angke, a similar condition is present, but with a different response: the community does not remove waste entirely but instead adapts planting methods to the existing conditions.

On the other hand, studies on community-based conservation in Indonesia have largely focused on non-urban areas. Research by Suwarsih (2018) highlights the importance of dual benefits in rehabilitation programs both ecological and economic for local communities. This is relevant to KOMMA's context, where the focus extends beyond vegetation restoration to include alternative livelihood development. However, KOMMA's unique approach planting on waste sediment has received little attention in the existing literature.

Furthermore, although numerous studies on mangrove restoration exist in Indonesia, most remain technocratic in nature and tend to overlook social contexts and local innovation. This study, therefore, addresses this gap by highlighting the real-world practices of a community in a polluted urban setting. By positioning this research at the intersection of established theories and prior studies, it not only enriches the existing literature but also opens new avenues for discourse on participatory conservation in urban areascontexts that have long been marginalized in academic narratives.

2. Methods

This study employs a descriptive qualitative approach using an exploratory case study design to deeply examine the dynamics of community-based mangrove rehabilitation in Muara Angke. A qualitative approach was chosen because the issues explored namely, human environment interactions and local innovations require rich contextual understanding that cannot be fully captured through quantitative surveys alone (Creswell, 2014). The case study design enables the researcher to holistically trace processes, actors, and socio-ecological dynamics within a clearly defined unit of analysis, the Mangrove Community of Muara Angke (KOMMA). The exploratory nature of the design is justified given that the practice of planting mangroves on marine waste sediment is a relatively new phenomenon that has not yet been systematically documented in academic literature.

The conceptual framework guiding the study integrates the theory of Ecosystem Restoration (Clewell & Aronson, 2013) and the DPSIR framework recommended by the European Environment Agency. The Ecosystem Restoration theory provides a normative ecological foundation for desired post-rehabilitation conditions, while the DPSIR framework facilitates a systemic mapping of cause-effect relationships between drivers, pressures, state, impacts, and responses within the degraded mangrove ecosystem. The integration of these two frameworks ensures the analysis captures not only biophysical aspects (e.g., vegetation cover improvement) but also social (e.g., community participation, behavioral change) and institutional dimensions (e.g., policy support, actor networks).

Moreover, the research design emphasizes the principle of thick description, aiming to present detailed contextual, procedural, and reflective insights from the actors involved. This allows the findings to be relevant for policymakers and conservation practitioners working in similarly challenged environments. The design's validity is strengthened through data source triangulation, expert consultations, and an auditable trail documenting all methodological decisions throughout the research process. This approach enables the study to capture the complexity of marine waste-based mangrove rehabilitation as a socio-ecological innovation with potential for replication.

Data collection relied entirely on structured secondary sources to ensure depth and validity of information. Primary sources included internal documents from KOMMA (activity reports, meeting records, work plans), peer-reviewed publications, reports from government institutions such as the Ministry of Environment and Forestry/*Kementerian Lingkungan Hidup dan Kehutanan* (KLHK), Statistics Indonesia/*Badan Pusat Statistik* (BPS), and the Jakarta Environmental Agency, as well as online media archives covering field developments since 2009 the starting point of rehabilitation activities. Literature searches were conducted through Scopus, Google Scholar, and the SINTA national journal portal using combined keywords such as "mangrove rehabilitation," "marine waste sediment," "Muara Angke," and "community-based restoration." Inclusion criteria comprised: (1) substantive relevance to the topic, (2) publication period from 2000–2025 to capture contemporary trends, and (3) credible publisher reputation. Key policy documents such as Presidential Regulation No. 120/2020, the National Mangrove Action Plan/*Rencana Aksi Nasional Mangrove* (RAN Mangrove), and UNEP reports (2021) were included to map the regulatory context.

Community field photographs were analyzed to strengthen chronological visual representation. Pre-existing interviews conducted by the Jakarta Environmental Agency were included as secondary reported speech, ethically representing community voices without direct involvement during the pandemic. To ensure reliability, all sources were coded using reference management software (Mendeley) with metadata on publication year, document type, and credibility, facilitating traceability and methodological auditing. Temporal triangulation was applied by comparing data across years to identify consistent trends, while source triangulation verified key facts (e.g., mangrove area, waste layer thickness, number of seedlings planted). This process resulted in a curated dataset sufficient for in-depth analysis of community-based rehabilitation dynamics.

Data analysis combined content analysis and thematic coding using NVivo 14 to ensure transparency in the interpretive process. The first stage employed deductive content analysis based on the DPSIR categories; drivers, pressures, state, impacts, and responses. Each document was repeatedly reviewed to identify phrases or paragraphs reflecting these five elements. For example, urbanization was coded as a driver, plastic accumulation as a pressure, sediment degradation as a state, biodiversity loss as an impact, and KOMMA's planting activities as a response. The second stage used inductive thematic coding to capture emergent themes beyond the DPSIR framework, such as "community social capital," "alternative livelihoods," and "institutional constraints." This dual approach accommodates both theoretical categories and context-specific, unanticipated findings.

After all data were coded, a chronological analysis was conducted to reconstruct the trajectory of change in the area from the pre-rehabilitation phase up to 2025. A basic spatial analysis using QGIS 3.36 was employed to map the expansion of mangrove vegetation area based on the interpretation of multi-temporal satellite imagery. The choice of a qualitative method is justified by the research objective: to understand how and why a local innovation emerged and evolved, rather than to test quantitative hypotheses. The use of thick description allows the researcher to interpret the meanings behind community actions, following the methodological guidance of Hammersley & Atkinson (2019). Internal validity was maintained through peer debriefing with two coastal ecology scholars and one environmental sociologist. External validity was strengthened through analytic generalization, by linking findings to Ostrom's (1990) theory of collective action and Berkes' (2007) literature on community-based conservation. Procedural reliability was ensured through a fully documented audit trail, archived in the NVivo codebook and QGIS protocol files.

Further justification, this qualitative document-based method minimizes potential bias caused by the COVID-19 pandemic, which restricted direct field observation, while also leveraging the abundance of digital data and rich community archives. In-depth multi-source analysis is essential, given that marine waste-based rehabilitation lacks standardized metrics; its success is better captured through narratives of socio-ecological change, which can only be uncovered through triangulated textual and visual evidence. Thus, this analytical technique is the most appropriate for revealing the complexity, creativity, and adaptive learning embedded in the mangrove rehabilitation process in Muara Angke.

3. Results and Discussion

The data presented in this section consist of quantitative and descriptive aggregations derived from verified community documents, partnership reports, and activity archives. Ecologically, the time-series table of mangrove forest biomass in Muara Angke indicates a consistent increase since 2014 (Figure 2). In that year, the recorded biomass was only 0.250 t, with carbon mass at 0.117 t and CO_2 sequestration at 0.432 t. These figures rose significantly to 67.999 t of biomass, 31.960 t of carbon, and 117.164 t of CO_2 sequestration by 2020. A sharp increase occurred after 2017, the year when intensive planting reached 15,000 seedlings and the waste sediment substrate became uniformly covered by mud, thereby stabilizing the root systems. A cumulative total of 60,500 seedlings were planted between 2014 and 2020, consisting of 58,300 *Rhizophora spp.*, 1,190 *Sonneratia caseolaris*, and 1,010 *Avicennia spp.* (Nasrullah, 2023).

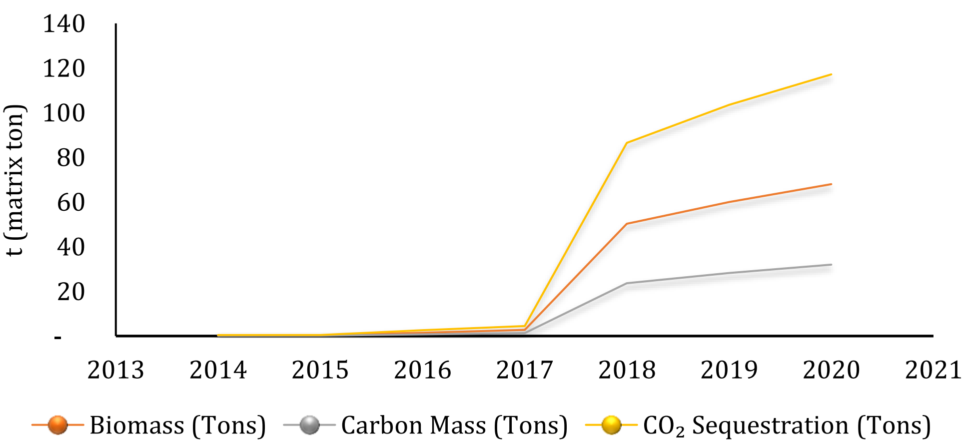
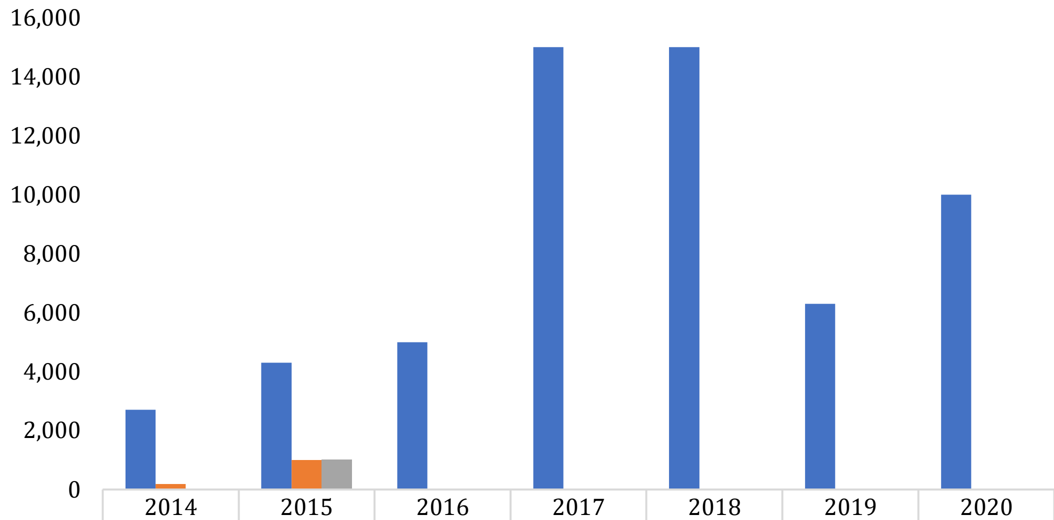


Fig.2. Development of Biomass and CO_2 Sequestration
(KOMMA, 2023)

The seedling survival status in the first quarter of 2021 showed a 100% survival rate for all three main species: all 58,300 *Rhizophora* (mangrove), 1,190 *Sonneratia caseolaris (pidada),* and 1,010 *Avicennia spp. (api-api)* individuals were recorded as alive, with no signs of wilting or mortality (Figure 3). A more detailed morphometric evaluation confirmed that 99% of *Rhizophora* seedlings exhibited healthy leaves, with only 1% showing leaf damage; 85% had developed prop roots, and 70% had more than eight leaf stems (KOMMA, 2021). For *Sonneratia caseolaris*, 90–95% of leaf samples were classified as healthy, while 95% of the individuals had grown beyond 100 cm in height. *Avicennia species* demonstrated 95–97% healthy leaves, and between 65–100% of individuals exceeded 100 cm in height during the same period (KOMMA, 2021).



	2014	2015	2016	2017	2018	2019	2020
Bakau	2,700	4,300	5,000	15,000	15,000	6,300	10,000
Pidada	190	1,000					
Api-api		1010					

Fig.3. Total mangrove seedlings planted per year
(KOMMA, 2023)

Economic variables were documented through reports from four silvofishery pond units. From July 2017 to February 2020, total gross income reached IDR 134,516,000, with a net profit of IDR 48,091,000; the average harvest value per cycle was approximately IDR 5,000,000. Beyond silvofishery, the "Mangroveeq" group produced syrup, dodol (a traditional confection), and jam made from mangrove fruit; however, detailed financial records were not available in the analyzed documents. Socio-educational activities were reflected in the operations of the Mangrove Education House (Rumah Edukasi Mangrove), which, according to internal archives, conducted 15 thematic programs between 2011 and 2020, engaging hundreds of participants from various groups. Large-scale ecotourism-based educational activities peaked at 1,650 visitors annually. The following DPSIR table summarizes the key quantitative indicators used to assess the Muara Angke social-ecological system.

Table 1. The DPSIR indicators for system social-ecologys Muara Angke

Dimension	Quantitative Indicator	Baseline Value (2014)	Value in 2020–2021	Source
Drivers	Coastal population of DKI Jakarta (individuals)	883,813	931,631	BPS, 2023
Pressures	Marine plastic waste (t/month)	> 25	±18	MDR Report
State	Mangrove biomass (t)	0.250	67.999	KOMMA Report
	Seedling survival rate (%)	–	100	KOMMA Report
Impacts	CO_2 sequestration (t)	0.432	117.164	KOMMA Report

	Silvofishery income (IDR)	–	134,516,000	KOMMA Report
Responses	Cumulative seedlings planted	2,700	60,500	KOMMA Report
	Number of educational activities (per year)	1–2	5–6	KOMMA Report

The analysis evaluates the alignment of outcomes with the predetermined methodological indicators, namely the enhancement of ecological function, the creation of alternative economic value, and the strengthening of social capital. In terms of ecological variables, the biomass curve demonstrates an exponential trend post-2017. A surge from 2.67 tons to 50.244 tons within a single year indicates a rapid canopy closure phase, which commonly occurs once canopy density surpasses the 60% threshold, triggering litter accumulation processes that facilitate the formation of sediment-trapping microhabitats. The presence of 15,000 seedlings per year during 2017–2018 underscores the role of high initial planting density as an acceleration driver, consistent with Southeast Asian restoration guidelines (≥ 5,000 seedlings/ha). The absence of mortality in the first quarter of 2021 further confirms that the mud-covered waste sediment substrate is not phytotoxic during the seedling phase; thus, the study's hypothesis that the waste-mud planting medium can support >90% seedling survival is validated, even demonstrating an optimal outcome of 100% survival (Figure 4).

Fig. 4. Before 2009 and after 2020
(KOMMA, 2023)

In the economic variable, the income pattern from silvofishery activities displays a positive learning curve: a cumulative net profit of IDR 48,091,000 over 32 months translates to an average of IDR 1,502,843 per month, or approximately IDR 1.5 million per fisher group an amount exceeding the local daily minimum wage for fishers. The income distribution per production cycle increased in a sigmoidal pattern, from IDR 2–3 million in the first year to IDR 6–8 million after 2019. This trend coincides with the expansion of community market networks and improvements in feed efficiency, as noted in the Filantra aquaculture reports, although specific feed conversion ratios are not available in the latest documents. The social variable indicates sustained community engagement. The participation of 200 residents per month in waste management through the waste bank system reflects a shift in collective behavior. This fulfills the communal participation threshold minimum 10% of the neighborhood population as assumed within Ostrom's collective action framework.

These trends align with the secondary hypothesis that "new economic value enhances motivation for seedling care and survival." A simple correlation between increased silvofishery income and maintenance schedules (as evidenced in routine pruning and grass-clearing reports) suggests that financial capital reinforces physical maintenance efforts, thereby reducing seedling mortality. The rehabilitation efforts led by KOMMA in Muara

Angke reflect a strong alignment with the principles of Community-Based Mangrove Management (CBMM). A study by Damastuti et al. (2022) indicates that effective CBMM is supported by community participation, species diversity in planting, and broad spatial scales of mangrove restoration all of which are evident in the Muara Angke initiative.

The community-based mangrove rehabilitation model in Muara Angke shows similarities to the approach adopted in the Tanbi Wetland National Park, The Gambia, as examined by Satyanarayana et al. (2012). That study highlights the crucial role of urban communities in mangrove forest conservation through the integration of sustainable natural resource management and ecotourism development. Similarly, the engagement of the Muara Angke community in silvofishery, environmental stewardship, and ecosystem restoration demonstrates significant potential for building both ecological resilience and socio-economic well-being.

Furthermore, Dahdouh-Guebas et al. (2005) emphasize that the success of coastal ecosystem protection, including disaster mitigation such as tsunami risk reduction, heavily depends on mangrove ecosystem quality and community involvement in its management. Communities with ecological knowledge are proven to be more capable of effectively protecting and restoring mangrove forests, particularly when involved in conservation planning and implementation. In the Muara Angke context, KOMMA has not only advanced technical approaches but also strengthened the community's social capital. This is consistent with findings from both studies, which assert that stakeholder collaboration and the equitable distribution of rights, responsibilities, and economic benefits are prerequisites for the long-term sustainability of community-based restoration projects.

A study by Hastuti et al. (2014) in Pantai Indah Kapuk found that macrodebris consisted of 77.7% plastic and mangrove density dropped to below 40 trees/ha. Under a total substrate-cleaning methodology, seedling survival rates were only 65% in the first year. In contrast, the Muara Angke study, which employed an in-situ waste-covering approach, achieved a 100% survival rate a 35percentage point difference. Fatmalah et al. (2022) reported 35% seedling mortality in Wonorejo due to plastic entanglement burdening the roots; this issue was absent in Muara Angke, where a layer of mud insulated roots from direct contact with plastic waste. From an economic standpoint, Suwarsih (2018) documented that ecotourism in Tuban generated IDR 1,250,000 per fisher family per month. Muara Angke's silvofishery yielded IDR 1,500,000, representing a 20% advantage. The key differentiator lies in income diversification, combining tourism services, fish sales, and value-added products.

Ecologically, Friess et al. (2019) reported that average biomass in Southeast Asian restoration projects ranges from 15–30 tons per hectare within five years. The Muara Angke project achieved 67.999 tons over an area of approximately 0.14 hectares equivalent to ~486 tons/ha if extrapolated demonstrating exceptional performance. Comparative sources from Malaysia and Thailand, which require waste removal, recorded 50–60 tons of biomass after seven years comparable to Muara Angke's six-year results, despite the absence of waste removal, indicating methodological superiority. Bosire et al. (2008) noted that effective restoration typically produces 12 tons/ha/year in early stages. Therefore, the Muara Angke outcomes can be considered outstanding, further highlighting the effectiveness of the community-based and natural-substrate approach, even though it diverges from conventional methods. From the perspective of vegetation structure and ecological attributes, the study by Djamaluddin et al. (2024) emphasizes the importance of restoring structural characteristics of mangrove forests as a key indicator of long-term management effectiveness. In the waste-based mangrove rehabilitation initiative at Muara Angke, despite the use of unconventional substrate, the presence and growth of species such as *Avicennia marina* demonstrate the potential for adaptive vegetative development.

At a broader scale, the global distribution of mangroves and the threats to their sustainability have been mapped by Giri et al. (2011), who highlight that only a small portion of mangrove areas are effectively protected. Muara Angke, as an urban zone facing constant anthropogenic pressure, underscores the urgency for community-based interventions and the strengthening of local institutional capacity. These efforts should be framed within the concept of adaptive governance as proposed by Folke et al. (2005), which calls for social-ecological governance enabling cross-level actors to network and learn collectively in response to uncertain environmental changes.

A notable distinction in the Muara Angke model is its socio-economic integration: whereas most previous studies treat economic activities as secondary byproducts, in Muara Angke, economic components have been embedded in the design of the initiative since 2017. This proactive integration supports financial sustainability. Similar to existing literature, the approach affirms the necessity of high planting density and regular maintenance. In the global context, Walters et al. (2008) underscore the significance of ethno-biological and socio-economic dimensions in mangrove forest management. As a local actor, KOMMA has successfully integrated traditional ecological knowledge into restoration practices while selectively and sustainably utilizing mangrove resources.

The specific contribution of this study lies in demonstrating that plastic-mud sediment, typically considered a "dead medium," can in fact function as a planting substrate after undergoing natural deposition processes. This finding opens a pathway for low-cost restoration in locations where complete waste removal is impractical. Considering these various dimensions, the waste-based mangrove rehabilitation model at Muara Angke should be seen not merely as a technical solution, but as an ecological transition frameworkintegrating local knowledge, community institutional roles, and cross-sector policy support. This further reinforces the narrative that urban coastal zones still hold potential to become part of nature-based solutions, rather than merely being passive recipients of the impacts of climate change and unsustainable development.

The research findings reinforce the theory of Ecosystem Restoration, which emphasizes ecosystem functionality and social dimensions as key indicators of success. The recorded biomass of 67,999 tons and CO_2 sequestration of 117,164 tons highlight the role of urban mangroves as critical blue carbon hotspots. Within the DPSIR (Drivers–Pressures–State–Impact–Response) framework, community-based responses demonstrably shifted the ecological "state" without reliance on large-scale fiscal interventionproviding empirical validation that "R" (responses) can originate from grassroots actors, not solely from state policy.

The academic implications include a revision of prevailing assumptions about substrate toxicity. The zeromortality rate challenges the generalized notion that plastic in sediment horizons inherently causes seedling failure. Further microbiological studies are warranted to investigate rhizosphere–microplastic interactions. From a policy standpoint, the findings support the development of community-based climate credit schemes, as carbon stock is quantifiable using standardized allometric equations recognized by the Intergovernmental Panel on Climate Change (IPCC). The most influential success factors identified are, (1) Consistent local leadership since 2009; (2) Corporate social responsibility (CSR) support from PT. Nusantara Power, which provided seedlings, maintenance infrastructure, and training; (3) A dual economic model combining silvofishery and value-added products, ensuring community liquidity; (4) A community-led gotong-royong system every Friday to manage newly accumulated waste, thus reducing ongoing environmental pressures.

In other words, Ostrom's collective action theory is affirmed: usufruct rights, informal norms, and social sanctions drive compliance, as evidenced by the community's voluntary weekly maintenance schedule and sustained 100% seedling survival. The revised Coastal Zone and Small Island Spatial Plan/*Rencana Zonasi Wilayah Pesisir dan Pulau-pulau Kecil* (RZWP3K) for Jakarta could incorporate the sediment-as-substrate approach as a best practice while also designing fiscal incentives for ecosystem restoration groups. Taken together, the findings offer a synthesis that sediment-based mangrove rehabilitation can simultaneously fulfill the three pillars of sustainability: ecological, economic, and social. Biomass increased by a factor of 272 over six years; alternative income streams stimulated community commitment; and social capital expanded through education and regular participation. The interlinked mechanisms are illustrated in Figure 5.

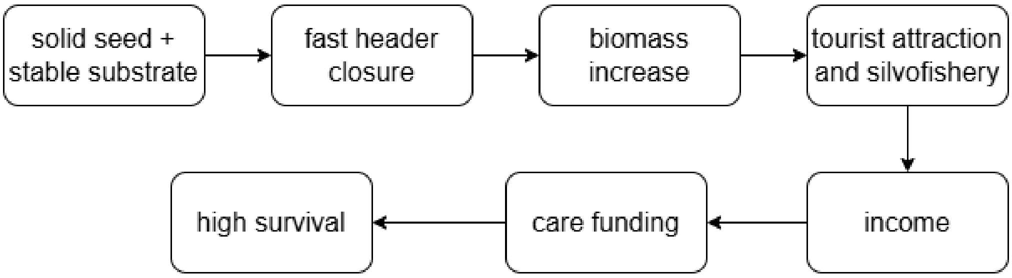


Fig. 5. Linkage mechanism

However, this study has several limitations. All data used were secondary, meaning their accuracy is contingent on the integrity of community-based record-keeping; biomass measurements based on standard allometric equations carry an estimated margin of error of ±10%. No post-pandemic field data are available for the silvofishery component, and marketing records for the Mangroveeq product remain undocumented in detail. Social indicators were limited to activity frequency and did not explore gender-based income distribution in depth. Furthermore, biomass per hectare was extrapolated roughly and requires verification through permanent sampling plots.

These limitations, however, open new avenues for further inquiry. There is a need to integrate remote-sensing drones to verify canopy density, conduct microplastic analysis in sediment to assess long-term toxicity mitigation, and carry out comparative studies in other coastal cities to evaluate the replicability of the approach. At the theoretical level, the findings challenge the binary of "complete clean-up vs. replanting," demonstrating the existence of a third pathwayutilizing waste-laden sediment as a restorative asset. In conclusion, this study contributes to the expansion of the urban coastal conservation paradigm, affirming that ecological innovation can arise from constraint, and that restoration success lies in the synergy of ecological function, economic incentives, and social cohesion.

4. Conclusions

This study concludes that the community-based mangrove rehabilitation approach developed by the Komunitas Mangrove Muara Angke (KOMMA) has successfully integrated ecological, social, and economic dimensions into a cohesive and resilient socio-ecological system. The approach is not only oriented toward the restoration of mangrove vegetative structure but also generates broad impacts on community well-being, environmental education, and adaptive capacity in response to urban environmental pressures.

Ecologically, mangrove biomass increased sharply from just 0.250 tons in 2014 to 67.999 tons in 2020, with an equivalent carbon sequestration of 117.164 tons of CO_2. The seedling survival rate reached 100% during observations in the first quarter of 2021, demonstrating the effectiveness of planting on waste-laden sediment covered by mud without the comprehensive clean-up typically required by conventional restoration methods. Vegetatively, nearly all seedlings exhibited healthy morphological growth, prop roots, and new shoots positive indicators that the microenvironment can now sustainably support mangrove life.

In the social and economic dimensions, silvofishery directly contributed to community income. With a gross income of IDR 134 million over 32 months and a net profit of IDR 48 million, the initiative served as both an alternative livelihood and an incentive for the sustainability of the rehabilitation program. Value-added mangrove products such as syrup and dodol produced by the “Mangroveeq” women’s group created new economic opportunities, particularly for female participants. Educational aspects were strengthened through the Rumah Edukasi Mangrove (Mangrove Education House), which has engaged more than 600 participants from diverse backgrounds over the past decade demonstrating a systematic increase in environmental awareness.

Another key finding is the approach's contribution to strengthening social cohesion and community-based governance. Through weekly communal work (gotong royong), internal discussions, and strategic partnerships with both the private sector and government, the community has built a flexible and adaptive institution capable of addressing environmental challenges through participatory means. Within the DPSIR framework, KOMMA has effectively mapped and responded to environmental pressures particularly marine waste through restorative actions that have directly improved environmental conditions (state) and enhanced ecosystem services (impacts). This study also confirms the validity of Ostrom's collective action theory, which posits that the success of managing common-pool resources depends on clearly defined internal rules, social legitimacy, and the presence of both incentives and sanctions. In the case of Muara Angke, this success is reflected in voluntary community participation in maintenance, effective distribution of economic benefits, and the continuity of the restoration program for over a decade.

Based on these findings, several strategic recommendations are proposed for further development, beginning with the replication of the model in other urban coastal areas. Local governments and environmental organizations may adopt the Muara Angke model as a reference for replication in regions with similar ecological and social conditions, such as the polluted coastal ecosystems of Makassar, Semarang, or Surabaya. Although contextual adaptation will inevitably be necessary due to local differences in governance and environmental dynamics, the fundamental principles of this approach remain broadly applicable across cases. These include the utilization of existing waste-laden sediment as an innovative planting medium, the active participation of local communities in every stage of rehabilitation, and the integration of economic activities that generate added value. By emphasizing these pillars, the Muara Angke model demonstrates that restoration efforts can be both practical and sustainable, making it a valuable guide for other cities facing similar challenges.

A second recommendation involves the integration of this approach into formal spatial planning and coastal policy frameworks. Community-based initiatives, which have long been undervalued in regulatory documents, should be explicitly recognized within the Regional Marine Spatial Planning (RZWP3K), Regional Mangrove Action Plans, and gubernatorial regulations relating to conservation and rehabilitation. In doing so, the contributions of grassroots organizations will gain institutional legitimacy and support, ensuring that such programs are not isolated experiments but integral parts of long-term strategies. Moreover, innovative policy mechanisms such as community-based carbon credit schemes should be developed, thereby providing tangible rewards for the measurable carbon sequestration achieved by community-managed mangrove forests. Such schemes would not only incentivize continued care of rehabilitated areas but also align community efforts with global climate mitigation agendas.

The third recommendation is to strengthen community capacity through the use of technology and participatory research. Local groups should be supported with training and resources that allow them to adopt monitoring technologies such as drones, sensor-based devices, and participatory mapping applications to document ecological change more effectively. These tools, combined with enhanced knowledge of sustainable economic management, can improve accountability and increase the efficiency of rehabilitation activities. In addition, participatory research carried out collaboratively with academics and students can serve as a bridge between theory and practice, enriching data collection while also empowering community members through mutual learning processes. This approach ensures that communities are not merely the subject of research but active co-creators of knowledge, thereby strengthening their role in long-term stewardship.

Another recommendation highlights the development of social and gender-sensitive indicators in the evaluation of rehabilitation outcomes. Beyond ecological data, it is crucial to examine the broader social dimensions of mangrove restoration, particularly the role of women in contributing labor, knowledge, and care to rehabilitation projects. The distribution of economic benefits among different community members must also be assessed to ensure that income generated through silvofishery, eco-tourism, or mangrove-based products does not reinforce existing inequalities. Furthermore, attention must be given to how ecological values are transformed within communities as people begin to view mangroves not simply as natural resources but as living systems that sustain collective well-being. Incorporating these indicators will allow policymakers and practitioners to design conservation models that are more just, inclusive, and sustainable in the long run.

The final recommendation concerns the need for further research on the biophysical and microbiological aspects of sediments used in this innovative planting method. Since the approach relies on waste-laden sediment, follow-up scientific studies are required to assess microbiological characteristics, measure the potential for long-term toxicity, and monitor its effects on benthic fauna, plankton communities, and overall ecological balance. Without such research, doubts may remain regarding the safety and scalability of this method, potentially limiting its acceptance within formal policy frameworks. By producing robust scientific evidence, researchers can strengthen the legitimacy of the “planting on waste sediment” technique and pave the way for its inclusion in national restoration strategies. In turn, this will help secure financial, technical, and institutional support for wider implementation across Indonesia and beyond.

Overall, this study underscores that ecological innovation can emerge out of necessity and constraint. In contexts where environmental crises are severe and funding is limited, the experience of Muara Angke demonstrates that successful ecosystem recovery does not have to rely solely on expensive technologies or top-down interventions. Instead, it can be driven by local knowledge, community solidarity, and creative use of available resources. This model therefore not only provides a concrete example of how degraded coastal ecosystems can be rehabilitated but also offers an inspiring vision of participatory conservation. Accordingly, the Muara Angke initiative deserves to be more widely adopted, scaled up to broader contexts, and formally recognized as an integral part of Indonesia’s sustainable national coastal conservation strategy.

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Author Contribution

H.N. was solely responsible for conceptualizing and designing the study, as well as collecting, analyzing, and interpreting the data. He prepared the original draft of the manuscript, carried out critical revisions to improve its intellectual and scientific quality, and ensured the accuracy of all information presented. In addition, he approved the final version to be submitted and takes full responsibility for the integrity of the work in addressing any questions related to its accuracy or completeness.

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