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Soil organic matter in natural and rehabilitated mangroves: Implications for environmental restoration and climate resilience

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ABSTRACT

Mangrove ecosystems contribute significantly to coastal stability, providing essential services like carbon sequestration and storm protection. The rehabilitation of mangroves in Indonesia is essential to restore ecological functions disrupted by coastal development. This study aims to compare the ratios of organic matter – carbon (C), nitrogen (N), and phosphorus (P) – in the soils of natural and rehabilitated mangroves in Benoa Bay, Bali. The research was conducted across eight plots in natural and rehabilitated mangrove forests, with soil samples collected using an auger at depths ranging from 0 to 100 cm. Organic matter analysis was performed using the loss on ignition (LOI) method for soil organic carbon (SOC), the FIA method for total nitrogen (TKN), and the colorimetric persulfate digestion method for total phosphorus (TP). The results indicate that rehabilitated mangroves have lower total organic carbon (1.1±0.5%) and higher total nitrogen content (0.07±0.02%) compared to natural mangroves. Total phosphorus content is also lower in rehabilitated areas (0.010±0.003%), possibly due to increased clay content that binds phosphorus in the soil. Several parameters are closely related to organic matter, including bulk density, soil type, oxidation-reduction potential (ORP), pH, and dissolved oxygen (DO) in pore water, as well as the structure of mangrove stands, such as tree and seedling density, stem diameter, canopy cover, and mangrove health condition. Variations in organic matter content and C:N ratios suggest that rehabilitated mangrove ecosystems have not yet reached the stability of natural ecosystems. This is reflected in altered biogeochemical cycles and nutrient availability. Therefore, ongoing efforts are needed to ensure a more comprehensive recovery in the mangrove rehabilitation process. These findings emphasize the need for targeted interventions in mangrove rehabilitation to restore nutrient balance, optimize carbon storage, and enhance resilience to climate change in tropical coastal ecosystems.

Keywords: Mangrove ecosystems, coastal stability, organic matter ratios, loss-on-ignition method, biogeochemical cycles, nutrient availability.

INTRODUCTION

Mangrove ecosystems are crucial coastal systems with tidal oscillations in tropical and subtropical locations (Giri et al., 2011). Mangroves provide habitats for various plants and animals and have a vital function in preserving the stability of coastal areas, preventing erosion, and offering important ecosystem services like carbon sequestration and storm protection (Mitra and Mitra, 2020; Asari, et al., 2021). Mangrove regeneration in Indonesia is essential to restore the ecological functions that have been significant disrupted by extensive coastal development, particularly in areas like Benoa Bay, Bali (Kusmana, 2014; Worthington and Spalding, 2018). Restoration efforts typically involve mangrove transplantation, re-establishing natural hydrology, and sustainable vegetation management practices to promote ecosystem recovery (Su et al., 2021). However, while significant progress has been made in rehabilitating mangroves, the impact of these efforts on nutrient cycling and ecosystem stability remains inadequately understood, which this study seeks to address. Mangroves also play a key role in coastal ecosystems by producing organic matter, including carbon, nitrogen, and phosphorus. This production enriches nutrient availability, supporting biodiversity and sustaining nutrient cycles within mangrove environments (Sanders et al., 2014; Boto, 2018).

The productivity of mangrove ecosystems relies on organic carbon, nitrogen, and phosphorus. Organic carbon is responsible for forming plant biomass, supports the physical structure of plants, and serves as a reservoir for carbon that can help mitigate climate change (Deb et al., 2015; Sugiana et al., 2024). Nitrogen is essential for the growth of leaves and the synthesis of proteins, whereas phosphorus is needed for cellular energy production and root development (Reef et al., 2010; Malhotra et al., 2018; Ernawati et al., 2024). The connection among these three components guarantees the efficiency and ability of mangroves to withstand environmental pressures while promoting biodiversity by providing habitats and nourishing for diverse creatures. The nutrient balance plays a crucial role in maintaining the health and functionality of mangrove ecosystems, including important functions like water filtration, coastal protection, and carbon storage (Alongi et al., 2018; Mack et al., 2024).

Comprehending the proportion of organic carbon (C), nitrogen (N), and phosphorus (P) in mangrove soil is essential because this ratio offers vital information on the well-being and operation of mangrove ecosystems (Das et al., 2022). The soil's C:N ratio indicates the nutritional equilibrium required for primary productivity and continuous biogeochemical activities. The ratio mentioned can serve as an indicator of nutritional circumstances and potential environmental stress (Alongi et al., 2018; Li et al., 2024). Specifically, a high carbon (C) content may signify a shortfall in nitrogen, whereas a low nitrogen (N) could indicate a limitation in phosphorus (Lovelock et al., 2006; Scharler et al., 2015). By examining these ratios, detection of the origins of pollutants and nutrients, including those naturally occurring and those caused by human activity (Masoud et al., 2019; Li et al., 2023). Additionally, evaluation of the capacity of mangrove soil to store carbon could be done, which is crucial for mitigating climate change. An optimal ratio facilitates the proliferation of microbes and mangrove plants, contributing to nutrient cycling and preserving ecosystem production (Alongi et al., 2021; Palit et al., 2022).

The Benoa Bay mangrove forest in Bali comprises a combination of restored and naturally occurring mangrove vegetation. The rehabilitated mangroves are primarily dominated by species such as *Rhizophora* spp. and *Bruguiera gymnorrhiza*, whereas the naturally occurring areas are predominantly dominated by *Sonneratia alba* (Sugiana et al., 2022; Wijaya et al., 2023). Rehabilitated mangrove soil frequently exhibit reduced quantities of organic content compared to naturally occurring mangroves. This phenomenon might be ascribed to replanting, which may entail using planting material or additives that differ from the natural surroundings (López-Portillo et al., 2017; Gnanamoorthy et al., 2019). Conversely, soil that occur naturally tend to have a greater buildup of organic material because of the inherent interplay between mangrove plants, bacteria, and environmental factors that facilitate the breakdown of organic matter. These variations have substantial ecological consequences, especially in the process of nitrogen cycling and the availability of substrate for benthic organisms (Scharler et al., 2015).

This study aims to analyze the levels of organic matter (carbon, nitrogen, and phosphorus) in the soil of both natural and rehabilitated mangroves in Benoa Bay, Bali. The purpose is to gain insights into the variations in nutrient composition that impact the overall health and functionality of the ecosystem. Previous studies have assessed the organic matter concentration in mangrove soil at similar sites (Dharmayasa et al., 2024; Ernawati et al., 2024; Sugiana et al., 2024b). However, they did not extensively examine the correlation dan comparison with the state of rehabilitated or naturally occurring mangroves. This research is of utmost importance as it can uncover the influence of mangrove restoration on the equilibrium of nutrients and the processes that govern the cycling of chemicals in the environment. These factors substantially impact efforts to mitigate climate change, store carbon, and enhance the productivity of coastal ecosystems. It provides new insights into how effective mangrove rehabilitation is in restoring ecosystem functions and maintaining nutrient stability and carbon cycling in tropical areas affected by human activities.

METHOD

Study site

The research is located in Benoa Bay, Bali, at the coordinates 8°42’50.46”S, 8°47’49.92”S, 115°10’9.42”E, and 115°15’13.19”E. Most mangrove forests have undergone conversion from aquaculture ponds in the last thirty years (JICA, 1999). The rehabilitated mangrove forest consists mainly of *Rhizophora* spp., whereas the natural region comprises *Sonneratia alba*. According to Sugiana et al. (2022), the overall condition of mangroves, as determined by the mangrove health index (MHI), is classified as moderate. The soil in this area is predominantly composed of fine sand (Prinasti et al., 2020; Sugiana et al., 2024b). Eight study plots were selected using a stratified random sampling method to ensure coverage across both natural and rehabilitated areas. In each zone, sampling was conducted at four different sites, ensuring spatial representation across varying distances from the waterline. This approach was chosen to capture potential environmental gradients that might affect soil organic matter content and nutrient cycling (Figure 1). Data was collected in January 2024 with a bright sky and low tide.

Data collection (soil, porewater and mangrove stand structures)

Soil samples were collected using a 5 cm-diameter soil auger, drilling to depths between 0 and 100 cm. Soil pH was measured using a Lutron 212 pH meter after the soil was mixed to ensure a uniform sample. Approximately 300 grams of soil were stored in plastic containers for subsequent chemical analysis. To determine water content, we dried 100 grams of soil at 70 °C for about 48 hours until it reached a stable weight. Another 100 grams were dried at 105 °C to determine the bulk density of the soil. The dried soil was then used for various tests: 10 grams for grain size analysis, 3 grams for measuring soil organic carbon (SOC), and the remaining portion (about 100 grams) for total Kjeldahl nitrogen (TKN) and phosphorus (TP) analysis.

For the soil particle size analysis, we used a dry sieve method, categorizing gravel at 2 mm, sand between 1.1 mm and 75 µm, and using the settling time method to classify silt and clay. SOC was measured using the loss on ignition (LOI) method by burning samples at 550 °C, following Chen et al. (2014). TKN was analyzed with a flow injection analyzer (FIA), and TP was measured with a colorimetric persulfate digestion method. Since the data were collected during low tide, most porewater samples were taken from 50-100 cm below the soil surface. We measured temperature, pH, salinity, and ORP with the Multimeter COM-600 water quality tester, and dissolved oxygen (DO) with a Lutron DO-5519 meter.

To assess the structure of the mangrove stands, we measured the density of trees and saplings by recording the Diameter at Breast Height (DBH), which is the tree trunk’s diameter at 130 cm above the ground. We classified trees with DBH ≥5 cm and saplings with DBH <5 cm. The height of the mangroves was estimated using a trigonometric approach, measuring the angles to the top of the canopy from

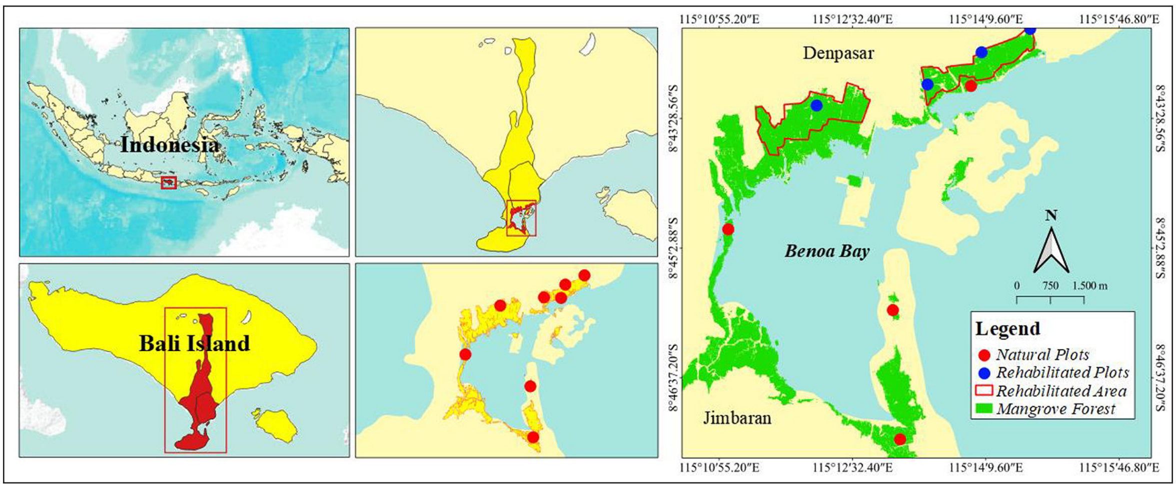

Figure 1. Distributions of research data collection plots in Benoa Bay, Bali, Indonesia

10 meters away. We used hemispherical photography to evaluate canopy coverage, capturing images from five positions in each plot (the four corners and the center) using a smartphone camera with more than 3 megapixels. These images were then analyzed using the ImageJ software (Dharmawan 2020). The mangrove health index (MHI) was calculated using data on sapling density, DBH, and canopy cover (Dharmawan and Ulumuddin, 2021).

Data analysis

We performed a T-test to assess whether there were significant differences in the levels of organic matter (carbon, nitrogen, and phosphorus) and ecological properties (soil, porewater, and mangrove stand structure) between natural and rehabilitated mangrove areas. Prior to the analysis, we checked for normality of the data using the Shapiro-Wilk test, and all variables demonstrated a normal distribution ($\rho>0.05$). Additionally, a Pearson correlation test was conducted to explore the relationship between organic matter content (SOC, TKN, TP) and ecological properties. The analysis was performed using R Studio version 4.0.2.

RESULTS AND DISCUSSION

Environmental condition and mangrove stand structure

The results show considerable disparities in environmental conditions between the natural and rehabilitated mangrove sites. There were significant variations observed in the bulk density and soil composition (sand, silt, and clay) ($\rho < 0.05$). It is also comparable to the stand structure, which encompasses tree density, stem diameter, canopy cover, and mangrove health condition (MHI) with a ρ value less than 0.01. Nevertheless, there were no notable disparities in porewater characteristics and atmospheric conditions between the restored and original mangroves. In addition, no significant variations were seen in soil pH, water content, gravel composition, or sapling density (Table 1).

Mangrove rehabilitation significantly affects soil structure and composition, evident in the differences between natural and rehabilitated areas (Datta and Deb, 2017). Incorporating organic or physical elements during rehabilitation has resulted in an augmentation in bulk density and alterations in sand, silt, and clay composition ratios. The alterations affect the soil's physical structure and permeability, affecting its ability to retain water.

Table 1. Comparison of environmental and mangrove stand structures condition of natural and rehabilitated mangrove growth

Object	Parameter	Natural	Rehabilitated
Atmospheric	Temperature (°C)	26.4±1.25	27.1±1.00
	Humidity (%)	77.5±5.1	80.5±3.7
Soil	pH	6.66±0.29	6.38±0.19
	Water content (%)	41.18±12.45	50.88±4.78
	Bulk density ($g\cdot cm^{-3}$)*	0.66±0.07	0.83±0.12
	Gravel (%)	5.4±3.7	2.5±3.8
	Sand (%)*	88.4±6.5	71.3±9.6
	Silt (%)*	4.5±5.2	20.3±9.2
	Clay (%)*	2.7±1.3	6.0±3.8
Porewater	Temperature (°C)	27.5±0.6	28.4±0.8
	pH	6.81±0.34	6.45±0.17
	Salinity (ppt)	19.50±2.07	22.01±1.21
	ORP (mV)	-95±59	-41±49
	DO (mgL^{-1})	1.25±0.37	1.88±0.52
Mangrove stand structure	Tree density ($ind\cdot ha^{-1}$)**	2121±247	3409±518
	Sapling density ($ind\cdot ha^{-1}$)	985±290	1439±290
	Trunk diameter (cm)**	11.5±0.8	8.7±1.0
	Canopy coverage (%)**	49.17±11.27	73.58±3.77
	Health index (%)**	42.13±3.81	55.49±4.61

Note: * significant level at $\rho < 0.05$, while ** at $\rho < 0.01$.

It is supported by the increased soil moisture and ambient humidity reported at the rehabilitated area. Conversely, the undisturbed area displayed elevated concentrations of silt and clay, suggesting a more uniform deposition of soil that has not been influenced by human activities. Furthermore, the restored mangrove exhibited a greater density of mangrove trees and sapling than the natural area, most likely due to intensive planting initiatives to expedite ecosystem restoration (Lewis et al., 2019; Gerona-Daga et al., 2022). Nevertheless, the smaller trunk diameters seen at the rehabilitation area indicate that the restoration process has yet to attain the same degree of ecosystem maturity as the natural environment, which is essential for ensuring long-term stability.

The environmental variations have noteworthy consequences for mangrove soil carbon, nitrogen, and phosphorus levels (Alongi et al., 2021; Zhu et al., 2022). The enhanced tree density and expanded canopy cover at the rehabilitated area may result in a more significant organic matter buildup, leading to higher carbon concentrations in the soil (Sugiana et al., 2024a). Conversely, alterations in soil composition and higher water levels could impact the process of nitrogen and phosphorus cycling (Alongi, 2018; Chen et al., 2023). Increased water content could potentially boost denitrification rates, thereby limiting the accessibility of nitrogen to plants (Shiau et al., 2016; Zhang et al., 2024). Higher clay content in rehabilitated mangrove soil may increase phosphorus binding, limiting its availability for plant absorption (You et al., 2022). Despite the initial success observed in the rehabilitated station, such as the improved mangrove health index (MHI) and increased canopy cover, fluctuations in groundwater conditions and smaller stem sizes suggest that the rehabilitation process has not yet fully achieved the stability and maturity of a natural ecosystem. It highlights the importance of continuously focusing on environmental elements to replicate better the circumstances of a stable and natural mangrove ecosystem.

Soil carbon-nitrogen-phosphorus content

There was a significant difference in TOC content between natural and restored stations ($\rho < 0.05$). The rehabilitated mangrove soil have lower TOC than the natural area. In contrast to the natural area, the rehabilitated area had a slightly higher total nitrogen (TN) content but a lower total phosphorus (TP) concentration (Figure 2). The rehabilitation area had a lower C:N ratio, indicating a better nitrogen-to-carbon ratio. N:P ratios in the restored region were also high, indicating a high nitrogen to phosphorus ratio. The restored area had a lower C:P ratio, indicating less carbon-to-phosphorus.

The variations in organic matter concentrations and ratios can be attributed to the differing dynamics of the ecosystem and environmental conditions in the rehabilitated and natural mangrove areas (McKee and Faulkner, 2000; Feng et al., 2019; Gnanamoorthy et al., 2019). The reduced presence of organic carbon in the rehabilitated mangrove area may be attributed

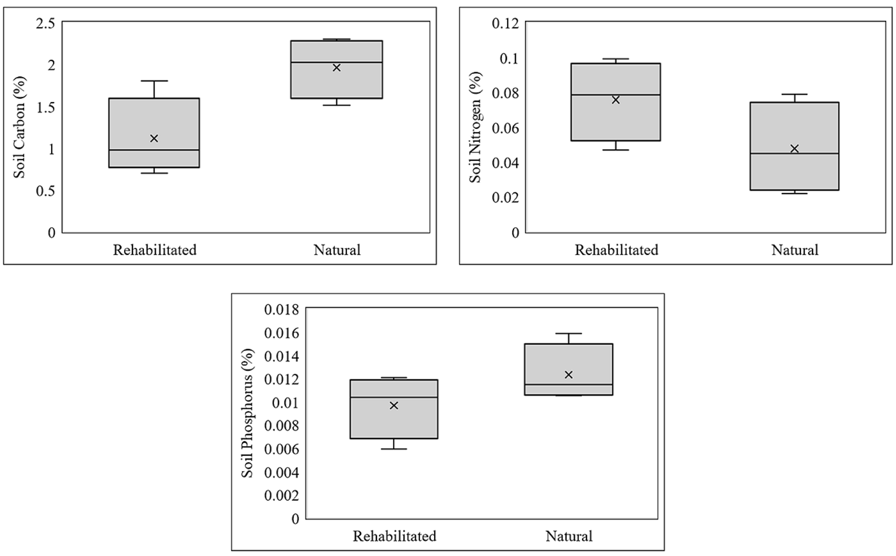

Figure 3. Soil carbon, nitrogen and phosphorus percentage of each mangrove area

to the first phases of organic matter buildup, where the decomposition process has yet to produce a carbon reserve comparable to that of the natural area. Older, larger trees in natural ecosystems, with extensive root systems, promote organic material accumulation of organic materials, increasing carbon content in the soil (Freitas et al., 2021; MacKenzie et al., 2021). On the other hand, the increased nitrogen levels in the rehabilitated area may result from adding fertilisers or other nitrogen sources during the rehabilitation process to promote the growth of young plants (Lovelock et al., 2010). However, there has not been a corresponding increase in the buildup of organic carbon. The reduced phosphorus level in the rehabilitated area may be attributed to the clay composition of the soil, which can bind phosphorus, hence decreasing the quantifiable availability of phosphorus (You et al., 2022).

The ratios also show biogeochemical differences between the two locations. The rehabilitated area's lower C:N ratio signals more nitrogen than carbon, which can help early plant growth. However, it indicates an imbalance in organic matter decomposition. The rehabilitated area's increased N:P ratio suggests an excess of nitrogen or a phosphorus deficiency, possibly due to the lack of a stable nutrient cycle (Ray et al., 2021). After rehabilitation, the carbon-to-phosphorus (C:P) ratio decreases, indicating that phosphorus availability remains the main limiting factor (Huang et al., 2024). Mangrove rehabilitation has improved some aspects of the ecosystem, but complete restoration, especially of the carbon, nitrogen, and phosphorus cycles, requires more time to reach natural equilibrium.

Relationship between organic matter, environment conditions and mangrove stand structures

Organic matter (carbon, nitrogen, and phosphorus), environmental conditions, and mangrove stand structure show various correlations. Table 2 shows that soil bulk density, sand percentage, clay, and silt percentages negatively and positively correlate with total organic carbon (TOC). TN is positively correlated with porewater ORP, DO, and sapling density, while TP is positively correlated with porewater pH but negatively correlated with canopy cover and the mangrove health index (MHI) (Table 2). These results show that soil texture, porewater quality, and mangrove stand structure affect mangrove soil carbon, nitrogen, and phosphorus concentration.

Table 2. The correlation of organic matter with environmental conditions and mangrove stand structure

Object	Parameter	TOC	TN	TP
Atmospheric	Temperature (°C)	-0.028	0.099	-0.525
	Humidity (%)	-0.238	0.184	-0.187
Soil	pH	0.110	-0.122	0.684
	Water content (%)	0.654	-0.084	-0.132
	Bulk density (g cm^{-3})	-0.939**	0.484	0.103
	Gravel (%)	-0.698	-0.177	0.098
	Sand (%)	-0.906**	0.126	-0.051
	Silt (%)	0.865**	-0.154	0.084
	Clay (%)	0.947**	-0.246	-0.100
Porewater	Temperature (°C)	-0.397	0.515	-0.408
	pH	0.243	-0.344	0.709*
	Salinity (ppt)	-0.390	0.254	-0.448
	ORP (mV)	-0.441	0.796*	-0.135
	DO (mgL^{-1})	-0.500	0.797*	-0.073
Mangrove stand structure	Tree density (ind·ha^{-1})	-0.589	0.238	-0.444
	Sapling density (ind·ha^{-1})	-0.503	0.884**	-0.404
	Trunk diameter (cm)	0.838**	-0.512	0.140
	Canopy coverage (%)	-0.385	0.685	-0.812*
	Health index (%)	-0.414	0.663	-0.804*

Note: * significant level at $\rho < 0.05$, while ** at $\rho < 0.01$.

Organic carbon is higher in soils with looser texture and smaller particles due to the strong inverse relationship between total organic carbon (TOC) and bulk density and sand percentage (Rakesh et al. 2020; Sugiana et al., 2024a). Fine-textured soils store organic matter better and decompose slower under less compact circumstances, explaining this trend. In contrast, the high correlation between total organic carbon (TOC) and clay and silt percentages supports these findings. Clay and silt-rich soils hold water and organic matter better, enabling carbon accumulation (Sung et al., 2017; Dharmayasa et al., 2024). The substantial positive link between TN, ORP, and sapling density indicates that more muscular oxidative conditions and sapling density could increase soil nitrogen (Alongi, 2021).

Conversely, TP, porewater pH, and sapling density are directly related, demonstrating that soil with higher alkalinity and vegetation density can raise phosphorus levels (Sun et al. 2020). However, the inverse relationship between TP and canopy cover and MHI suggests that increased phosphorus levels may not constantly improve ecosystem well-being, possibly due to the disruptive effects of excessive phosphorus on natural nutrient equilibrium. These studies have shown how environmental variables and mangrove stand structure affect soil organic matter.

Redfield stoichiometry

The Redfield Stoichiometry, which uses a 106:16:1 molar ratio of C:N:P, helps explain ecosystem nutrient balance. The rehabilitated mangrove ecosystem had less soil organic carbon than the natural one. This shows that the rehabilitation method has improved soil carbon levels but not totally. Lower carbon levels at the rehabilitated site suggest a C:N imbalance, probably due to nitrogen-rich materials added during restoration (Reis et al., 2017). This carbon-nitrogen imbalance may hasten organic matter breakdown, reducing the ecosystem's long-term carbon storage capacity (Craig et al., 2021). Moreover, an excess of nitrogen without corresponding carbon accumulation could disrupt nitrogen cycling, potentially increasing greenhouse gas emissions, such as nitrous oxide (N_2O), which could negate the climate mitigation benefits of mangrove rehabilitation efforts.

Organic matter breaks down faster at the rehabilitated site due to its reduced C:N ratio (Farooqui et al., 2014; Xia et al., 2021). This quick disintegration could impair the site's long-term carbon storage, which is a crucial goal of mangrove recovery (Wu et al., 2020). High nitrogen and low carbon content may accelerate organic carbon loss, making ecosystem maintenance more challenging (Meng et al., 2022; Zeng et al., 2023). Following Redfield principles, adding organic materials with a more balanced C:N ratio may help store carbon and stabilize nutritional balance. This would improve biogeochemical cycles and support the rehabilitated mangrove ecosystem.

Despite identical phosphorus levels in natural and rehabilitated sites, phosphorus management remains crucial, despite similar levels across sites. Phosphorus negatively correlated with canopy cover and the mangrove health index (MHI), notably in the rehabilitated region. This shows that too much phosphorus may harm ecosystems and induce nutritional imbalances (Hashemi et al., 2016; Ngatia et al., 2019). Therefore, rehabilitation programs must address phosphorus management to balance nutrient inputs and meet ecosystem needs. Following Redfield Stoichiometry standards for nutrient management will help mangrove rehabilitation restore ecosystem functioning and preserve these vital coastal habitats (Scharler et al., 2015).

CONCLUSIONS

This study identifies significant differences in environmental variables, stand structure, and soil nutrient composition between rehabilitated and natural mangrove areas, highlighting the ongoing recovery challenges in restored sites. This suggests that fertilizer application increased TOC in the natural station and TN in the restored station. TP levels were similar in both locations. TOC, bulk density, and sand content correlated negatively. However, TN and oxidized ambient circumstances correlated positively. The observed carbon, nitrogen, and phosphorus imbalances in rehabilitated mangrove soil indicate deviations from Redfield Stoichiometry, which could hinder the long-term stability and health of restored mangroves. Addressing these nutrient imbalances in future restoration efforts could support more effective ecosystem recovery.

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REFERENCES

1. Alongi D.M. (2018). Impact of global change on nutrient dynamics in mangrove forests. *Forests*, 9(10), 596.
2. Alongi D.M. (2021). Macro-and micronutrient cycling and crucial linkages to geochemical processes in mangrove ecosystems. *J Mar Sci Eng,* 9(5), 456.
3. Asari N., Suratman M.N., Mohd Ayob N.A., Abdul Hamid N.H. (2021). Mangrove as a natural barrier to environmental risks and coastal protection. In: Rastogi R.P., Phulwaria M., Gupta D.K. (eds). *Mangroves*: *Ecology*, *Biodiversity and Management*. Springer, Singapore.
4. Boto K.G. (2018). Nutrients and mangroves. In: Connell D.W., Hawker D.W. (eds). *Pollution in Tropical Aquatic Systems*. CRC Press, Taylor and Francis Group.
5. Chen G.C., Ulumuddin Y.I., Pramudji S., Chen S.Y., Chen B., Ye Y., Ou D.Y., Ma Z.Y., Huang H., Wang J.K. (2014). Rich soil carbon and nitrogen but low atmospheric greenhouse gas fluxes from North Sulawesi mangrove swamps in Indonesia. *Sci Total Environ*, 487, 91-96.
6. Chen J., Huang Y., Chen G., Zhu H., Qiu Y., Ye Y. 2022. Effect of site elevation and soil depth on the biomass and carbon, nitrogen, and phosphorus stocks of roots in planted Kandelia obovata mangrove forests. *Restor Ecol*, 31(3), e13712.
7. Craig H., Antwis R.E., Cordero I., Ashworth D., Robinson C.H., Osborne T.Z., Bardgett R.D., Rowntree J.K., Simpson L.T. (2021). Nitrogen addition alters composition, diversity, and functioning of microbial communities in mangrove soils: An incubation experiment. *Soil Biol Biochem*, 153, 108076.
8. Das S.C., Das S., Tah J. (2022). Mangrove ecosystems and their services. In: Das S.C., Pullaiah M., Ashton E.C. (eds). *Mangroves*: *Biodiversity*, *Livelihoods and Conservation*. Springer Nature Singapore.
9. Datta D., Deb S. (2017). Forest structure and soil properties of mangrove ecosystems under different management scenarios: Experiences from the intensely humanized landscape of Indian Sunderbans. *Ocean Coast Manag*, 140, 22–33.
10. Deb S., Bhadoria P.B., Mandal B., Rakshit A., Singh H.B. (2015). Soil organic carbon: Towards better soil health, productivity and climate change mitigation. *Climate Change and Environmental Sustainability*, 3(1), 26–34.
11. Dharmawan I.W.E., Ulumuddin Y.I. (2021). *Mangrove Community Structure Data Analysis*: *A Guidebook for Mangrove Health Index* (*MHI*) *Training*. Nas Media Pustaka, Makassar. [Indonesian].
12. Dharmawan I.W.E. 2020. Hemispherical Photography: Analisis Tutupan Kanopi Komunitas Mangrove. Nas Media Pustaka, Makassar. [Indonesian].
13. Dharmayasa I.G., Sugiana I.P., Putri P.Y., Boonyasana K. 2024. Assessment of soil fraction, carbon storage capacity, and rate of carbon uptake from three coastal ecosystems: Mangroves, seagrass, and mudflats in Benoa Bay, Indonesia. *Biodiversitas*, 25(6), 2541-2549.
14. Ernawati N.M., Astarini I.A., Suarna I.W., As-Syakur A., Perwira I.Y., Krisna Dewi A.P., Sugiana I.P. 2024. Comparison of soil carbon-nitrogen ratio at two different mangrove ecosystem in Bali, Indonesia. *Ecol Eng Environ Technol*, 25(7), 343-354.
15. Farooqui Z., Siddiqui P.J., Rasheed M. (2014). Changes in organic, inorganic contents, carbon nitrogen ratio in decomposing Avicennia marina and Rhizophora mucronata leaves on tidal mudflats in Hajambro creek, Indus delta, Pakistan. *J Trop Life Sci*, 4(1), 37-45.
16. Feng J., Cui X., Zhou J., Wang L., Zhu X., Lin G. (2019). Effects of exotic and native mangrove forests plantation on soil organic carbon, nitrogen, and phosphorus contents and pools in Leizhou, China. *Catena*, 180, 1-7.
17. Freitas R.F., Brauko K.M., Pagliosa P.R. (2021). Relationships between mangrove root system and benthic macrofauna distribution. *Hydrobiologia*, 848(6), 1391-407.
18. Gerona-Daga M.E., Salmo S.G. III. (2022). A systematic review of mangrove restoration studies in Southeast Asia: Challenges and opportunities for the United Nation's Decade on Ecosystem Restoration. *Front Mar Sci*, 9, 987737.
19. Giri C., Ochieng E., Tieszen L.L., Zhu Z., Singh A., Loveland T., Masek J., Duke N. (2011). Status and distribution of mangrove forests of the world using earth observation satellite data. Glob Ecol *Biogeogr*, 20(1), 154-169.
20. Gnanamoorthy P., Selvam V., Ramasubramanian R., Chakraborty S., Pramit D., Karipot A. (2019). Soil organic carbon stock in natural and restored mangrove forests in Pichavaram south-east coast of India. *Indian J Mar Sci*, 48(5), 801-808.
21. Hashemi F., Olesen J.E., Dalgaard T., Børgesen C.D. (2016). Review of scenario analyses to reduce agricultural nitrogen and phosphorus

loading to the aquatic environment. *Sci Total Environ*, 573, 608-626.

22. Huang X., Xian T., Long T., He L., Donald M.L., Deng D., Dong T. (2024). Impacts of vegetation restoration strategies on soil nutrients and stoichiometry of the earthquake-induced landslides in Jiuzhaigou, eastern Qinghai-Tibet Plateau. *Front Environ Sci*, 11, 1296187.
23. Japan International Cooperation Agency (JICA) (1999). The Final Report of Project Administration: The Development of Sustainable Mangrove Management Project Bali and Lombok, Republic of Indonesia. Jakarta, Indonesia: Ministry of Forestry and Estate Crops in Indonesia - Japan International Cooperation Agency.
24. Kusmana C. (2014). Distribution and current status of mangrove forests in Indonesia. In: Hanum I.F., Latiff A., Hakeem K.R., Ozturk M. (eds). *Mangrove Ecosystems of Asia*: *Status*, *Challenges*, *and Management Strategies*. Springer, New York.
25. Lewis R.R. III, Brown B.M., Flynn L.L. (2019). Methods and criteria for successful mangrove forest rehabilitation. In: Perillo G.M.E., Wolanski E., Cahoon D.R., Hopkinson C.S. (eds). *Coastal Wetlands* (*Second Edition*). Elsevier.
26. Li R., Liang Z., Hou L., Zhang D., Wu Q., Chen J., Gao L. (2023). Revealing the impacts of human activity on the aquatic environment of the Pearl River Estuary, South China, based on sedimentary nutrient records. *J Clean Prod*, 385, 135749.
27. Li X., Cheng X., Cheng K., Cai Z., Feng S., Zhou J. 2024. The influence of tide-brought nutrients on microbial carbon metabolic profiles of mangrove sediments. *Sci Total Environ*, 906, 167732.
28. López-Portillo J., Lewis R.R., Saenger P., Rovai A., Koedam N., Dahdouh-Guebas F., Agraz-Hernández C., Rivera-Monroy V.H. 2017. *Mangrove forest restoration and rehabilitation*. In: Rivera V.H., Lee S.Y., Kristensen E., Twilley R.R. (eds). *Mangrove Ecosystems*: *A Global Biogeographic Perspective*: *Structure, Function, and Services*. Springer, Cham.
29. Lovelock C.E., Feller I.C., Ball M.C., Engelbrecht B.M., Ewe M.L. (2006). Differences in plant function in phosphorus and nitrogen limited mangrove ecosystems. *New Phytol*, 172(3), 514-522.
30. Lovelock C.E., Sorrell B.K., Hancock N., Hua Q., Swales A. (2010). Mangrove forest and soil development on a rapidly accreting shore in New Zealand. *Ecosystems*, 13, 437-451.
31. Mack M.R., Langley J.A., Feller I.C., Chapman S.K. (2024). The ecological consequences of nutrient enrichment in mangroves. *Estuar Coast Shelf Sci*, 300, 108690.
32. MacKenzie R., Sharma S., Rovai A.R. 2021. Environmental drivers of blue carbon burial and soil carbon stocks in mangrove forests. In: Sidik F., *Friess D. (eds). Dynamic Sedimentary Environments of Mangrove Coasts*. Elsevier.
33. Malhotra H., Vandana, Sharma S., Pandey R. (2018). Phosphorus nutrition: Plant growth in response to deficiency and excess. In: Hasanuzzaman M., Fujita M., Oku H., Nahar K., Hawrylak-Nowak B. (eds). *Plant Nutrients and Abiotic Stress Tolerance*. Springer, Singapore.
34. Masoud M.S., Abdel-Halim A.M., El Ashmawy A.A. (2019). Seasonal variation of nutrient salts and heavy metals in mangrove (Avicennia marina) environment, Red Sea, Egypt. Environ Monit *Assess*, 191(7), 425.
35. McKee K.L., Faulkner P.L. (2000). Restoration of biogeochemical function in mangrove forests. *Restor Ecol*, 8(3), 247-259.
36. Meng D., Cheng H., Shao Y., Luo M., Xu D., Liu Z., Ma L. 2022. Progress on the effect of nitrogen on transformation of soil organic carbon. Processes, 10(11), 2425.
37. Mitra A. (2020). Ecosystem services of mangroves: An overview. In: Mitra A. (eds). *Mangrove Forests in India*: *Exploring Ecosystem Services*. Springer, Cham.
38. Ngatia L., Grace J.M. III, Moriasi D., Taylor R. (2019). Nitrogen and phosphorus eutrophication in marine ecosystems. In: Fouzia H.B. (eds). *Monitoring of Marine Pollution*. IntechOpen.
39. Palit K., Rath S., Chatterjee S., Das S. (2022). Microbial diversity and ecological interactions of microorganisms in the mangrove ecosystem: Threats, vulnerability, and adaptations. *Environ Sci Pollut Res*, 29(22), 32467-32512.
40. Prinasti N.K., Dharma I.G., Suteja Y. (2020). Community structure of mangrove vegetation based on substrate characteristic in Ngurah Rai Forest Park, Bali. *J Mar Aquat Sci*, 6(1), 90-99.
41. Rakesh S., Sinha A.K., Mukhopadhyay P. (2020). Vertical distribution of TOC, TN and other important soil attributes and their relationship in Alfisol and Entisol of West Bengal. Int J Environ Clim *Change*, 10(1), 62-73.
42. Ray R., Mukhopadhyay S.K., Jana T.K. (2021). Nitrogen and phosphorus budget in mangrove ecosystem. In: Rastogi R.P., Phulwaria M., Gupta D.K. (eds). *Mangroves: Ecology*, *Biodiversity and Management*. Springer, Singapore.
43. Reef R., Feller I.C., Lovelock C.E. (2010). Nutrition of mangroves. *Tree Physiol*, 30(9), 1148-1160.
44. Reis C.R., Nardoto G.B., Oliveira R.S. (2017). Global overview on nitrogen dynamics in mangroves and consequences of increasing nitrogen availability for these systems. *Plant Soil*, 410, 1-9.
45. Sanders C.J., Eyre B.D., Santos I.R., Machado W., Luiz-Silva W., Smoak J.M., Breithaupt J.L., Ketterer M.E., Sanders L., Marotta H., Silva-Filho E. (2014). Elevated rates of organic carbon, nitrogen, and

phosphorus accumulation in a highly impacted mangrove wetland. *Geophys Res Lett*, 41(7), 2475-2480.

46. Scharler U.M., Ulanowicz R.E., Fogel M.L., Wooller M.J., Jacobson-Meyers M.E., Lovelock C.E., Feller I.C., Frischer M., Lee R., McKee K., Romero I.C. (2015). Variable nutrient stoichiometry (carbon: nitrogen: phosphorus) across trophic levels determines community and ecosystem properties in an oligotrophic mangrove system. *Oecologia*, 179, 863-876.
47. Shiau Y.J., Dham V., Tian G., Chiu C.Y. (2016). Factors influencing removal of sewage nitrogen through denitrification in mangrove soils. *Wetlands*, 36, 621-630.
48. Su J., Friess D.A., Gasparatos A. (2021). A meta-analysis of the ecological and economic outcomes of mangrove restoration. *Nat Commun*, 12(1), 5050.
49. Sugiana I.P., Andiani A.A.E., Dewi I.G.A.I.P., Karang I.W.G.A., As-Syakur A.R., Dharmawan I.W.E. (2022). Spatial distribution of mangrove health index on three genera dominated zones in Benoa Bay, Bali, Indonesia. *Biodiversitas*, 23(7), 3407-3418.
50. Sugiana I.P., Prartono T., Rastina R., Koropitan A.F. (2024a). Ecosystem carbon stock and annual sequestration rate from three genera-dominated mangrove zones in Benoa Bay, Bali, Indonesia. *Biodiversitas*, 25(1), 153-165.
51. Sugiana I.P., Prartono T., Rastina R., Koropitan A.F. (2024b). Warming effect from soil greenhouse gas emission of each mangrove zone during the dry season in Ngurah Rai Forest Park, Bali, Indonesia. *Environ Nat Resour J*, 22(5), 449-463.
52. Sun H., He Z., Zhang M., Yen L., Cao Y., Hu Z., Peng Y., Lee S.Y. (2020). Spatial variation of soil properties impacted by aquaculture effluent in a small-scale mangrove. *Mar Pollut Bull*, 160, 111511.
53. Sung C.T., Ishak C.F., Abdullah R., Othman R., Panhwar Q.A., Aziz M.M. (2017). Soil properties (physical, chemical, biological, mechanical). In: Ashraf M.A., Othman R., Ishak C.T. (Eds). *Soils of Malaysia*. CRC Press, Taylor and Francis Group.
54. Wijaya I.M.S., Sugiana I.P., Wijana I.M.S., Assyakur A.R. (2023). Comparison of mangrove vegetation in natural and ex-fisheries area in Benoa Bay, Bali. *Aquac Aquarium Conserv Legis*, 16(2), 825-836.
55. Worthington T., Spalding M. 2018. Mangrove restoration potential: A global map highlighting a critical opportunity. Conference: The 5th International Mangrove Macrobenthos and Management Meeting (MMM5), University of Cambridge, England.
56. Wu M., He Z., Fung S., Cao Y., Guan D., Peng Y., Lee S.Y. (2020). Species choice in mangrove reforestation may influence the quantity and quality of long-term carbon sequestration and storage. *Sci Total Environ*, 714, 136742.
57. Xia S., Song Z., Li Q., Guo L., Yu C., Singh B.P., Fu X., Chen C., Wang Y., Wang H. (2021). Distribution, sources, and decomposition of soil organic matter along a salinity gradient in estuarine wetlands characterized by C ratio, δ13C-δ15N, and lignin biomarker. *Glob Change Biol*, 27(2), 417-434.
58. You S., Loh P., Li Z., Qin H., Pradit S., Le T.P., Oeurng C., Mohamed C.A., Lee C.W., Lu X., Anshari G.Z. (2022). Geochemical behavior of sedimentary phosphorus species in northernmost artificial mangroves in China. *Forests*, 13(4), 610.
59. Zeng W., Wang Z., Chen X., Yao X., Ma Z., Wang W. (2023). Nitrogen deficiency accelerates soil organic carbon decomposition in temperate degraded grasslands. *Sci Total Environ*, 881, 163424.
60. Zhang N., Guo R., Wang F., Dai Z., Li Y., Cao W. (2024). Warming tends to promote nitrogen conservation but stimulate N2O emissions in mangrove sediments. *Ecosystems*, 27(2), 235-229.
61. Zhu D.H., Song Q.L., Nie F.H., Wei W., Chen M.M., Zhang M., Lin H.Y., Kang D.J., Chen Z.B., Hay A.G., Chen J.J. (2022). Effects of environmental and spatial variables on bacteria in Zhanjiang mangrove sediments. *Curr Microbiol*, 79(4), 97.