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| Literature Review

Role of Mangrove Ecosystem in Mitigating Climate Change: A Review

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Abstract: The mangrove ecosystem can absorb and store organic carbon higher than other ecosystem, significantly mitigating climate change. Unfortunately, a large portion of mangrove areas has been deforested, degraded, or converted to other land uses, leading to a significant increase in greenhouse gas emissions. This article presents a review of mangroves' role in the cycle of carbon, the mechanism of carbon storage (blue carbon), greenhouse gas emissions, other gases (methane and nitrous oxide), and the support of the ecosystem for adaptation and resilience on the beach. This review method involves analyzing the scientific literature and reporting policy from 2000 to 2024. The results show that mangroves can keep carbon up to 1,023 Mg C/ha in sediment, with a level of accumulation of 1.5–3.0 Mg C/ha/ year. In addition, mangrove management and restoration can reduce equivalent CO_2 emissions by up to 10–25% in coastal tropical zones. Implementing policies and mechanisms in the payment service ecosystem is key to maximizing potential mangrove mitigation.

Keywords: Mangrove; Blue Carbon; Climate Mitigation; Carbon Storage; Policy Environment

1. INTRODUCTION

Climate change is characterized by increased global temperatures, rising sea levels, and an increase in the frequency of extreme weather events, which has become the most urgent environmental issue of the century (IPCC, 2019). Changes in the global climate are characterized by increasing greenhouse gas concentrations (GHG) to an average of 1.1 °C above the pre-industrial era, which has triggered a shift in climate and a rise in sea levels in various coastal areas (IPCC, 2019). One of the primary strategies for mitigating the impact of climate change is enhancing carbon storage in natural ecosystems. Mangrove ecosystems, which are found across tropical and subtropical regions, are among the most efficient carbon absorbers.

Mangroves grow in tidal areas rich in organic material and exhibit high productivity, as well as the ability to retain carbon in the soil for an extended period. Its potential as an ecosystem blue carbon makes it a key element in mitigating climate change based on nature (nature-based solutions). Natural climate solutions (NCS) for addressing climate change involve conserving, restoring, and enhancing land management practices that either boost carbon sequestration or prevent greenhouse gas emissions across ecosystems such as forests, wetlands, grasslands, and farmlands (Griscom et al., 2017). Due to their substantial carbon reserves and the

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significant emissions released upon their conversion, preserving and restoring mangroves represents a highly effective NCS.

The mangrove ecosystem, as a transition area between land and sea, plays a crucial role in absorbing and storing organic carbon (known as blue carbon) in both biomass and sediment to depths of several meters. A decade-long study's final results show that mangroves are capable of retaining carbon sediment up to 1,200 Mg C/ha and sequestering 1.5–3.0 Mg C/ha/year, exceeding the rate of accumulation in tropical forests (Kauffman et al., 2020; Adame et al., 2021). In addition to CO_2 mitigation, mangrove restoration has also been reported to lower equivalent CO_2 emissions by up to 20–25% in coastal zones, improving the ecosystem's stock carbon and recovery function (Friess et al., 2016; Alongi, 2014). However, the pressure anthropogenic, such as conversion land and pollution, causing mangrove degradation 1–2% per year, so that required policies and mechanisms financing based on service ecosystems (REDD+, blue carbon markets) for conservation and restoration sustainable (Richard et al., 2016; Griscom et al., 2020). This article will discuss the role of mangroves in mitigating climate change, including their carbon absorption capacity, the role of the role in protecting against disasters, and the impact on social and economic aspects. This Review Method uses a systematic approach, choosing journals, IPCC reports, and national environmental agencies. The criteria for inclusion cover publications between 2000 and 2025, which discuss the role of mangroves in the carbon cycle and policy mitigation.

2. CAPACITY CARBON STORAGE

The mangrove ecosystem can store carbon beyond its normal capacity, making it a crucial component in the mitigation strategy to combat climate change. Carbon is stored in various compartments, including biomass (top, stem, and leaves), biomass in the lower soil (roots), and especially in rich soil organic matter (Curtis et al., 2016). The mangrove ecosystem stores carbon in biomass and sediment. Mangrove sediments can store up to 1,023 Mg C/ha, far exceeding the capacity of tropical forest land (Donato et al., 2011). A study in Banda Aceh (Dewiyanti et al., 2019) reveals that mangrove biomass comprises stems at 117.9 tons/ha, roots at 47.2 tons/ha, and dead wood at 2.2 tons/ha. The carbon stored is 55.43 tons/ha (stem), 22.17 tons/ha (root), and 1.04 tons/ha (wood). In the other coastal areas of Banda Aceh, the average biomass reaches 1,450.18 kg/100 m² with storage carbon of 68.16 tons/ha (Farahisah et al., 2025). Another study in Myanmar found that mangrove forests had an average carbon storage capacity of 100.34 ± 50.70 Mg C/ha for biomass above ground and 34.76 ± 16.59 Mg C/ha for biomass below ground (Win and Lin 2023).

Mangrove soil stores a large part of the carbon in the ecosystem. Research in Thailand shows that carbon-rich land contributes 74% to 90% of the total carbon in the ecosystem, with total carbon estimates ranging from 650 to 829 Mg C/ha (Hu et al. 2024). Global studies confirm that carbon-rich organic soils can contribute between 50% and almost 100% of the total mangrove carbon stock and can persist for centuries to thousands of years (Alogi et al., 2020; Kauffman et al., 2020).

Research in Indonesia indicates that preserved mangrove forests have a higher carbon stock than rehabilitated forests. In Biduk-Biduk, the stock carbon reached 1,266,997.73 Mg C, whereas in the rehabilitation areas, such as Pati and Indramayu, the stock carbon ranges between 2,878.31 and 43,885.63 Mg C (Alfiati et al., 2024). In Pasarbanggi, Rembang, Central Java, the restored mangrove ecosystem has a total stock potential carbon of 0.02 × 10^6 Mg C, with approximately 65% of the carbon stored in sediment (Soeprobowati et al., 2024). The production of mangrove roots is important for carbon accumulation in lowland areas. Globally, production of mangrove roots reaches an average of about 770 ± 202 g biomass dry /m²/ year, close to the production of the most productive tropical forest (Arnauld et al., 2023). This contributes significantly to the carbon buried in mangroves. Mangrove restoration can significantly increase the capacity for storing carbon. In Dongzhai Harbor, Hainan, China, mangrove restoration increased the regional carbon stock by 210,001.68 tons between 2015 and 2021, with a 97% increase attributed to ecological restoration. The average carbon stored reached 443 tons per hectare (Zhu et al., 2024). Thus, the mangrove ecosystem can store high carbon, especially in the land, making it an important tool in mitigating climate change. Mangrove conservation and restoration efforts are crucial to maximizing potential. Thus, the mangrove ecosystem can storage high carbon, especially in the land, making it a tool in mitigation change climate. Mangrove conservation and restoration efforts are very important.

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3. ROLE IN DAMPEN THE IMPACT OF EXTREME CLIMATE

Mangroves also function as a protective feature for the coast. Roots and structure of mangrove vegetation dampen the energy waves, hold sediment, and reduce erosion on the beach. During the 2004 tsunami disaster, areas with mangrove forests showed more damage than those without mangrove cover (Alongi, 2008). Mangrove ecosystems protect coastal areas from the impacts of extreme climate events, including tropical storms, high waves, and tidal flooding. Structure dense roots and a crown capable of dampening energy waves and reducing tall waves that reach land. Studies show that mangrove forests can reduce the height of tall waves by up to 66% in every 100-meter-wide forest, depending on the density and structure of the vegetation (Wei et al., 2025). In addition, mangroves also contribute to mitigating the economic consequences of storms. Global analysis reveals that coastal areas with greater mangrove cover have experienced a greater loss of economic activity following tropical storm impacts compared to areas with less mangrove cover (Bao, 2011).

However, the effectiveness of mangroves in mitigating the impact of climate extremes can be influenced by various factors, including water depth, type of vegetation, and wave conditions. Recent studies highlight the need for an adaptive approach in managing and protecting coastal ecosystems, considering the variability of the environmental conditions and challenges of changing climate (NIH, 2021; Khan et al., 2023; Jhonson et al., 2025). Overall, mangrove conservation and restoration are important strategies for mitigating the impact of climate extremes and providing adequate protection for the natural resources of coastal communities.

4. SOCIAL AND ECONOMIC CONTRIBUTIONS

Mangroves provide a source of important Power, such as fish, crab, honey, and wood burning. For the coastal community, the existence of mangroves means a sustainable economy. In mitigation, mangroves can also be integrated into the scheme, trading carbon and providing environmental services, thereby incentivizing the public to protect the ecosystem (Uddin et al., 2019). The mangrove ecosystem provides a significant contribution to the welfare of the social and economic public (World Bank 2021). This covers the provision of Power, nature development, ecotourism protection, and income improvement through various economic activities based on mangrove ecosystems.

Mangroves provide various sources of power that support the livelihood of the public on the Coast. Products such as wood, wood construction, charcoal, honey, fish, crabs, and shellfish are utilized in mangrove forests by the community (Lin and Lu, 2024; Rahmawaty et al., 2019; Widodo et al., 2015). For example, on Gusung Island, District Bontoharu, Regency of Selayar Archipelago, the value of the economy from the utilization of wood burned reached Rp. 3,679,000, fish Rp. 168,557,000, and crab of Rp 77,504,000 (Sribianti et al., 2017). In addition, mangroves are an important habitat for various fish and invertebrate species, supporting traditional fishery and cultivated ponds. Healthy mangrove ecosystems enhance fisheries productivity, contributing to resilience, food security, and the local economy.

The uniqueness of the mangrove ecosystem and its diversity of life make it a destination for interesting ecotourism. Activities such as tour education, nature photography, boat rentals, and bird observations are emerging in various coastal areas (Vanderkop et al., 2015; Riaz and Shah et al., 2019). The development of mangrove ecotourism not only increases public income by providing local services and products but also promotes environmental preservation. For example, in some areas, mangrove ecotourism has become society's primary source of income, creating jobs as guides, artisans, and managers of tourism facilities (Das and Mukrejee 2020). Mangrove forests function as natural fortresses that protect coastal areas from natural disasters like abrasion, tidal waves, and storms. Structure mangrove roots and crowns dampen energy waves, reduce erosion on the beach, and prevent seawater intrusion into the land. In Pekalongan City, the valuation of the mangrove ecosystem indicates that the loss of mangroves can result in a loss of approximately Rp. 13,664.7 billion for settlements and Rp 24,096.275 billion for fishery ponds (Sarastika 2017).

Mangroves have marked important cultural and educational value. Many local communities possess traditional wisdom in mangrove management, which has been passed down from generation to generation. In addition, mangroves become a location for research and an educational environment, thereby improving public awareness about the importance of conserving the coastal ecosystem (Wood and Vance 2016). Valuing the economy to support the mangrove ecosystem aids in informed policy decisions and development planning (Iskandar et al., 2023). With an evaluated mark economy from service arrangements, provision, and culture provided by mangroves, the government, and stakeholders, conservation and sustainable utilization strategies

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can be designed to meet their interests. For example, the approach valuation economy used for cost replacement from service protection provided by mangroves, which can reach a high mark in some countries, such as Thailand, with an estimated value between USD 10,158 and USD 12,392 per hectare (Ariesta and Harini, 2019). Overall, the mangrove ecosystem makes a broad social and economic contribution to the public Coast. Therefore, the preservation and management of mangrove sustainability are essential to support the community's welfare and the environment's resilience.

5. THREATS AND CHALLENGES

Although the benefits are considerable, mangroves are facing pressure from land conversion, cultivation ponds, and coastal development. Approximately 35% of the world's mangroves have been lost over the last 30 years (IUCN, 2020). For this reason, mangrove protection, restoration, and integration in a policy framework such as REDD+ are crucial. Although Indonesia has the largest mangrove ecosystem in the world, its management faces various complex challenges.

Management in Indonesia involves various government agencies, such as the Ministry of Environment and Forestry (KLHK), the Ministry of Maritime Affairs and Fisheries (KKP), and the Restoration Agency for Peat and Mangrove (BRGM). As much as 79% of the mangrove ecosystem is in the area under the authority of KLHK and BRGM, while the remaining 21% is outside the area under KKP's authority. Overlapping authority. This often makes implementing conservation policies and programs difficult. The Design Regulation Government (RPP) on the Protection and Management of the Mangrove Ecosystem has been discussed since 2022, but has not yet shown significant progress (Kurniawansyah et al., 2023). This RPP is criticized because not yet accommodated public involvement in mangrove management and tends to be centered on the state. In addition, this RPP lacks a clear policy position for protecting the mangrove ecosystem from a government extractive approach with industry-oriented implications. Some chapters in the RPP even legalize the conversion of mangrove ecosystems. Another weakness is sanctions on perpetrators of mangrove destruction, which is only a natural administrative action and considered too light) (Subambang et al., 2024). Mangrove rehabilitation efforts driven by the government often conflict with planned project reclamation and the expansion of mining activities. WALHI data records that the project exists in Indonesia, covering an area of 79,348 hectares, and will continue to be built, covering an area of 2,698,734.04 hectares. In addition, the expansion project, particularly in oil and gas mining and sand extraction, covering an area of 12,985,477 hectares, contributes to worsening mangrove conditions. Mining Nickel in the Sulawesi and North Maluku regions also accelerates mangrove damage (Salampessy et al., 2024).

Achieving mangrove restoration targets on a large scale faces significant obstacles, including finding and accessing suitable areas in a biophysical sense, as well as overcoming socio-economic challenges. Although nine provinces target areas with potential for extensive restoration, identifying socially suitable coastal areas for restoration is challenging. This is because planting on the coastline is a space that is not suitable for long-term mangrove growth. The survival rate after large-scale restoration has been reported, for example, in the Philippines, where the continuity of life term length is 10-20% of planted mangroves (Malabrigo, 2021).

Data discrepancies exist regarding the broad mangrove ecosystem in Indonesia between the Central Bureau of Statistics (BPS) and the National Mangrove Map (PMN). BPS noted vast mangrove forests of 2,320,609.89 hectares, while PMN recorded more than 3,364,080 hectares. This data discrepancy reveals inconsistencies in management information that can hinder the planning and implementation of conservation programs. Effective mangrove management requires the involvement of the public, local stakeholders, and recognition from the local community (Rumarhorbo et al. 2019). However, in practice, many policies and programs have not been fully accommodating in terms of their role as well as the community. For example, in Jayapura, Papua, mangrove forests are managed

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by women. The ethnic group Enggros faces a serious threat to their development and cultural heritage, despite their rich culture and social values (Salsabilla and Soertikanti, 2024). Thus, mangrove management in Indonesia requires a holistic and inclusive approach, involving the interests of various stakeholders, as well as strengthening regulations and enforcement laws to ensure the sustainability of the mangrove ecosystem.

6. IMPLICATIONS OF MANGROVE POLICY IN INDONESIA

Indonesia has developed various policies to protect and manage its power sources, given its status as a country with the world's largest mangrove ecosystem. However, the implementation policy faces complex challenges. The Indonesian government has set ambitious targets for rehabilitating 600,000 hectares of mangroves by 2024. This target is twofold: 200,000 hectares through community planting and 400,000 hectares through the sustainable management of mangrove landscapes, including the protection of intact mangrove areas by strengthening regulations and empowering the community (Sasmito et al., 2023). The government formed a Restoration Agency for Peat and Mangrove (BRGM) through Regulation President Number 120 of 2020 to support this. BRGM is tasked with facilitating mangrove rehabilitation and restoring land peat. In addition, the Regulation President Number 82 of 2020 simplifies mangrove management by forming a National Coordination Team for managing the Mangrove Ecosystem (Tsabitah et al., 2023). The Indonesian Blue Carbon Strategy (IBCSF) is also proposed for mainstreaming blue carbon in national policy, focusing on policy, scientific knowledge, communication, financing sustainability, and project locations. Marine and Coastal Policy Research. Although a policy has been formulated, its implementation faces various obstacles:

1. Overlapping Overlap Authority: As much as 79% of the mangrove ecosystem is in the area that is the forest below the authority of the Ministry of Environment and Forestry (KLHK) and BRGM, while the remaining 21% is outside the area of the forest below the authority of the Ministry of Maritime Affairs and Fisheries (KKP). Overlapping overlap. This makes it challenging to coordinate and implement conservation programs.
2. Weakness Regulations: Several regulations, such as Law No. 11 of 2020 concerning Job Creation and PP No. 27 of 2021, provide room for the conversion of mangrove ecosystems for strategic national projects, which can threaten mangrove sustainability
3. Data Limitations: Differences in data regarding wide mangrove ecosystems between the Central Statistics Agency (BPS) and the National Mangrove Map (PMN) show inconsistency in management information, which can hinder the planning and implementation of conservation programs.

To overcome the challenge mentioned, some steps can be taken by:

1. Strengthening Coordination: Enhance coordination among KLHK, KKP, BRGM, and the relevant government agencies to align mangrove management policies and programs.
2. Revision Regulations: Reviewing return regulations that allow conversion of mangrove ecosystems to ensure more protection of mangroves.
3. Data and Information Enhancement: Develop an integrated and accurate mangrove information system to support planning and decision-making.
4. Empowerment: Involving the public in mangrove management through intensive programs, work, training, and development of an economy based on mangroves. kkp.go.id

By implementing the outlined steps, Indonesia can strengthen sustainable mangrove management, support climate change mitigation, and enhance public welfare.

4. CONCLUSION

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Mangroves play a strategic role in mitigating climate change through storing large amounts of carbon, protecting against extreme climate impacts, and contributing to public welfare. Conservation and restoration efforts within the ecosystem must become an integral part of climate policy, both nationally and internationally. Support policies, adequate financing, and participation of the public and local communities become key to sustainable mangrove management.

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