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Review

Carbon and Nitrogen Management in Mangrove Ecosystems in Reducing Greenhouse Gas Emissions: Ecological and Islamic Perspective

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ABSTRACT

Mangrove ecosystems, located along tropical and subtropical coastal areas, play a vital role in carbon storage and the nitrogen cycle, both of which significantly influence greenhouse gas emissions. These ecosystems store atmospheric CO_2 in their biomass and sediments. However, widespread mangrove degradation disrupts their ecological functions and environmental stability. This study aims to examine the relationship between carbon and nitrogen cycling in mangrove ecosystems and explore sustainable management strategies to reduce greenhouse gas emissions, integrating ecological perspectives and Islamic ethics. The research employs a comprehensive review of existing studies to analyze the roles of mangroves in carbon sequestration, nitrogen cycling, and their degradation's impacts on greenhouse gas emissions. It also discusses the integration of Islamic principles into mangrove conservation. Findings indicate that mangroves significantly contribute to carbon storage and nitrogen cycle regulation. Mangrove degradation affects their carbon sequestration capabilities, alters environmental conditions, and disrupts microorganisms essential for the nitrogen cycle. Furthermore, incorporating Islamic ethics into mangrove management can strengthen conservation efforts by fostering a sense of responsibility and sustainability. This study highlights the ecological importance of mangrove ecosystems in mitigating climate change through carbon and nitrogen management. It underscores the need for integrating Islamic ethical principles in conservation strategies to enhance sustainable environmental management. Preserving mangroves is critical for reducing greenhouse gas emissions and promoting climate resilience.

1. INTRODUCTION

Mangrove ecosystems are unique habitats for various organisms and serve as a link between marine and freshwater ecosystems. Mangrove ecosystems also serve as nurseries for a variety of aquatic organisms such as shrimp, fish, crabs and others, making mangrove ecosystems essential in coastal ecosystems. Thus, mangroves contribute significantly to biodiversity (Paingankar & Deobagkar, 2018). Indonesia has such a long coastline and has high diversity because of the coastal ecosystem, especially in the mangrove ecosystem. In 2020, the total mangrove area in Indonesia is around 2.7 hectares and is the largest mangrove forest ecosystem in the world (Basyuni et al., 2022). Blue carbon ecosystems such as mangrove forests have vast potential to sequester and store carbon derived from carbon dioxide from the atmosphere through photosynthesis and store it in the form of biomass in the roots, leaves, stems and sediments of mangrove ecosystems. In addition, this ecosystem is also able to reduce greenhouse gass emissions such as nitrogen oxides, methane, which are released by the ecosystem. Thus, mangrove ecosystems can serve as a nature-based solution for climate change mitigation (Luisetti, 2021). Previous studies have shown that

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each hectare of mangrove forest is able to absorb 1000 kg of carbon dioxide and release 730 kg of oxygen every day during its growth period in mature plants (Zhu & Yan, 2022).

Mangrove deforestation in Indonesia has reduced the function of mangrove ecosystems. This can occur due to the conversion of mangrove land for aquaculture, especially in shrimp and fish ponds, illegal logging of mangroves as building materials and firewood, as well as changes in mangrove areas into oil palm plantations, and the construction of settlements in coastal areas due to human activities (Goldberg et al., 2020).

Mangroves have an important ability to sequester anthropogenic nitrogen, nutrients and heavy metals, which makes them a natural filter for the surrounding marine ecosystem. Through biogeochemical transformation and nutrient retention, mangroves help protect marine ecosystems from land-based nutrient pollution, such as agricultural runoff and industrial waste. This process ensures that excess nutrients do not enter the ocean directly, thus maintaining the health of adjacent marine ecosystems (Valiela & Cole, 2002). However, this capability has limits. When there is excessive nutrient enrichment from agricultural runoff, domestic or industrial waste (Reef et al., 2010; Vikas & Dwarakish, 2015), the filtering function of mangroves can be compromised, especially when nutrient flows exceed the threshold that the ecosystem can absorb and metabolize (UNEP, 2014). This eutrophication has far-reaching impacts on the mangrove ecosystem and its surroundings. Not only does it disrupt the growth of mangrove plants, but it also puts pressure on faunal communities that live in or near mangrove ecosystems, such as fish, crabs and mollusks. These conditions lead to reduced water quality and low oxygenation, reducing the ability of mangrove ecosystems to provide various ecosystem services, such as nursery grounds for fish and other marine organisms (Dobson et al., 2006).

The review aims to examine the complex relationship between carbon and nitrogen cycling in mangrove ecosystems and management approaches through ecological perspectives and Islamic ethics for climate change mitigation.

2. RESEARCH METHODS

This research uses a qualitative approach by providing explanations and describing data after understanding the data that has been found. In addition, this research uses research methods sourced from literature, namely the search for relevant literature. Farid et al. 2023 revealed that literature research is a method carried out by collecting, analyzing, and describing the results of the literature that has been collected. We collected relevant data on carbon and nitrogen in mangrove ecosystems and conducted a comprehensive review. The database sources used came from trusted sources such as Google Scholar and ResearchGate. The keywords used are “Carbon flux and Nitrogen cycle and management; mangrove degradation and deforestation; Mangrove ecosystems; Greenhouse gas emission; Ecological data/field data; Islamic perspective”. Furthermore, collecting data on carbon data in Indonesia and the nitrogen cycle that occurs in mangrove ecosystems. Furthermore, collecting sources and providing ecological perspectives and Islamic ethics in the management of carbon and nitrogen cycles in mangrove ecosystems.

3. RESULTS AND DISCUSSIONS

3.1. The Role of Mangrove Ecosystems in Carbon Storage

Carbon emissions have been recognized as a cause of climate change and global warming, mainly due to anthropogenic actions such as illegal logging, fossil fuel combustion and land conversion. This leads to increased concentrations of greenhouse gases, including carbon dioxide (CO2), which have adverse impacts on the global ecosystem, such as rising global temperatures, rising sea levels, climate change, and increasingly extreme weather (Farrelly et al., 2013; Lal, 2008). One strategy to address climate change is through carbon sequestration, which is the removal of CO2 from the atmosphere and its storage (Schrag, 2007).

Mangroves, as blue carbon ecosystems, play an important role in climate change mitigation. Mangroves absorb and store large amounts of carbon, both in soil and forest biomass. Mangroves, seagrass meadows, and tidal marshes are ecosystems that function as carbon sinks and reduce CO2 emissions generated by human activities that cause global warming to occur (Alongi, 2022; Ahmed et al., 2018). Carbon stored in mangroves is not only limited to living biomass (such as stems, leaves, and roots), but also in dead biomass such as litter and dead wood and other organic materials integrated into mangrove ecosystems. The dual capacity of mangrove ecosystems makes them the most potential ecosystems for long-term carbon cycling. This carbon can be stored in sediments for thousands of years, thus making a long-term contribution to the reduction of atmospheric carbon and providing a balance against increasing CO2 levels due to human activities (McLeod et al., 2011).

Globally, mangrove forests are estimated to store about 6.5 billion tons of carbon out of a total of 11.5 billion tons stored in blue carbon ecosystems that occur in coastal areas (Siikamaki et al., 2012). Mangroves' high productivity and significant carbon storage capabilities make them an important ecosystem for climate change mitigation. In addition to the importance of conservation and restoration of mangrove habitats as part of global warming mitigation efforts, mangroves have currently shown very high levels of productivity. The combination of high productivity and mangrove's potential to sequester carbon could be a key ecosystem in terms of climate change mitigation. Thus, protecting and conserving mangrove forests is not only about maintaining biodiversity, but is also crucial in mitigating the impacts of climate change (Duarte et al., 2013; Howard et al., 2017).

3.2. The Role of Nitrogen Cycling in Mangrove Ecosystems

Nitrogen is an essential nutrient that has a very important role in an ecosystem. Physiologically, nitrogen nutrients absorbed by plants are used for various metabolic reactions such as protein, nucleotide and enzyme metabolism. The unique mangrove ecosystem is highly dependent on the performance of microbes that play a role in nitrogen cycling and nitrogen conversion with mechanisms owned by microbes (Alongi, 2020). A comprehensive study on nitrification in mangrove ecosystems showed that there are a variety of microorganism groups that play a role in the nitrogen cycle. This study found lime types of microorganisms that play a role in the nitrogen cycle, especially in nitrification such as AOA (Ammonia-Oxidizing Archaea), AOB (Ammonia-Oxidizing Bacteria), NOB (Nitrite-Oxidizing Bacteria), Anammox Bacteria, Comammox Bacteria (Complete Ammonia Oxidizers), which have their respective mechanisms in converting nitrogen (Mubaraq et al., 2024a).

Ammonia in mangrove ecosystems is one of the compounds caused by nitrogen pollution that can come from urban river flows, accumulation of fish waste on the bottom of the waters, and ponds located around mangrove ecosystems. Excess ammonia conditions can become nitrogen pollution which in severe conditions can cause death to organisms living in mangrove ecosystems. Ammonia-oxidizing bacteria use ammonia compounds as a primary source and convert ammonia (NH_4^+) to nitrite (NO_2-) and then to nitrate (NO_3-), which is less toxic to the environment. Through the nitrification process, these bacteria are able to reduce ammonia levels more efficiently (Putri et al., 2021).

The NOB bacteria convert nitrite into nitrate (NO_3-) with examples of NOB bacteria being Nitrospina, Nitrococcus, and Nitrospira. In addition, newly discovered bacteria capable of performing a complete one-step process in the conversion of nitrogen from ammonia to nitrate are carried out by Comammox bacteria. Comammox bacteria can be found in mangrove ecosystem environments such as sediments. Another group of nitrifying bacteria that are also found in mangrove rhizosphere areas are anammox (Anaerobic Ammonium Oxidation) bacteria which are very unique because they occur under anaerobic conditions and convert nitrogen in the form of ammonium (NH_4^+) oxidized anaerobically using nitrite (NO_2-) as an electron acceptor. The end result is nitrogen gas (N_2) released into the atmosphere and a small amount of nitrate (NO_3-). This nitrification process helps reduce excess nitrogen accumulation in mangrove ecosystems (Meng et al., 2022). Figure 1 shows the nitrogen conversion that occurs in mangrove ecosystems and the genes that play a role.

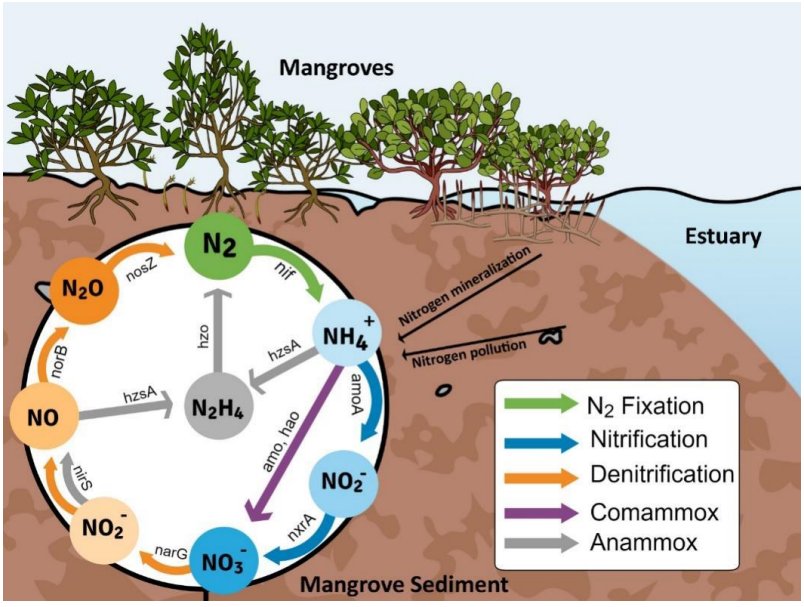


Figure 1. Nitrogen cycling in mangrove ecosystems (Mubaraq et al., 2024a)

The nitrogen (N) cycle in mangrove ecosystems and associated tidal waters is complex. The cycle is characterized by rapid turnover of low concentrations of dissolved nitrogen, while turnover of particulate nitrogen occurs more slowly. About 96% of this particulate nitrogen is stored in sediments, with total nitrogen storage in global mangrove forests reaching 52.03 Mg N per hectare, a much higher amount than in terrestrial tropical ecosystems, which store about 22.33 Mg N per hectare (Alongi, 2020).

3.3. Current Status of Mangrove Degradation in Indonesia

Table 1. Distribution and gap of mangrove area in Indonesia in 2000 – 2020 (Basyuni et al., 2022)

Province	Island	2000	2020	Gap 2000-2020
Bali	Bali Nusa	1,834.88	1,823.83	11.05
East Nusa Tenggara	Bali Nusa	19,007.60	18,665.03	342.57
West Nusa Tenggara	Bali Nusa	4,847.26	4,675.28	171.98
Banten	Jawa	2,542.73	2,406.12	136.61
Central Java	Jawa	10,431.40	10,166.91	264.49
East Java	Jawa	25,873.11	25,630.19	242.93
Jakarta	Jawa	89.91	89.46	65.50
West Java	Jawa	5,867.70	5,802.20	65.50
Yogyakarta	Jawa	3.36	3.36	0.00
Central Kalimantan	Kalimantan	47,027.12	40,248.50	6,778.62
East Kalimantan	Kalimantan	242,670.03	203,105.15	39,564.88
North Kalimantan	Kalimantan	192,192.00	153,240.68	38,951.32
West Kalimantan	Kalimantan	123,564.91	113,271.25	10,293.66
West Kalimantan	Kalimantan	70,806.82	61,180.16	9,626.66
Maluku	Maluku	193,599.12	192,203.87	1,395.25
North Maluku	Maluku	41,217.75	40,321.17	896.58
Papua	Papua	734,337.27	726,407.79	7,929.48
West Papua	Papua	486,563.10	481,480.48	5,082.63
Central Sulawesi	Sulawesi	33,230.52	30,196.10	3,034.42
Gorontalo	Sulawesi	11,604.67	9,420.94	2,183.73
North Sulawesi	Sulawesi	11,403.53	11,011.56	391.97
South Sulawesi	Sulawesi	27,111.29	23,449.21	3,662.07
Southeast Sulawesi	Sulawesi	67,214.10	61,013.16	6,200.94
West Sulawesi	Sulawesi	4,910.52	3,584.74	1,325.78
Aceh	Sumatera	33,142.06	31,321.79	1,820.27
Bangka Belitung Island	Sumatera	65,486.96	61,664.34	3,822.61
Bengkulu	Sumatera	2,065.63	1,969.47	96.15
Jambi	Sumatera	4,194.57	3,843.25	351.32
Lampung	Sumatera	6,596.02	5,941.21	654.82
North Sumatra	Sumatera	66,873.10	57,010.06	9,863.04
Riau	Sumatera	153,722.45	143,596.70	10,125.75
Riau Islands	Sumatera	56,098.22	52,008.02	4,090.20
South Sumatra	Sumatera	166,199.91	142,681.40	23,518.50
West Sumatra	Sumatera	18,023.26	17,552.48	470.79
		2,930,352.90	2,736,985.87	193,367.03

Several anthropogenic human activities have had significant impacts and resulted in a decrease in the area and function of mangroves in sequestering carbon. Human needs in aquaculture by expanding aquaculture to increase production resulted in mangrove deforestation (Duguma et al., 2022). The urbanization system has resulted in human immigration and requires residential land to coastal areas, road construction, and other infrastructure often results in the conversion of mangrove land in coastal areas into urban land. The side effects of settlements in coastal areas have brought negative impacts in the form of pollution to mangrove ecosystems and caused damage to mangrove forests (Dhargalkar et al., 2015). In addition, in terms of agricultural needs, mangrove ecosystems are

often targeted for conversion, resulting in the degradation of mangrove forest areas. Eutrophication that occurs due to agricultural land and often empties into mangrove ecosystems also causes damage to mangrove forests (Duguma et al., 2022). Currently, there has been a lot of damage to mangrove ecosystems due to illegal logging and land conversion into land cover that is not able to function like mangrove ecosystems caused by humans. This also has an impact on the disruption of the habitat of organisms that live in mangrove ecosystems such as fish, crustaceans, birds, including microorganisms which result in a decrease in existing biodiversity (Mubaraq et al., 2024b). Table 1 shows the distribution of mangrove areas in Indonesia and the land cover change from 2000 to 2020, showing the amount of degraded land area.

Illegal logging of mangrove forests is also often carried out by humans due to the need for boards, charcoal, and firewood, resulting in excessive and uncontrolled degradation of mangrove forests. Mangrove trees that have been cut down will be very difficult to regrow and can result in permanent plant death and deforestation (Dhond, 2012). Oil exploration by humans often crosses coastal areas and results in pollution of mangrove ecosystems. Massive oil spills can pollute mangrove ecosystems, making it difficult for mangroves to grow and even die (Dhargalkar et al., 2015). Often waste from industry and waste from urban waste empties into mangrove ecosystems. Garbage that collects in mangrove ecosystems causes pressure on the habitat of organisms that live in mangrove ecosystems and makes it difficult for mangroves to grow due to unstable ecosystems (Maiti and Chowdhury, 2013). Illegal mining that occurs in coastal areas rich in mangroves has disrupted the habitat of organisms in mangrove ecosystems such as crabs, shrimps and fish, causing death (Beiser, 2017).

3.4. Sustainable Mangrove Ecosystem Management

The Indonesian government is currently implementing various strategies to restore the function of mangrove ecosystems. The most recent strategy is to increase the mangrove rehabilitation target in the period 2020-2024 with an overall target of 600,000 ha through the government-established Peatlands and Mangrove Restoration Agency (BRGM) (Sasmito et al., 2023). However, without clear planning and strategy this ambitious goal may not be achieved. A successful rehabilitation program can contribute to the reduction of community poverty (SDG 1) and maintain food security functions with community livelihoods (SDG 2) that can ultimately improve the welfare of Indonesian people. In addition, mangrove rehabilitation serves to reduce greenhouse gas emissions (Goldberg et al., 2020).

Preserving mangrove ecosystems from damage can rehabilitate degraded mangrove forest areas so that they can function again as carbon sinks and mitigate greenhouse gases. Mangrove conservation activities in Indonesia involve various stakeholders such as institutions, local communities, and often the private sector with the aim of conserving mangrove forests. Steps that can be taken to conserve mangrove forests include regulations and policies to protect and rehabilitate mangroves (Basyuni et al., 2022). Monitoring mangrove species is also needed to maintain the biodiversity of mangrove ecosystems and maintain environmental conservation functions. Previous research developed one method, namely deoxyribonucleic acid (DNA) barcoding to monitor and guide in determining species. Newer methods are needed to make identification efficient (Basyuni et al., 2024) .In addition, participatory mangrove management activities involving local communities are also needed as well as other economic strengthening to increase awareness of coastal communities, such as, ecotourism without destroying mangrove vegetation (Purwanti et al., 2021).

Mangrove rehabilitation strategies should be focused and have clearer planning with measurable implementation and transparent evaluation. The target of mangrove rehabilitation should be based on the improvement of the mangrove ecosystem. Furthermore, the restoration program should not only focus on planting seeds and reforestation but with a broader function of restoring the function of the mangrove ecosystem. The implementation requires various stakeholders involved with their respective functions including local government, community organizations, and local communities. Evaluation must be carried out regularly with transparency in reporting. In addition, rehabilitation also focuses on ecological and social impacts that can increase the social and economic benefits of the community (Sasmito et al., 2023). This will provide a broader function and achieve ambitious targets and contribute to sustainable goals.

3.4. Islamic Perspective on Mangrove Ecosystem Management

In the Islamic perspective, Allah has created humans as the best creatures on earth. Humans have a greater responsibility, namely *khilafatullah fil ardh*, which means being Allah's representative on earth. So it should be human responsibility to manage and maintain the earth both on land and at sea (Irfan et al., 2020). Islam has comprehensive guidance regarding environmental management and human responsibility towards nature. Some of the key principles in Islam that are relevant for mangrove ecosystem management and climate change mitigation are:

3.4.1. Khilafah (Leadership)

Humans are given the responsibility of being khalifah (leader) on earth, which includes protecting and caring for nature and its resources. Allah says in the Qur'an:

> *"And it is He who has made you successors upon the earth and has raised some of you above others in degrees [of rank] that He may try you through what He has given you. Indeed, your Lord is swift in penalty; but indeed, He is Forgiving and Merciful." (Q.S. Al-An'am: 165)*

This concept of stewardship places a divine obligation on humans to protect and preserve natural ecosystems, including mangroves, which are crucial for coastal protection, biodiversity, and the livelihoods of communities that rely on them.

3.4.2. Ecosystem balance

Maintaining the balance of the ecosystem is the obligation of humans as khalifah. The Mizan Principle teaches the importance of maintaining the balance of nature, including the balance of carbon and nitrogen in the mangrove ecosystem.

> *"As for the sky, He raised it high, and set the balance of justice. So that you don't defraud the scales." (QS. Ar-Rahman: 7-8)*

Furthermore, Islam advocates for the public ownership of natural resources, viewing ecosystems like mangroves as communal assets. This position is based on the Hadith: "The people are partners in three things: water, pasture, and fire (fuel)" (Sunan Ibn Majah), which Islam demotes to mean that natural resources critical to societal well-being should be managed collectively, not exploited for private gain. Thus, mangroves, being vital to environmental stability and community livelihoods, would fall under public management in an Islamic system. Instead, mangrove should be managed for the benefit of the community as a whole, which includes ensuring the sustainability and health of mangrove forests.

3.4.1 Wise management

In every action related to the environment, including the utilization of mangrove resources, it must be done with good intentions and in a prudent manner. Islam prohibits all forms of destruction on earth, including environmental destruction. This concept is especially relevant to mangrove ecosystems, which are vulnerable to industrial development, deforestation, and pollution. Islam stresses the importance of balanced and sustainable use of natural resources, in line with the Qur'anic verse:

> *"Don't spread corruption in the land after it has been set in order....." (Q.S. Al-A'raf: 56)*

Therefore the exploitation of mangrove ecosystems for short-term economic gains, at the expense of long-term environmental health, is a form of corruption (*fasad*) that Islam forbids. The Islamic perspective on mangrove ecosystem management emphasizes human responsibility as stewards of nature, the collective ownership and preservation of resources, and the prohibition of environmental harm, aligning with broader Islamic principles of environmental sustainability and justice. These views reflect a broader commitment to sustainable environmental practices within the framework of Islamic governance.

4. CONCLUSION

Mangrove ecosystems play an important role in carbon and nitrogen management, which contributes to reducing greenhouse gas emissions. From an ecological perspective, mangrove conservation and restoration is an important step in dealing with climate change. Meanwhile, from an Islamic ethical perspective, good mangrove management is part of humanity's responsibility as khalifah on earth. Thus, mangrove conservation is not only important from a scientific and ecological perspective, but also from a spiritual and moral one. Islam had a detailed environmental policy specifically focused on mangroves, their general principles of stewardship, prohibition of harm, public ownership, and rejection of capitalist exploitation would suggest a strong emphasis on sustainable and responsible mangrove ecosystem management.

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