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Article

Aquatic Biodiversity as an Impact of Mangrove Restoration in Lubuk Kertang, North Sumatra

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Abstract

Abstract: Mangrove restoration is widely promoted as a nature-based solution to reverse coastal wetland degradation while sustaining fisheries productivity and other ecosystem services. This study evaluated whether a mangrove restoration program in Lubuk Kertang (North Sumatra, Indonesia) is associated with enhanced aquatic biodiversity and supporting water-quality conditions. Mangrove vegetation structure was assessed across restoration ages (2009–2013 plantings; 7–11 years old at the time of survey), and fish assemblages and water quality were sampled in June, August, and December 2021. We recorded 828 individual fishes representing 44 species, 27 families, and 17 orders. Fish diversity was moderate (mean Shannon–Wiener $H' = 2.15$; evenness = 0.83; dominance = 0.17), with Engraulidae contributing the highest abundance. Water quality conditions were within ranges typical for estuarine mangrove habitats (DO 3.5–5.15 mg L⁻¹; pH 6.6–7.85; salinity 17.5–28.5; temperature 28.3–31.55 °C). Mangrove vegetation diversity indices were low to moderate (0.05–1.12) across restoration ages. These findings indicate that restored mangrove stands can function as aquatic habitat supporting diverse fish assemblages while maintaining basic water-quality conditions, reinforcing the role of mangrove restoration in sustainable coastal development and the Sustainable Development Goals (SDGs).

Keywords: mangrove restoration; fish assemblage; aquatic biodiversity; water quality; estuary; coastal resilience; blue carbon; sustainable development goals; *Rhizophora*; *Mugilidae*

1. Introduction

Mangroves are among the most productive ecosystem on Earth, providing unique habitats that support many species and offer valuable services to humans [1–3]. Known for their high biodiversity [4], mangroves serve as critical nurseries and food sources [5] by supplying organic matter and nutrients that sustain aquatic communities [6–8]. Furthermore, mangroves play an important component in the trophic chain [9] and are key sources of food for fish and invertebrates [10]. However, some of the mangrove habitats have been lost due to human activities [11,12]. In Indonesia, this decline is largely due to the expansion of aquaculture ponds [13,14] and oil palm plantations [15,16] reported that up to 80% of mangrove losses in six Southeast Asian countries were attributed to human activities, driven by regional pressures to expand aquaculture for economic development. In addition, [17] noted that Indonesia is one of the largest contributors to global carbon emissions due to mangrove conversion into ponds. Restoring degraded mangrove ecosystems is critical. According to [18], the rehabilitation and restoration of mangrove ecosystems are vital for the ecology, economy,

and well-being of coastal communities. The restoration and rehabilitation program are a step to build ecosystem services to carry out community-based biodiversity conservation [19]. These initiatives must consider hydrology, mangrove vegetation, and associated fauna. While restoration aims to return habitats to their natural conditions, rehabilitation focuses on optimizing ecosystem services beyond biodiversity. Long-term success depends on many aspects [20], highlighting the importance of well-managed mangrove restoration in coastal development [21]. However, natural challenges can affect restoration efforts, as coastal areas are subject to environmental adaptations [22]. Mangroves have a profound effect on surrounding waters. For example, [23] demonstrated a positive relationship between mangrove coverage and shrimp catches in Indonesia, the Philippines, Australia, and Mexico. In addition, estuarine fish in the tropics are closely linked to mangrove habitats [24]. The restoration of mangroves is critical, as these ecosystems provide important habitats for various species [25]. In addition, mangrove litter becomes the basis of the food web, breaking down into detritus which ultimately serves as food source within the ecosystem. Given the importance of the ecological economic benefits of mangrove restoration and its role in supporting biodiversity, this study aims to determine the diversity of fish species in restored mangrove areas. The findings will help for mangrove restoration activities worldwide, especially in Indonesia.

Beyond local ecological objectives, mangrove restoration is increasingly framed as a pathway to deliver multiple Sustainable Development Goals (SDGs), including climate action (SDG 13), life below water (SDG 14), life on land (SDG 15), resilient coastal settlements (SDG 11), and livelihoods and food security (SDGs 1–2 and 8) (United Nations, 2015). Linking restoration outcomes to these development targets can strengthen the rationale for continued investment and help identify monitoring indicators that capture both ecological recovery and coastal-development benefits.

2. Materials and Methods

2.1. Study Area

The research was conducted in restored mangrove areas located in Lubuk Kertang, Pangkalan Brandan, North Sumatra (Figure 1). Sampling of aquatic fauna was carried out in June, August, and December 2021.

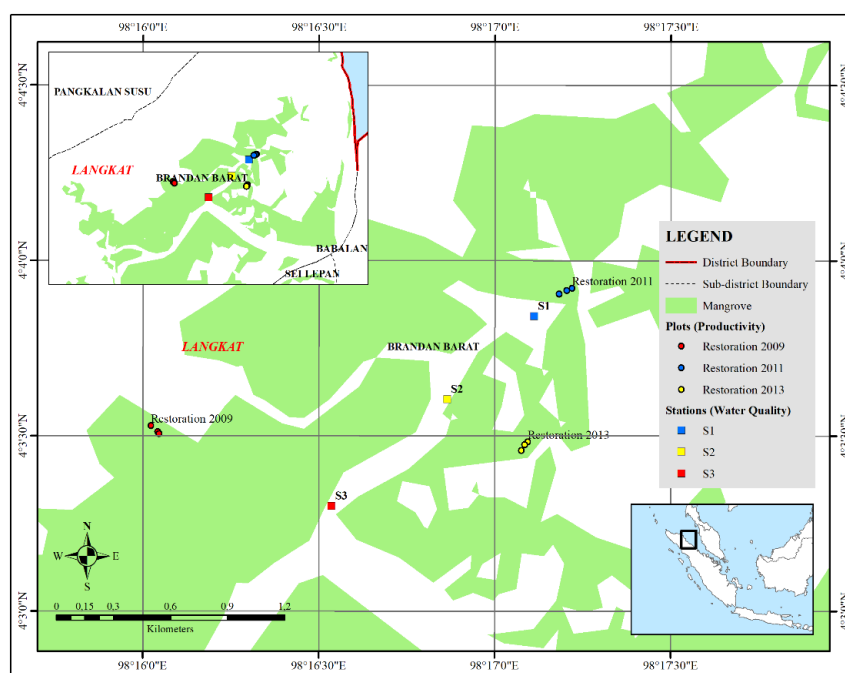


Figure 1. Research sites in restored mangroves from 2009 (S1; blue), 2011(S2; yellow) and 2013 (S3; red) along the east coast of North Sumatra.

2.2. Procedure

- Observation of mangrove vegetation; Mangrove vegetation was observed at three locations, corresponding to restoration years: 2009, 2011, and 2013, all situated in North Sumatra. In each site, 10 plots were established using a combination of stripe and gridline methods [26] to analyze the vegetation.
- *Observation of aquatic fauna*; Fish collection was carried out in the waters surrounding the restored mangrove forests in Lubuk Kertang. Sampling was carried in June, August, and December 2021 at the locations shown in Figure 1. Local fishing methods were employed using boats and 'kedera' nets, which have a length of 150 m and a width of 1.5 m. The mesh size of the nets consists of three layers, namely 1, 1.5, and 1.6 inches. After collecting the specimens, they were identified based on [27] and [28], with species verification through FishBase.org.
- *Water quality measurement*; Water quality parameters were measured for each fish sampling period in June, August, and December 2021. These parameters measured included; DO (mg/L), pH, salinity (ppm), and temperature (°C). The data was compiled and analyzed using Microsoft Excel 2016.

2.3. Data Analysis

Data analysis included the composition of fish species, diversity index (H'), evenness (J), and dominance (C). The species composition was analyzed by grouping the fish species and determining their percentage relative to the total number of fish sampled. The diversity index (H') is calculated following the Shannon and Wiener formula [29] where n_i is the number of species i and N is the total number of all fish.

$$H' = - \sum_i \frac{n_i}{N} \ln \frac{n_i}{N} \quad (1)$$

Evenness index (J) follows Pielou's equation [30], with the analysis that H' is the Shannon-Wiener diversity index compared to \ln number of species (S), which is presented in the formula as below:

$$J = \frac{H'}{\ln S} \quad (2)$$

While the analysis to obtain the dominance index (C) follows [31], C is the dominance index, n_i is the number of species i and N is the total number of all fish. The equal follows the formula as below:

$$C = \sum \left(\frac{n_i}{N} \right)^2 \quad (3)$$

3. Results

3.1. Density and Diversity of Mangrove Vegetation

Mangrove restoration in Lubuk Kertang, Pangkalan Brandan, Langkat, North Sumatra has progressed through several stages, with reforestation efforts initiated in in 2009, followed by additional plantings in 2011 and 2013 at different locations within the Lubuk Kertang area. Observations at these three locations described the different densities of mangrove vegetation. The restoration in 2009 showed well progress, indicated by the presence of *Rhizophora apiculata*, *Sonneratia alba*, *Xylocarpus granatum*, and *Ceriops tagal*. The restoration area in 2011 had two species of mangroves, namely *Rhizophora apiculata* (planting) and *Sonneratia alba*. Likewise, the 3rd restoration area, namely the restoration in 2013 has 2 species, namely *Rhizophora apiculata* (planting) and *Sonneratia alba*. The restoration age of the study sites ranged from 7 to 11 years, with varying densities at different growth stages (Figure 2). Tree growth rates were the lowest compared to saplings and seedlings. Tree growth rates in the 2009 restoration area for *Rhizophora apiculata* was 350 ind/ha and

Sonneratia alba was found with a density of 190 ind/ha. While *Xylocarpus granatum* and *Ceriops tagal* were not found at the tree level, the 2011 restoration area *Rhizophora apiculata* and *Sonneratia alba* were found with a density of 130 ind/ha. The 2013 restoration area tree level was found to have a higher density than the 2011 restoration area.

The sapling growth rate in all restoration areas had a higher density than the other tree growth rates. However, this did not occur at the level of sapling growth in the species *Xylocarpus granatum* and *Ceriops tagal*. In both species, the seedling level had a higher density than the sapling growth rate. The seedling growth rate were highest in 2013 restorations area, with densities of 4750 ind/ha (*Rhizophora apiculata*) and 3000 ind/ha (*Sonneratia alba*). The growth rate of saplings and seedlings in the 2009 and 2011 restoration areas were lower.

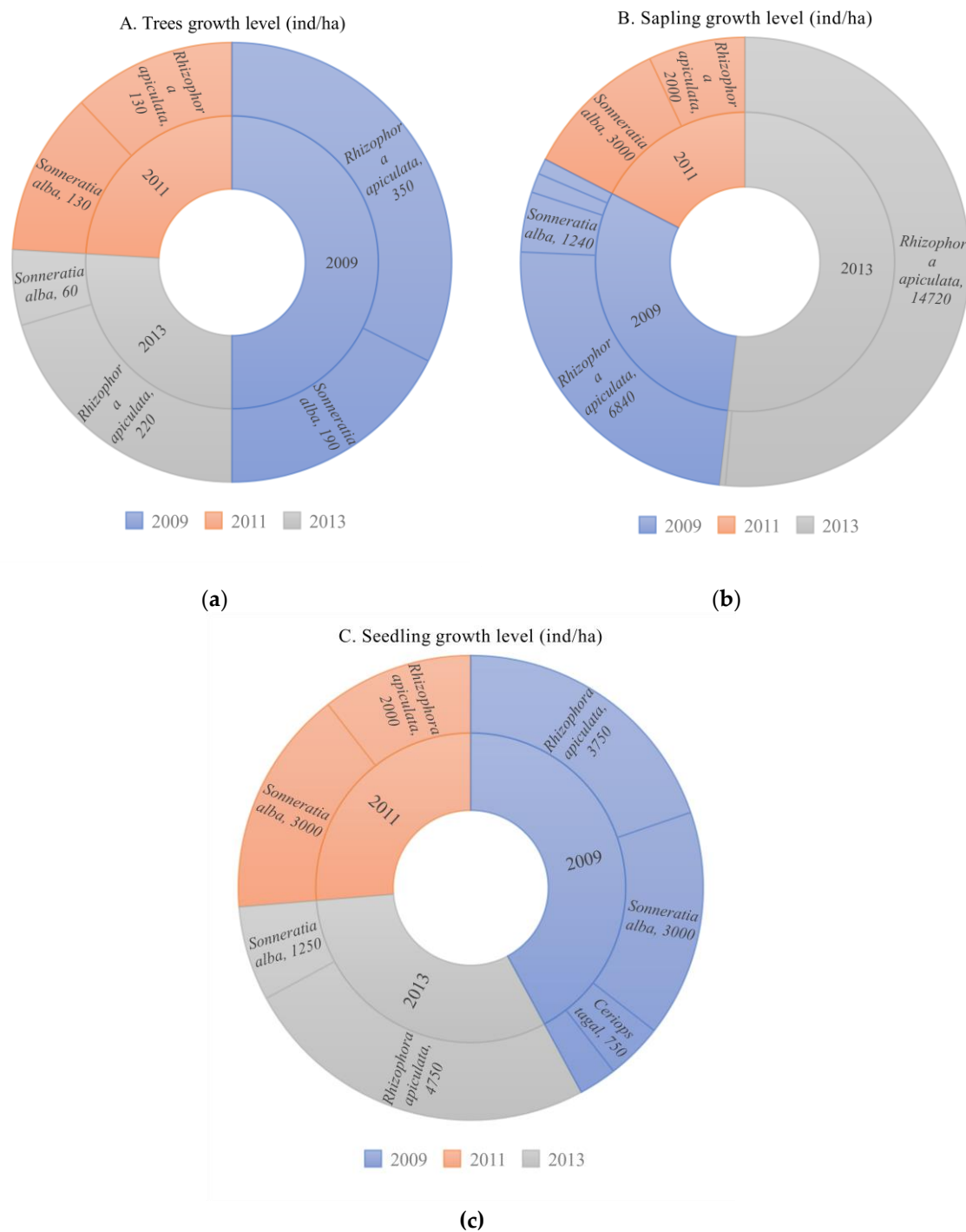


Figure 2. Density patterns of mangrove species (ind/ha) at various growth stages in different restoration areas; A) tree growth level, B) Sapling growth level, and C) Seedling growth level.

The mangrove vegetation diversity index was low across all restoration areas, ranging from 0.05 to 1.12. The highest diversity index was observed in the 2013 restoration (Figure 3). The average diversity indices were 0.62 (tree growth rate), 0.29 (sapling growth rate), and 0.77 (seedling growth rate). The 2013 restoration area had the highest diversity index for both saplings and seedlings.

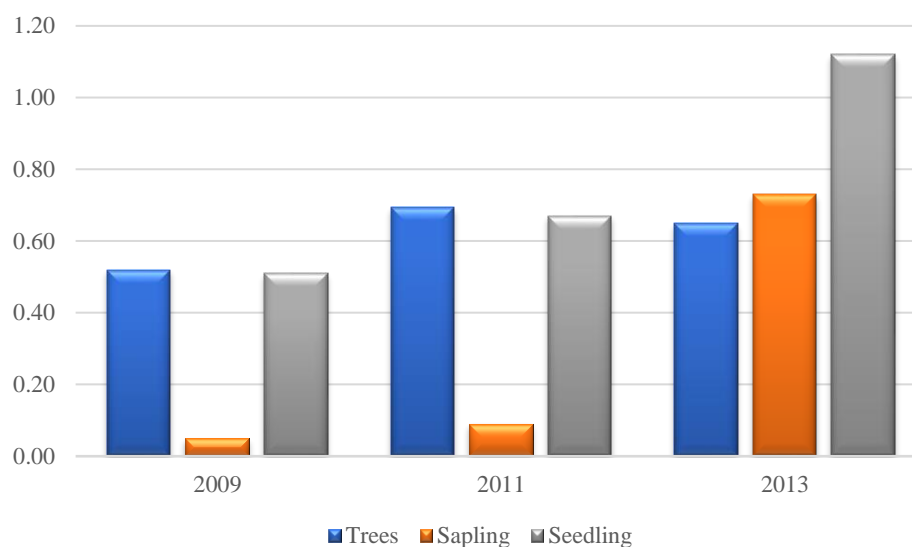


Figure 3. Variations in mangrove vegetation diversity index based on the year of restoration.

3.2. Diversity and Composition of Fishes

A total of 828 fish individuals were sampled, representing 44 fish species from the class Actinopteri, which consists of 17 orders, 27 families, 39 genera (Table 1). The fish species composition as follows; total of all species of fish caught 4.71% were found with a percentage of less than 0.6% (20 species), 12.56% were found in the range 0.6% to 1.93% (13 species) and 79.23% were found with a percentage between 2.66% to 25.36% (11 species). Figure 4 shows the species composition based on the percentage of fish species caught during the study (percentages less than 0.60% are not shown in the figure).

Table 2. The diversity of fish found in the waters of the restored mangrove ecosystem is based on order, family, genus and species.

Order	Family	Genus	Species	Relative abundance (%)
Acanthuriformes	Ephippidae	Ephippus	<i>Ephippus argus</i>	0.36
	Leiognathidae	Eublekeeria	<i>Eublekeeria jonesi</i>	3.26
		Secutor	<i>Secutor interruptus</i>	1.21
	Scatophagidae	Scatophagus	<i>Scatophagus argus</i>	0.60
	Siganidae	Siganus	<i>Siganus canaliculatus</i>	0.60
Anabantiformes	Channidae	Channa	<i>Channa striata</i>	0.12
Anguilliformes	Muraenesocidae	Muraenesox	<i>Muraenesox cinereus</i>	0.36
Beloniformes	Hemiramphidae	Hemiramphus	<i>Hemiramphus</i> sp.	1.93
		Hyporhamphus	<i>Hyporhamphus quoyi</i>	0.12
Carangaria	Sphyraenidae	Sphyraena	<i>Sphyraena barracuda</i>	0.36
	Toxotidae	Toxotes	<i>Toxotes jaculatrix</i>	0.97
Carangiformes	Carangidae	Scomberoides	<i>Scomberoides</i> sp.	0.24

		Atule	<i>Atule mate</i>	0.24
		Selaroides	<i>Selaroides leptolepis</i>	0.24
	Xiphiidae	Xiphias	<i>Xiphias</i> sp.	0.24
Clupeiformes	Clupeidae	Herklotsichthys	<i>Herklotsichthys dispilonotus</i>	0.60
		Anodontostoma	<i>Anodontostoma chacunda</i>	0.48
	Dussumieriidae	Dussumieria	<i>Dussumieria acuta</i>	1.33
			<i>Dussumieria elopsoides</i>	3.62
	Pristigasteridae	Ilisha	<i>Ilisha striatula</i>	2.54
	Engraulidae	Setipinna	<i>Setipinna tenuifilis</i>	1.33
		Stolephorus	<i>Stolephorus indicus</i>	25.36
		Stolephorus	<i>Stolephorus waitei</i>	3.62
	Thryssa	<i>Thryssa hamiltonii</i>	8.45	
Eupercaria	Sciaenidae	Johnius	<i>Johnius tracheyephalus</i>	0.12
	Gerreidae	Gerres	<i>Gerres filamentosus</i>	0.36
	Lutjanidae	Lutjanus	<i>Lutjanus</i> sp.	0.12
			<i>Lutjanus ehrenbergii</i>	0.72
Gobiiformes	Gobiidae	Periophthalmodon	<i>Periophthalmodon schlosseri</i>	0.12
Gonorynchiformes	Chanidae	Channos	<i>Channos channos</i>	0.12
Mugiliformes	Mugilidae	Crenimugil	<i>Crenimugil buchanani</i>	8.82
		Crenimugil	<i>Crenimugil seheli</i>	4.11
		Ellochelon	<i>Ellochelon vaigiensis</i>	10.14
		Mugil	<i>Mugil cephalus</i>	1.93
		Planiliza	<i>Planiliza planiceps</i>	2.66
			<i>Planiliza subviridis</i>	0.12
Mulliformes	Mullidae	Upeneus	<i>Upeneus sulphureus</i>	0.36
Ovalentaria	Ambassidae	Ambassis	<i>Ambassis vachellii</i>	1.09
			<i>Ambassis gymnocephalus</i>	1.93
			<i>Ambassis nalua</i>	6.64
Pleuronectiformes	Cynoglossidae	Cynoglossus	<i>Cynoglossus lingua</i>	0.12
Scombriformes	Scombridae	Rastrelliger	<i>Rastrelliger kanagurta</i>	1.81
Synbranchiformes	Synbranchidae	Monopterus	<i>Monopterus albus</i>	0.24
Tetraodontiformes	Tetraodontidae	Lagocephalus	<i>Lagocephalus inermis</i>	0.24

The most common fish species were from the Engraulidae family (321 ind), which consisted of 3 genera, namely Setipinna, Stolephorus, and Thryssa. of the 340 ind observed about 74.76% is the genus Stolephorus, the rest are the genera Thryssa and Setipinna. During the study, the Mugilidae family found about 230 individuals consisting of 4 genera with the most genera being Crenimugil (46.52%) and Ellochelon (36.52%), the remaining 16.96% consisting of the genera Mugil and Planiliza. Another family that has a higher number than other families is Ambassidae which consists of 1 genus (3 species) with a total of 80 individuals. There were 20 species of fish with a number between 1-4 individuals during the study, the rest were found to be more than 5 individuals. Several families were found (Ephippidae, Scatophagidae, Siganidae, Channidae, Sphyrnaenidae, Toxotidae, Xiphiidae, Pristigasteridae, Sciaenidae, Gerreidae, Gobiidae, Chanidae, Mullidae, Cynoglossidae, Scombridae, Synbranchidae and Tetraodontidae) consisting of 1 genus and one species.

The total number of fish species present was the presence of 20 species which made up 4.71% of the total fish species found, namely *Anodontostoma chacunda*, *Atule mate*, *Channa striata*, *Channos*

channos, *Cynoglossus lingua*, *Ephippus argus*, *Gerres filamentosus*, *Hyporhamphus quoyi*, *Johnius tracheyephalus*, *Lagocephalus inermis*, *Lutjanus* sp., *Monopterus albus*, *Muraenesox cinereus*, *Periophthalmodon schlosseri*, *Planiliza subviridis*, *Scomberoides* sp., *Selaroides leptolepis*, *Sphyraena barracuda*, *Upeneus sulphureus*, *Xiphias* sp. While the fish percentages with 16.06% and 79.23% are presented in Figure 4.

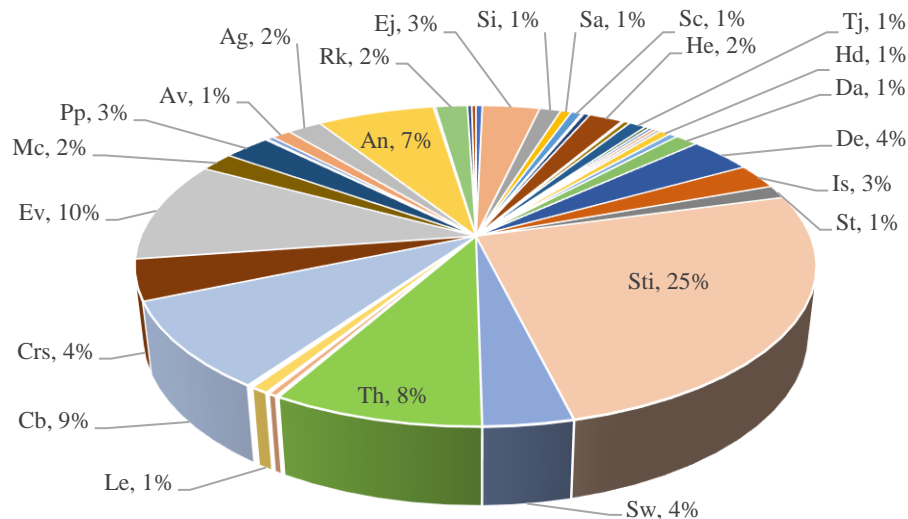


Figure 4. Fish species composition percentages greater than 0.6% during observations in June, August, and December 2021, Ag: *Ambassis gymnocephalus*, An: *Ambassis nalua*, Av: *Ambassis vachellii*, Cb: *Crenimugil buechanani*, Crs: *Crenimugil seheli*, Da: *Dussumieria acuta*, De: *Dussumieria elopsoides*, Ej: *Eublekeeria jonesi*, Ev: *Ellochelon vaigiensis*, He: *Hemiramphus* sp., Hd: *Herklotsichthys dispilonotus*, Is: *Ilisha striatula*, Le: *Lutjanus ehrenbergii*, Mc: *Mugil cephalus*, Pp: *Planiliza planiceps*, Rk: *Rastrelliger kanagurta*, Sa: *Scatophagus argus*, Sc: *Siganus canaliculatus*, Si: *Secutor interruptus*, St: *Setipinna tenuifilis*, Sti: *Stolephorus indicus*, Sw: *Stolephorus waitei*, Tj: *Toxotes jaculatrix*, Th: *Thryssa hamiltonii*.

The fish composition of 16.06% was composed of 13 species of fish, namely: *Ambassis gymnocephalus*, *Ambassis vachellii*, *Dussumieria acuta*, *Hemiramphus* sp., *Herklotsichthys dispilonotus*, *Lutjanus ehrenbergii*, *Mugil cephalus*, *Mugil cephalus*, *Rastrelliger kanagurta*, *Scatophagus argus*, *Secutor interruptus*, *Setipinna tenuifilis*, *Siganus canaliculatus*, *Toxotes jaculatrix*. The largest composition is 79.23%, consisting of 11 species which include *Ambassis nalua*, *Crenimugil buechanani*, *Crenimugil seheli*, *Dussumieria acuta*, *Eublekeeria jonesi*, *Ellochelon vaigiensis*, *Ilisha striatula*, *Planiliza planiceps*, *Stolephorus indicus*, *Stolephorus waitei*, *Thryssa hamiltonii*.

3.3. Fish diversity Index

The diversity index (H') of fish during the study period (June, August, and December 2021) ranged at a medium level (Figure 5). The average diversity index was 2.15, evenness 0.83, and dominance at 0.17. June exhibited the highest diversity, while August had the lowest. The evenness and dominance indices remained relatively stable across the months, with a slight increase in dominance in August 2021.

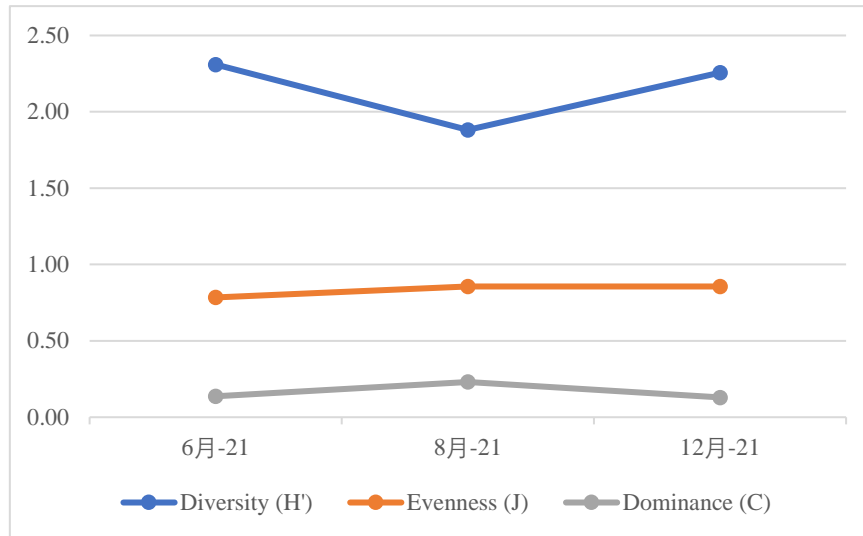
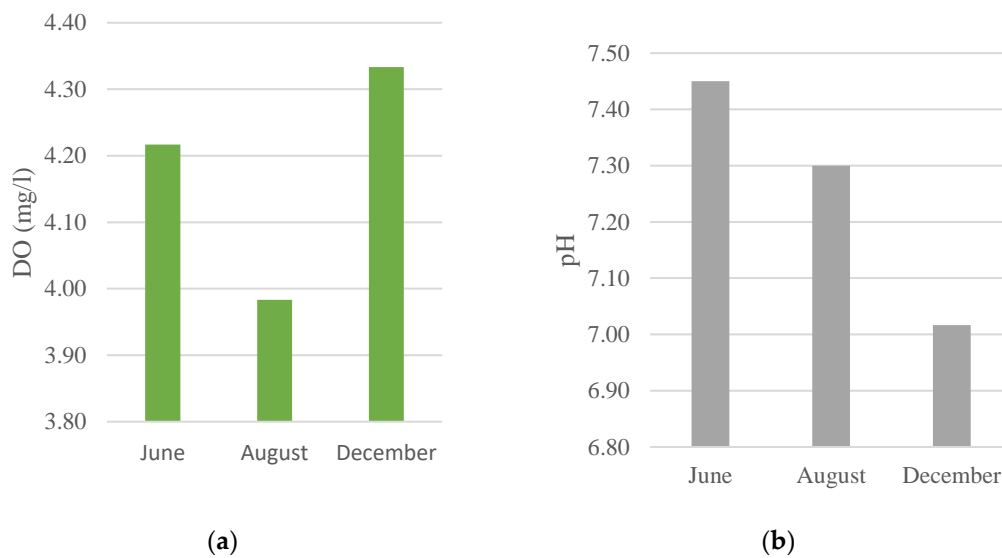


Figure 5. Diversity index (H'), Evenness (E), and dominance (C) of fish species during the study period in June, August, and December 2021.

3.4. Water Quality

Water quality parameters namely measurements were carried out including dissolved oxygen (DO), pH, salinity, and temperature are presented in Figure 6. Dissolved oxygen concentration ranged from 3.5-5.15 mg/L, pH ranged 6.6-7.85, salinity ranged 17.5 -28.5 ppt, and temperature ranged 28.3 - 31.55°C.



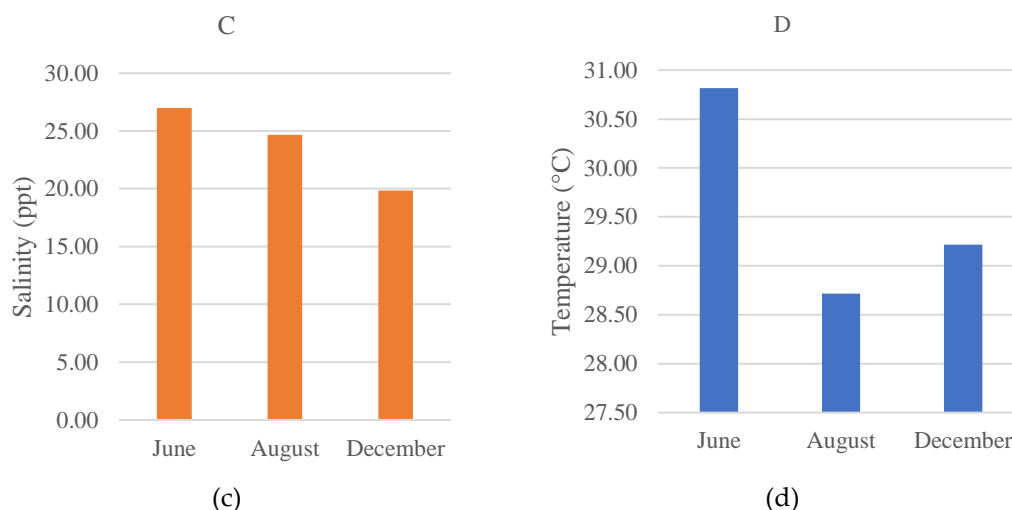


Figure 6. Water quality parameters during the study; A) DO (mg/L), B) pH, C) salinity (ppm), D) Temperature (°C) in June, August, and December 2021.

4. Discussion

4.1. Density and Diversity of Mangrove Vegetation Restoration

The density of mangrove vegetation in the restoration area as presented in Figures 2A, B and C, reflects the progress of the restoration efforts that began in 2009. The dominant species, *R. apiculata*, has consistently been prevalent, as observed in the restoration efforts in 2011 and 2013. This condition is expected, as *R. apiculata* is commonly used in [32] mangrove replanting projects due to its adaptability to tidal water channels and soft, muddy soils [33,34] in addition, its high survival rate and abundance in Southeast Asia and Australia further justify its use in restoration [35,36].

The mangrove density in 2009 was higher compared to 2011 and 2013, likely due to the earlier planting and subsequent growth. *Sonneratia alba*, which was less dense compared to *Rhizophora apiculata*, is also noted for its wide distribution in the Asian region and grown in estuarine areas [37].

The similar density in 2011 for sapling and seedling (2000 ind/ha for *Rhizophora apiculata* and 3000 ind/ha for *Sonneratia alba*) suggests comparable restoration conditions, with environmental factors influencing the outcomes [38], in which the combination of light and salinity will affect exogenous gibberellic acid (GA3).

By 2013, the tree density of *Rhizophora apiculata* <2009 and > 2011, indicating a natural progression in vegetation density. In contrast to *Sonneratia alba*, the density of trees in restoration forest was 2009>2011>2013. This is presumably because the age of vegetation in 2009 was longer so that the number of trees was more numerous and denser. Even though if we look at the diameter of the trees, the 2009 restoration forest is considered to have a lower tree diameter compared to other restoration years. Restoration forest in 2013 has a range between 10.83-16.88 cm, restoration in 2011 with a range of 10.19-18.15 cm, and restoration forest in 2009 is in the range of 10.19-16.24 cm.

4.2. Diversity and Composition of Fishes

The study identified 44 species comprise 27 families, with *Stolephorus* being the most abundant (74.76%), particularly *Stolephorus indicus* and *Stolephorus waitei*. The high abundance of this genus noted during the August 2021 sampling. This genus includes Engraulidae, and according to [39] and [40], they are often found in flocks in coastal areas, although some move into brackish waters to find food or lay eggs, while others settle permanently. *Stolephorus* has a wide distribution in tropical areas, such as in the Indo-West Pacific [40]. In addition, various locations have been recorded in India [41,42], Pakistan [43], Taiwan [44], Turkey [45], and the Mediterranean Sea, including Israel [46].

The abundance of this genus at the research location is similar to the mangrove area of Segara Anakan Cilacap, Central Java [47], where it is more abundant compared to other species. These two species are thought to be found in large numbers because the mangrove waters serve as a feeding ground. This suggests that the mangrove area of the Lubuk Kertang restoration can support the genus well and provide sufficient food. This assumption is well-founded, as crustacean groups are also found around the fishing grounds (not presented in this study). Research conducted in the Purworejo mangrove area highlights the richness of the crustacean group, which is around 19 species recorded [48]. It is suspected that one of the reasons for the presence of *Stolephorus* in mangrove waters is that these areas are rich in food sources.

The relationship between the presence of fish and food sources indicates that mangrove restoration forests can provide essential food for fish. This hypothesis is supported by [49] who reported that this group of species primarily feeds on crustaceans (Copepoda, Lucifer, Mysids, Acetes, and Amphipoda) and mollusks (Bivalves and gastropods), small fish, Tintinnida and Dinoflagellates. Furthermore, *Stolephorus* is recognized as a crustacevore fish group [50].

Another fish species often found in the study area is from the Mugilidae, commonly known as mullet. The Mugilidae caught during the study belonged to the *Crenimugil*, *Ellochelon*, *Mugil*, and *Planiliza*. The Mugilidae group is commonly found in mangrove areas as reported in the Kedungmalang Jepara mangrove region [51]. Mugilidae found in the study accounted for 27.66%, which is 11% lower than the Engraulidae. Based on the distribution patterns, the order Mugilliformes is distributed in coastal and brackish waters, with 20 genera and 75 species [52]. These results suggest that the habitat in the study is well-suited for the Mugilidae group.

It is hypothesized that the mangrove restoration area can meet the ecological needs of these fishes. This assumption is supported by [53], who stated that muddy substrate with microphytobenthos is positively correlated with fish density in this group. In addition, factors such as proximity to rivers, water depth, water clarity, and accessibility of food sources from benthic microalgae are influential.

Other families (25), apart from the two families discussed above, had occurrence rates below 9%. However, the existing diversity suggests that restoring degraded mangrove ecosystems through restoration efforts can be an alternative for improving the diversity of surrounding aquatic biota. This research highlights the importance of restoration programs for the diversity of aquatic biota, particularly fish, as mangrove ecosystems provide essential food sources for surrounding species.

As reported by [54], analysis of the stomach contents of fish caught in the Lubuk Kertang mangrove ecosystem shows that these fish consume a higher proportion of plant fragments and litter, compared to other food sources. This underscores the role of mangrove restoration in enhancing aquatic productivity. In the fisheries sector, mangrove restoration is known to increase aquatic productivity. [55] and [56] also stated that fish productivity and resources are likely to increase with the expansion and productivity of mangrove areas.

Changes in mangrove ecosystem, such as deforestation, can significantly affect aquatic biota communities [57], as mangroves are an important ecosystem in coastal areas, and form the basis for food webs in both aquatic and terrestrial ecosystems [58]. Therefore, measuring the productivity of mangrove ecosystems should include assessments of fisheries productivity [59], as was done in this research.

4.3. Diversity Index of Fishes

The average results of the analysis related to the fish diversity index in the waters of the restored mangrove ecosystem indicated a medium level (2.15), reflecting the complex interactions between species in the area. Monthly variations in the diversity, evenness and dominance indices during the study were consistently in the medium range. Community stability can be described based on biodiversity [60]. The impact of land-use change at the ecosystem level is also believed to influence the distribution of exotic species, as the main factors shaping the community diversity patterns are related to trophic niches - processes like nutrition cycling or energy transfer [61].

The findings of this research further support the notion that mangrove forest restoration plays a significant role in enhancing fish species diversity. The surrounding aquatic ecosystem showed a diversity index >2 , and a dominance value of 0.17. This indicates that the fish species present at the study site are diverse, with no single species dominating. This assumption is also supported by the evenness index, which has a higher value in each sampling month. These findings strengthen the idea that restoration of degraded mangrove ecosystems can help restore ecological conditions, as indicated by increased fish species diversity and improved water quality. In this context, the increase in species diversity contributes to greater functional diversity, which in turn enhances ecological stability [62].

4.4. Water Quality

The water quality around the mangrove restoration area should remain within tolerable ranges for estuarine fish communities because physicochemical conditions can directly influence fish distribution, growth, and survival. In this study, dissolved oxygen ranged from 3.5 to 5.15 mg/L, indicating generally oxygenated conditions for a tropical estuary. Nevertheless, dissolved oxygen in estuaries and mangroves can vary substantially with tidal stage, temperature, and organic matter inputs; therefore, repeated sampling across tides and seasons would strengthen inference about habitat quality.

The pH at the research site ranged from 6.6 to 7.85, which is within the tolerable range for most estuarine fishes and consistent with a slightly acidic to near-neutral mangrove environment. Mangroves can influence pH dynamics through organic matter decomposition and carbonate system processes, and they may locally buffer acidity under certain conditions [63,64]. Salinity at the study site varied from 17.5 to 28.5 ppt (as recorded during field measurements), reflecting typical estuarine mixing between freshwater inputs and tidal seawater. Such salinity variability can structure fish assemblages by favoring euryhaline taxa and influencing nursery habitat use in mangrove creeks.

Temperature at the research site ranged from 28.3 to 31.55°C, within the typical range for tropical estuarine systems. Together with the observed pH and salinity ranges, these conditions suggest that the restored mangrove area provides a physiochemically suitable habitat for aquatic biota during the study period.

4.5. Implications for Sustainable Coastal Development and the SDGs

Mangrove restoration can be understood as “green” or nature-based infrastructure that supports coastal development by maintaining ecosystem functions while reducing risk and safeguarding livelihoods. In the 2030 Agenda for Sustainable Development, such multi-benefit interventions are central to achieving the SDGs through integrated social–ecological outcomes [65].

Coastal protection is a key development co-benefit of mangroves. By attenuating waves and reducing storm-surge impacts, intact or recovering mangrove belts can lower flood damages and enhance the resilience of coastal settlements and infrastructure—supporting SDG 11 (sustainable cities and communities) and SDG 13 (climate adaptation) [66,67]. Although coastal hazard reduction was not directly measured in this study, the presence of structurally developing stands (trees, saplings, and seedlings) suggests potential for increasing protective functions as restoration sites mature.

Fisheries support and food security are also closely linked to mangrove condition. Mangroves provide nursery habitats, shelter, and detrital food pathways that can enhance coastal and offshore fisheries; prioritizing conservation or restoration near human populations can maximize returns for fisheries enhancement [68]. The moderate fish diversity observed in Lubuk Kertang (44 species; $H' \approx 2.15$) is consistent with the role of restored mangroves as functional habitat for a range of estuarine and coastal taxa, and it underpins SDG 2 (zero hunger), SDG 8 (decent work and economic growth), and SDG 14 (life below water).

Mangroves are additionally important “blue carbon” ecosystems. Protecting and restoring mangroves can contribute to climate mitigation through long-term carbon storage in biomass and

especially in soils, while delivering adaptation, biodiversity, and livelihood co-benefits [69]. These attributes strengthen the case for incorporating mangrove restoration into climate and development planning (e.g., NDCs, coastal zoning, and sustainable financing mechanisms), aligning local restoration outcomes with SDG 13 and SDG 15.

To better evidence and communicate coastal-development benefits, future monitoring in Lubuk Kertang could combine ecological indicators (vegetation structure, fish assemblages, and water quality) with socio-economic and risk metrics (e.g., fisheries catch or effort, shoreline change, flood exposure, and community benefits), enabling a more direct linkage between restoration performance and SDG-relevant outcomes.

5. Conclusions

This study shows that mangrove restoration in Lubuk Kertang (7–11 years after planting) supports a moderately diverse fish assemblage (44 species; mean $H' \approx 2.15$) under estuarine water-quality conditions, alongside low-to-moderate vegetation diversity across restoration ages. These ecological outcomes suggest that restored stands can function as productive habitat for aquatic biota and can contribute to broader coastal development objectives. In particular, maintaining and restoring mangroves can help sustain fisheries resources and food security (SDGs 2, 8, 14), enhance coastal resilience to erosion and storm hazards as natural infrastructure (SDGs 11, 13), and contribute to climate-mitigation potential through blue-carbon storage (SDG 13), while reinforcing biodiversity conservation (SDG 15).

6. Recommendation

To ensure the continued success of mangrove restoration in Lubuk Kertang, long-term monitoring should be maintained for both vegetation structure and associated aquatic biota, supported by consistent water-quality measurements across seasons and tidal conditions. Monitoring could also incorporate indicators directly relevant to coastal development (e.g., fisheries effort/catch trends, shoreline change, and community benefits), and be linked with participatory management involving local communities, government agencies, NGOs, and the private sector to support SDG-aligned outcomes and sustained financing

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