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The relationship between habitat quality and the diversity of phytoplankton, zooplankton, and nekton in mangrove ecosystems of Bawean Island, Indonesia

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Abstract. *Retnaningdyah C, Arisoesilaningsih E, Vidayanti V, Salsabila Q, Purnomo P. 2024. The relationship between habitat quality and the diversity of phytoplankton, zooplankton, and nekton in mangrove ecosystems of Bawean Island, Indonesia. Biodiversitas 25*: 3017-3026. Mangrove ecosystem consists of biotic and abiotic components that interact with each other to form a food chain. This study aims to analyze the relationship between the diversity and abundance of phytoplankton, zooplankton, and nekton and water quality, human activities, and carbon stock in the mangrove ecosystem in Bawean Island, Gresik District, Indonesia. Data was collected from 11 sampling locations across the island. At each location, we observed the diversity of phytoplankton, zooplankton, and nekton and carbon stock of mangroves along with data of water quality (salinity, pH, dissolved oxygen/DO, biochemical oxygen demand/BOD, nitrate, orthophosphate, dihydrogen sulfide/H_2S, dissolved lead/Pb) and human activities based on the hemeroby index. The research results showed that the level of DO, H_2S, nitrate, and orthophosphate did not meet the quality standard according to the Indonesian government. The level of disturbance from human activities varied from β-mesoherobic to metahemerobic categories. Human activities and higher levels of H_2S in waters had a negative relationship with mangrove ecosystem carbon stock and the diversity and taxa richness of phytoplankton, zooplankton, and nekton. Phytoplankton diversity had a positive relationship with zooplankton, while zooplankton diversity had a positive relationship with nekton. High carbon stock in the mangrove ecosystem will likely increase the diversity of phytoplankton, zooplankton, and nekton. The result of this study implies that anthropogenic activities need to be controlled to improve the Bawean Island mangrove ecosystem services.

Keywords: Carbon stock, food chain, hemeroby index, water biota

INTRODUCTION

Mangroves are halophyte woody plant communities that have high productivity. They are found along tropical and subtropical coastlines (Boto 2018; Biswas and Biswas 2021). Mangrove ecosystem provides various ecosystem services. It preserves coastal habitats by regulating the food chain to maintain ecosystem balance, such as serving as a nursery and feeding ground for marine organisms (John et al. 2022). Mangrove ecosystem also has various protection functions including as coastal protectors from waves, storms, floods, and abrasion, as a barrier to seawater intrusion, and as a sediment trap (Ong and Gong 2013; Sofian et al. 2019). In addition, mangrove vegetation plays a role as the largest carbon stock after tropical rainforests (Chen et al. 2018). In a socio-economic context, mangrove ecosystems provide cultural services, for example being developed as ecotourism spot which can improve the community's economy around the mangrove ecosystem (Getzner and Islam 2020). Mangroves are also widely used by humans for building materials and fuel, and fruit for food (Commonwealth of Australia 2009).

Mangrove ecosystem is composed of biotic and abiotic components that interact with each other in a complex manner (Das et al. 2022). Mangrove plants, as one of the components of the mangrove ecosystem, are a source of food for many organisms, most of which is transferred to other trophic levels through litter and detrital pathways. For example, litter from mangroves is generally used directly by crabs. Dissolved nutrients produced from detritus and decomposition processes are also used by phytoplankton, seagrass, benthic algae, and epiphytes (Retnaningdyah et al. 2022). In general, detritivores will eat organic material that has been degraded. Falling mangrove leaves will be degraded by various fungi, bacteria, and protozoa into small pieces that can be consumed by the surrounding invertebrates. Apart from that, the detritus produced by mangrove plants can be a source of nutrition for shrimp (*Penaeus merguiensis* De Man 1888) that live in tidal areas. Other invertebrates can also eat leaf litter and various microalgae that live in mangrove waters (Medina Contreras et al. 2018).

The primary producers in the mangrove ecosystem are mangrove vegetation and phytoplankton. On the other hand, zooplankton are the primary consumers of phytoplankton, while fish or nekton are the secondary consumers, both of which are heterotrophic. Mangrove crabs, mangrove-eating insects, and snails are some other examples of primary consumers found in mangrove ecosystems (Alongi 2020). The next component of the food chain is predators in the mangrove root system. This trophic level contains fish that eat crabs when they fall into the water, seahorses that prey on small zooplankton, and octopuses that hunt for prey in supporting roots. Above the water surface, various birds, reptiles, and mammals, such as raccoons, prey on insects and crustaceans (Walker et al. 2019; Husain et al. 2020).

Because of the complex interactions, some groups of aquatic biota, such as plankton, nekton, and macrozoobenthic, can be used as bioindicators of mangrove ecosystem quality (Ridlo et al. 2020; Febriansyah et al. 2022; Retnaningdyah et al. 2022; Febriansyah et al. 2023). Plankton can be used as bioindicator due to their low mobility, short life cycle, and quick response to environmental change (Singh et al. 2017). Macrozoobenthic are macrofauna often live attached to substrate and the bottom of the water in the mangrove ecosystem. Macrozoobenthic can be used to detect ecosystem changes due to their long and sedentary life cycles (Retnaningdyah et al. 2022). Other aquatic biota that can be used as bioindicator is nekton, in which its movement rapidly follows food availability in the mangrove ecosystem (Ridlo et al. 2020).

Mangrove ecosystems can be found on almost all islands in Indonesia, including in Bawean Island, Gresik District, East Java, Indonesia which has never been evaluated before. It is widely accepted that many mangrove ecosystems in Indonesia have been degraded (Richards and Friess 2015; Rudianto et al. 2020; Febriansyah et al. 2022; Retnaningdyah et al. 2022; Febriansyah et al. 2023). Several factors that cause damage to the mangrove forest ecosystem in Indonesia include land conversion for housing, agriculture, aquaculture, industry, and tourism. Mangrove degradation is also caused by illegal logging for commercial purposes, environmental pollution, and climate change (Indawan et al. 2017). Degradation of mangrove ecosystems can change the quality of aquatic habitats, which in turn will affect community structure and the diversity of aquatic biota (Lapolo et al. 2018). Such changes influence the interaction between biotic and abiotic components as well as the food chain in mangrove ecosystem, which result in decreasing ecosystem services (Lee et al. 2014; Faridah-Hanum et al. 2019; Sofian et al. 2019). Therefore, this study aims to assess the diversity and abundance of phytoplankton, zooplankton, and nekton, especially fish, as constituents of trophic levels in mangrove ecosystem in Bawean Island and its relationship with water quality, human activities, and carbon stock. This information can then be used as a basis for recommendations for mangrove ecosystem management in Bawean Island.

MATERIALS AND METHODS

Study area and period

This research was conducted in 11 locations of mangrove ecosystem located in Bawean Island, Gresik District, East Java Province, Indonesia, namely Sawahmulya, Sungai Rujing, Hijau Daun, Sidogedungbatu, Pamona, Pasir Putih, Bangsal, Dekatagung, Jherat Lanjheng, Lebak, and Pulau Cina (Figure 1). At each location, three sampling plots were established randomly as replicates. The research was conducted from July to November 2023.

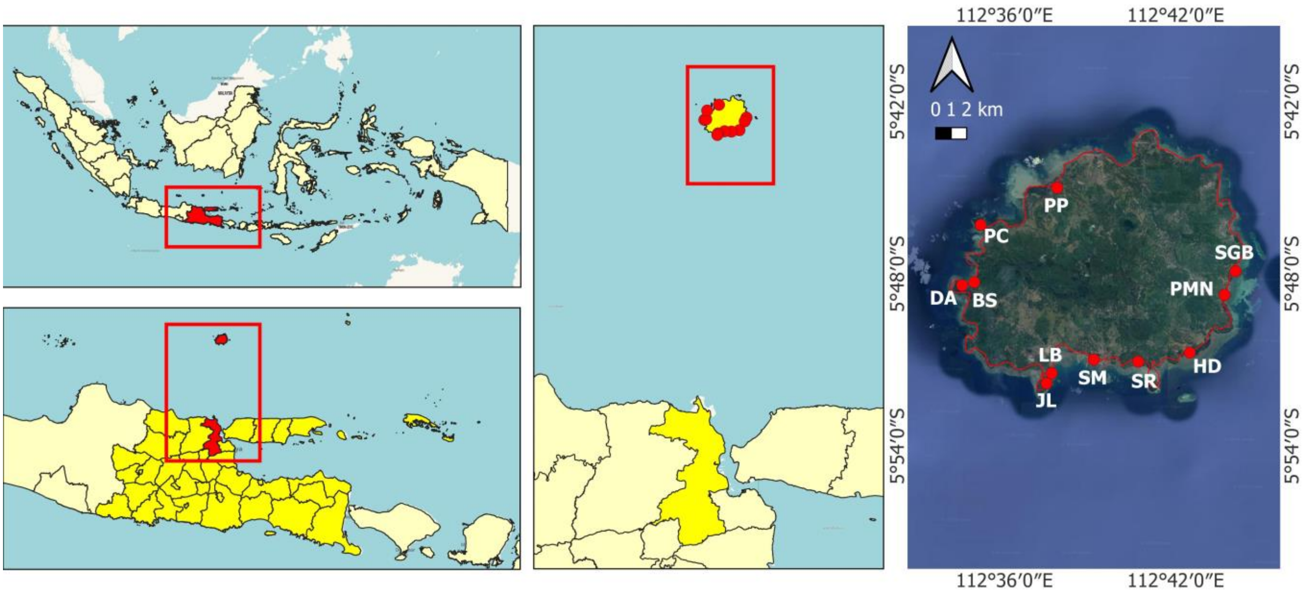

Figure 1. Map of study area in Bawean Island, Gresik District, East Java, Indonesia showing 11 sampling locations (Note: SGB: Sidogedungbatu; PMN: Pamona; HD: Hijau Daun; SR: Sungai Rujing; SM: Sawahmulya; LB: Lebak; JL: Jherat Lanjheng; DA: Dekatagung; BS: Bangsal; PC: Pulau Cina; PP: Pasir Putih)

Research procedures

This research used an ex-post facto method based on a final causal relationship approach to the object being assessed, namely human activity around the mangrove ecosystem, which was evaluated based on the hemeroby index, the physical-chemical quality of water, the carbon stock of mangrove vegetation, the community structure and diversity of plankton and nekton found at the sampling location.

Water, plankton, and fish sampling methods and monitoring of environmental quality

Water sampling was carried out using a 1 L water sampler. Physico-chemical parameters such as pH, salinity, dissolved oxygen (DO), biochemical oxygen demand (BOD), nitrate, orthophosphate, dihydrogen sulfide, and dissolved lead (Pb) content were measured (Table 1).

Plankton samples were taken by filtering 3 L of water collected at each sampling location of the mangrove ecosystem using a plankton net with size of 30 mesh (Monsheva and Parr 2010). The filtered plankton was put into a sample bottle containing formalin and saturated $CuSO_4$ and brought to the laboratory for identification. Phytoplankton and zooplankton samples were identified and counted using a microscope. Mangrove fish sampling was conducted at the same time as water and plankton sampling. Fish sampling was performed using double gill and fishing nets with a size of 5 mm mesh with cruising methods in a sample plot area of 5×5 m. Fish sampling was also observed using the visual encounter method with an observation time for each location of around 1-2 h (Retnaningdyah et al. 2024a). The fish samples obtained were stored in a collection bottle given a 70% alcohol solution and labeled with the date, time, and sampling site. Plankton and fish identification was conducted in the Ecology and Restoration of Tropical Ecosystem Laboratory, Department of Biology, Faculty of Mathematics and Natural Sciences, Universitas Brawijaya, Malang, Indonesia.

Meanwhile, observations of environmental factors include land use conditions around the mangrove ecosystem and human activities using the hemeroby index (Walz and Stein 2014; Saputra et al. 2023). This hemeroby index can be used to measure the impact of past and present human interventions on the locations and the land use in an ecosystem using vegetation classification rules (Tian et al. 2020). The equation used to calculate the hemeroby index value is as follows (Tian et al. 2020):

$$HI = \sum_{i=1}^{n} fn \times Hi$$

Where: HI is the hemeroby index, n is the number of hemeroby degrees, fn is the proportion of landscape type with Hi, and Hi is the degree of hemeroby. The human disturbance was divided into seven categories i.e. ahemerobic (almost no human impact), oligohemerobic (low human impact), mesohemerobic (moderate human impact), β-euhemerobic (moderate-strong human impact), α-euhemerobic (strong human impact), polyhemerobic (very strong human impact), and metahemerobic (too strong human impact).

Monitoring of carbon stock in mangrove ecosystems

Carbon stock was estimated using the allometric formula based on the basal area and plant height of saplings and poles of mangrove vegetation (Table 2) (Komiyama et al. 2005; Hairiah et al. 2010; Kauffman and Donato 2012; Wilda et al. 2020). Those data were found from vegetation analysis carried out on mangroves of sapling (if the height was >1 m and the diameter at breast height/DBH was <4 cm) and poles (if the height was >1 m with DBH >4 cm) by making plots measuring 5×5 m (saplings) and 10×10 m (poles/trees). Monitoring of the species, density of each species found, plant height, and DBH were carried out in each plot.

Table 1. Physico-chemical parameters measured with units and methods used in this study (Clesceri et al. 1998)

Parameter	Unit	Equipment/method
pH	-	pH meter
Dissolved Oxygen (DO)	mg/L	Digital oxygen meter
Biochemical Oxygen Demand (BOD)	mg/L	Digital oxygen meter
Salinity	%	Refractometer
Nitrate	mg/L	Brucine Methods
Orthophosphate (dissolved phosphate)	mg/L	Stannous chloride
Dihydrogen Sulfide (H_2S)	mg/L	Spectrophotometry
Dissolved Pb	mg/L	Spectrophotometry

Table 2. Allometric equation of various mangrove species using DBH (cm) as the predictor (Komiyama et al. 2005)

Species	Aboveground tree biomass (W_{top} in kg)
Avicennia germinans (L.) L.	$W_{top} = 0.140DBH^{2.40}$ $r^2 = 0.97$
	$W_{top} = 0.0942DBH^{2.54}$ $r^2 = 0.99$
Avicennia marina (Forssk.) Vierh.	$W_{top} = 0.308DBH^{2.11}$ $r^2 = 0.97$
Laguncularia racemosa (L.) C.F.Gaertn.	$W_{top} = 0.102DBH^{2.50}$ $r^2 = 0.97$
	$W_{top} = 0.209DBH^{2.24}$ $r^2 = 0.99$
Rhizophora apiculata Blume	$W_{top} = 0.235DBH^{2.42}$ $r^2 = 0.98$
Rhizophora spp.	$W_{top} = 0.128DBH^{2.60}$ $r^2 = 0.92$
	$W_{top} = 0.105DBH^{2.68}$ $r^2 = 0.99$
Bruguiera gymnorhiza (L.) Lam.	$W_{top} = 0.186DBH^{2.31}$ $r^2 = 0.99$
Bruguiera parviflora (Roxb.) Wight & Arn. ex Griff.	$W_{top} = 0.168DBH^{2.42}$ $r^2 = 0.99$
Ceriops australis (C.T.White) Ballment, T.J.Sm. & J.A.Stoddart	$W_{top} = 0.189DBH^{2.31}$ $r^2 = 0.99$
Xylocarpus granatum J.Koenig	$W_{top} = 0.0823DBH^{2.59}$ $r^2 = 0.99$
Common equation	$W_{top} = 0.251\,\rho D^{2.46}$ $r^2 = 0.98$
	$W_{top} = 0.168\rho DBH^{2.47}$ $r^2 = 0.99$

The average carbon storage for aboveground and pneumatophore was then divided into four categories following Hutchison et al. (2014), i.e. very low/degraded (<80 mgC/ha), low (80-280 mgC/ha), medium (280-350 mgC/ha), and high (>350 mgC/ha).

Data analysis

Data on physical and chemical water parameters in each location were compiled and inserted into one table. From this data, the average value and standard error were calculated for each parameter and each location. The level of water pollution was also determined by comparing the average value of water quality obtained with the water quality standards based on Indonesian government regulations of PP No. 22 of 2021 regarding the implementation of environmental protection and management.

The different data of water physicochemical parameters were analyzed by SPSS 16.0. The data with normal distribution and homogeneous variance were analyzed by using one-way ANOVA continued with using the Tukey test; data with normal distribution and heterogeneous variance were analyzed using the Brown-Forsythe test and continued using Games Howell test; and data which have abnormal distribution were analyzed using Mann-Whitney test and continued using Kruskal Wallis.

Data on plankton and fish density were compiled and used to determine the Shannon-Wiener diversity index (H'), taxa richness, and total density/abundance based on Retnaningdyah and Arisoesilaningsih (2019). The following is the Shannon-Wiener Diversity Index (H') equation used in this analysis.

$$H' = -\sum_{i=1}^{s} (Pi * \ln Pi)$$

Where:

H' : Shannon-Wiener diversity index

s : Total number of species in the community

Pi : The proportion of the number of individuals of species i to the total number

The grouping of mangrove ecosystem quality in Bawean Island based on the environmental factors, water quality, carbon stock, structure community, and diversity of mangrove plankton and fish was conducted by biplot analysis from principal component analyses (PCA) using PAST 4.12b software. Whereas, the correlation between hemeroby index and water quality, carbon stock, structure community, and diversity of mangrove plankton and fish in the mangrove ecosystem on Bawean Island was conducted by Pearson correlation analysis using PAST 4.12b.

RESULTS AND DISCUSSION

Water physicals and chemical quality of mangrove ecosystems in Bawean Island

Table 3 shows the variations in water physicals and chemical quality. Almost all studied locations of mangrove ecosystems in Bawean Island had similar water pH (7.45-8.16) which meet the Indonesian government regulation of PP No. 22 of 2021 regarding seawater quality standards for marine biota which range from 7 to 8.5. This value is close to the value in the mangrove ecosystem on the south coast of East Java and is still able to support biota life in the mangrove ecosystem (Wassie and Melese 2017; Retnaningdyah et al. 2022). Meanwhile, DO levels in mangrove ecosystems in Bawean Island were lower (1.39-3.11 mg/L) than that in the south coast of East Java with (3.55-5.42 mg/L) (Retnaningdyah et al. 2022). This value does not meet the quality standard value set by the Indonesian government, which requires a minimum DO value of 5 mg/L. This low DO value will have an impact on reducing the carrying capacity of the mangrove ecosystem for biota in aquatic ecosystems such as plankton, fish, and benthos, which require a minimum DO of 5 mg/L (Faturrohman et al. 2017). Generally, low DO levels are caused by high levels of organic matter in the waters, which is indicated by the BOD value. The low value of DO in the mangrove water might be caused by microbes' activity to degrade organic matter which comes from human activities around the mangrove ecosystem, such as land conversion into agriculture or ponds, and residential houses that produce a lot of organic and inorganic waste (Retnaningdyah et al. 2022). As a result of these microbes' activity, the levels of organic matter in the Bawean Island mangrove ecosystem were low, ranging from 0.44 to 4.20 mg/L. This BOD level still meets the quality standard value set for marine biota (20 mg/L). Based on these results, it was shown that the mangrove ecosystem still supports human activities around waters so organic pollutants can be immediately purified naturally by microbes in the waters (Sannigrahi et al. 2020; Retnaningdyah et al. 2022). The low DO level can be caused by activities of microorganisms that consume large amount of oxygen as a result of metabolizing activities (Romin et al. 2021). The levels of organic matter can influence changes in the community structure of aquatic organisms, and each organism has a varying tolerance range for organic materials (Mizwar and Surapati 2020).

The water salinity value in this study ranged from 1.8 to 3.8‰. This value partially meets the water quality standards for mangrove ecosystems based on PP No. 22 of 2021, which requires a maximum value of 3.4‰. The level of salinity is influenced by sea tides (Retnaningdyah et al. 2022). Sulfide (H_2S) levels had values of <0.01-0.06 mg/L. Meanwhile, dissolved Pb levels ranged from <0.0015 to 0.0047 mg/L. Based on PP No. 22 of 2021, the maximum limit of sulfide levels required for biota life is 0.01 mg/L, while dissolved Pb levels are <0.008 mg/L. High sulfide levels are generally associated with high levels of organic matter with low DO, so organic material degradation occurs anaerobically, which has an impact on increasing high H_2S levels (Retnaningdyah et al. 2022; Sherief and Hassan 2022).

Nitrate and orthophosphate levels in the 11 locations of the mangrove ecosystem in Bawean Island ranged from 0.07 to 0.22 mg/L and 0.00 and 0.058 mg/L, respectively. Nitrate levels in all locations and orthophosphate levels in several locations have exceeded the quality standard set by the government with a maximum of 0.06 mg/L (nitrate) and

0.01 mg/L (orthophosphate). Nitrate and orthophosphate levels are greatly influenced by human activities in the surrounding waters. These high levels of nitrate and orthophosphate indicate high levels of nutrients will have a significant role in the food web of the mangrove ecosystem. This nutrient can trigger eutrophication, which will then result in algae blooming (Hoquea et al. 2015; Saifullah et al. 2016; Barcellos et al. 2019).

Hoquea et al. (2015) reported that nutrient concentrations in water can influence fish abundance. This is associated with the utilization of nutrients, such as ammonium and nitrate, by several phytoplankton species, which support the formation of food chains in the mangrove ecosystem. Other nutrients are also produced from mangroves, such as mangrove litter or the release of other organic materials through the roots/stems. During the rainy season, litter from the land, which is washed away and enters the estuary, also increases nutrient concentrations and turbidity. Dissolved nutrients will influence the abundance and diversity of phytoplankton, which is also reported by Canini et al. (2013) and Saifullah et al. (2014).

Carbon stock, diversity and abundance of phytoplankton, zooplankton, and nekton in the mangrove ecosystem in Bawean Island

We calculated the mangrove ecosystem services based on the value of the carbon stock as presented in Table 4. The results showed that the carbon stock of the mangrove ecosystem in Bawean Island ranged from 79.47 to 414.83 mgC/ha, with low values (79.47-181.35 mgC/ha) recorded in Pulau Cina, Dekatagung, and Lebak and medium values (221.88-295.73 mgC/ha) in Sawahmulya, Sungai Rujing, Pasir Putih, Bangsal, and Jherat Lanjheng and high in Hijau Daun, Sidogedungbatu, and Pamona with 308.07-414.83 mgC/ha. Variations in carbon stock values in the Bawean Island mangrove ecosystem are similar to those in the mangrove ecosystem on the south coast of East Java, which ranged from 73.8 to 445.8 mgC/ha. Variations in the carbon stock in mangrove ecosystems will affect the aquatic biota, such as phytoplankton, zooplankton, and fish.

The level of mangrove ecosystem services based on carbon stock values is influenced by the level of the naturalness and human activities around the mangrove ecosystem. Increasing the carbon stocks due to the restoration or revegetation activities by planting various types of mangrove plants. Moreover, it is necessary to control anthropogenic activities around mangroves such as illegal logging, and use a part of mangrove plants for daily needs (Retnaningdyah et al. 2024b).

The total abundance of phytoplankton in the mangrove ecosystem of Bawean Island was generally higher (2400-12070 Ind/L) than the total abundance of zooplankton (252-1438 Ind/L). In terms of fish abundance, it ranged from 64-165 ind/25m^2 as shown in Table 4. Similarly, phytoplankton had higher taxa richness (26-42 species) compared to zooplankton (6-15 species), while fish comprised of 2-9 species. The abundance of each species and the taxa richness at each location determine the species diversity index of a community.

The Shannon-Wiener diversity index for phytoplankton, zooplankton, and fish was 3.82-4.89, 2.34-3.06, and 0.02-0.21, respectively (Table 4). It showed a similar phenomenon in total abundance and taxa richness: i.e. there was a decrease in the diversity index value at higher trophic levels. The diversity index (H') can also be used to indicate the level of pollution in a body of water. For example, a phytoplankton community is categorized as not contaminated with toxic pollutants of H'>3, moderately polluted if H'=1-3, and heavily polluted if H'<1 (Wu et al. 2014). High ecosystem services are indicated by high species diversity. Thus, the results of this research indicated that the mangrove ecosystem on Bawean Island generally has good quality, which supports the food chain process in the ecosystem. Producers in the mangrove ecosystem in the form of mangrove vegetation and phytoplankton have been able to support zooplankton and fish as first and second consumers.

The level of human disturbance in the 11 locations of the mangrove ecosystem in Bawean Island varied as presented in Figure 2. Human activities in Bangsal, Dekatagung, Sidogedungbatu, and Pasir Putih were high since there were settlements, agriculture, and livestock (hemeroby index value 5-6 or categories as polyhemerobic and metahemerobic). Mangrove ecosystems in the polyhemerobic and metahemerobic categories indicated high mechanical soil disturbance, direct mechanical disturbance to vegetation, and chemical disturbance (Saputra et al. 2023). The mangrove ecosystem at Hijau Daun location had the lowest human activity in the form of ecotourism activities and was included in the β-mesoherobic category (index value 2), while other locations had moderate human activity, such as docks, plantations, and settlements, with a hemeroby index value of 3-4 categories as α-mesoherobic and euhemerobic.

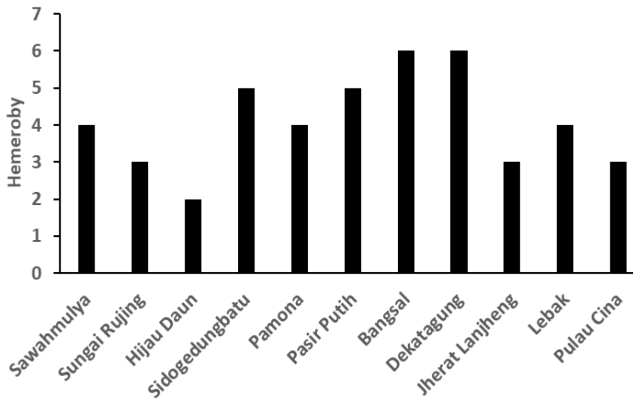

Figure 2. The human disturbance levels around the mangrove ecosystem in Bawean Island, Gresik District, Indonesia based on the Hemeroby index

Table 3. Variations in the physical and chemical quality of water in mangrove ecosystems on Bawean Island, Gresik District, Indonesia

Locations	pH	DO (mg/L)	BOD (mg/L)	Salinity (‰)	Nitrate (mg/L)	Orthophosphate (mg/L)	Dihydrogen Sulfide (mg/L)	Dissolved Pb (mg/L)
Sawahmulya	7.74-7.89 a	2.03-2.38 a	1.88-4.20 b	3.0-3.1 a	0.15-0.17 a	0.028-0.058 a	<0.014-0.028 abcd	<0.0015 a
Sungai Rujing	7.62-8.02 a	1.68-2.62 a	2.84-3.56 b	3.0-3.4 ab	0.09-0.12 a	0.021-0.041 a	<0.014-0.025 abc	<0.0015 a
Hijau Daun	8.04-8.10 a	2.82-3.11 a	1.60-2.08 ab	3.1-3.2 a	0.09-0.29 a	0.018-0.042 a	0.022-0.034 cd	<0.002-0.007 a
Sidogedungbatu	7.45-7.87 a	1.54-2.89 a	1.00-2.44 ab	3.2-3.3 ab	0.07-0.10 a	0.029-0.042 a	0.022-0.199 cd	<0.0015 a
Pamona	7.59-7.88 a	2.38-3.03 a	1.48-2.68 ab	2.7-3.1 ab	0.11-0.15 a	0.005-0.025 a	<0.014-0.015 a	<0.0015 a
Pasir Putih	8.08-8.13 a	2.65-2.70 a	0.44-1.20 a	3.1-3.4 ab	0.08-0.10 a	0.005-0.010 a	0.016-0.035 bcd	<0.002-0.002 a
Bangsal	7.79-8.01 a	2.03-2.74 a	1.52-2.56 ab	1.8-3.2 ab	0.07-0.18 a	0.006-0.043 a	<0.0136	<0.002-0.003 a
Dekatagung	7.63-8.07 a	1.39-2.81 a	0.96-2.64 ab	3.0-3.4 ab	0.07-0.12 a	0.015-0.079 a	<0.014-0.019 ab	<0.0015 a
Jherat Lanjheng	7.84-8.06 a	1.83-2.99 a	1.16-1.76 ab	3.1-3.5 ab	0.11-0.14 a	0.019-0.030 a	0.027-0.056 d	<0.0015 a
Lebak	7.80-7.96 a	2.49-2.79 a	0.56-0.80 a	3.4-3.8 ab	0.09-016 a	0.029-0.034 a	<0.014-0.032 abcd	<0.002-0.003 a
Pulau Cina	8.06-8.16 a	2.38-2.63 a	2.76-3.64 b	3.5-3.5 b	0.11-0.22 a	0.000-0.026 a	0.017-0.026 bc	<0.02-0.005 a
Standard	7-8.5	>5	<20	<3.4	<0.06	<0.015	<0.01	<0.008

Note: Results with similar notation showed that there was no significant difference based on the ANOVA test followed by the Tukey test (BOD, nitrate, orthophosphate), the Brown Forsythe test followed by the Games Howell test (DO, pH, salinity), and the Kruskall Wallis test followed by the Mann Whitney test (H_2S, Dissolved Pb)

Table 4. Diversity and abundance of phytoplankton, zooplankton, and nekton and carbon stock in the mangrove ecosystem on Bawean Island, Gresik District, Indonesia

Locations	Phytoplankton			Zooplankton			Nekton/Fish			Carbon stock mangrove (mg C/ha)
	Abundance (ind./L)	Taxa richness	H' Shannon Wiener	Abundance (Ind/L)	Taxa richness	H' Shannon Wiener	Abundance (ind./25m^2)	Taxa richness	H' Shannon Wiener	
Sawahmulya	7,904	42	4.81	1,002	15	3.06	75	8	0.14	271.64
Sungai Rujing	12,070	34	4.53	1,438	11	2.70	132	7	0.12	221.88
Hijau Daun	5,597	37	4.89	690	13	2.89	100	8	0.18	397.09
Sidogedungbatu	8,633	34	4.55	1,045	10	2.48	64	2	0.02	308.07
Pamona	5,524	36	4.66	689	11	2.84	93	9	0.18	414.83
Pasir Putih	6,238	33	4.79	643	7	2.34	158	4	0.07	280.42
Bangsal	4.776	31	4.68	439	7	2.50	164	7	0.19	295.73
Dekatagung	4,860	26	3.82	424	6	2.52	165	4	0.13	137.90
Jherat Lanjheng	2,708	32	4.76	252	8	2.54	103	7	0.15	270.18
Lebak	2,400	29	4.37	271	7	2.61	61	4	0.15	181.35
Pulau Cina	3,032	31	4.07	288	8	2.59	139	8	0.21	79.47

The lands around the mangrove ecosystem in Bawean Island have been converted into residential areas, agriculture, and plantations. This land conversion causes high levels of pollutants entering to mangrove ecosystem habitat, both from anthropogenic waste and synthetic fertilizers and pesticides (Semiun et al. 2020; Erdős et al. 2022). Mangrove vegetation significantly influences water quality in mangrove ecosystems, while water quality will be reduced if anthropogenic activity in the ecosystem is high (Li et al. 2022). Human activities around the Bawean Island mangrove ecosystem have influenced the quality of the mangrove ecosystem, as reflected in the carbon stock value.

The relationship between habitat quality and phytoplankton, zooplankton, and, nekton in some mangrove ecosystems in Bawean Island

Sawahmulya, Hijau Daun, and Pamona mangrove ecosystems had the best ecosystem quality (Figure 3), characterized by the highest carbon stock, diversity, and highest taxa richness of phytoplankton, zooplankton, and fish with the lowest level of human activity level/hemeroby index and also the lower concentration of H_2S in the waters. Conversely, the quality of the mangrove ecosystem in Dekatagung, Lebak, Bangsal, Pasir Putih, Pulau Cina, and Sidogedungbatu was lower, with the opposite characteristics. The quality of the mangrove ecosystem in the Rujing and Jherat Lanjheng Rivers is moderate.

Based on the result of PCA, it showed that a high carbon stock in the mangrove ecosystem has a positive relationship with taxa richness and diversity of phytoplankton, zooplankton, and fish. The food chain in the mangrove ecosystem starts with phytoplankton, which acts as primary producers. Phytoplankton will be eaten by zooplankton as the first consumers. Zooplankton will be eaten by small fish as secondary consumers. These small fish become food for larger fish and so on. The results of this study indicated that phytoplankton diversity and taxa richness have a positive effect on zooplankton diversity and taxa richness. In addition zooplankton diversity and taxa richness have a positive effect on fish diversity and taxa richness. The higher human activity, as indicated by the higher value of the hemeroby index and also the higher concentration of H_2S in the waters, has a negative effect on carbon stock and the diversity and taxa richness of phytoplankton, zooplankton, and fish. H_2S in waters has a detrimental impact because it causes poisoning in aquatic biota, such as fish. This result was also supported by the result of correlation analysis, as shown in Figure 4. Based on the correlation results, it showed that the diversity and taxa richness of phytoplankton had no direct effect on the diversity and taxa richness of fish.

The result of this study supports the previous research by Hoquea et al. (2015), which showed that there was a positive correlation between chlorophyll α, phytoplankton, zooplankton, and several fish species within a food chain system. Accordingly, Pasquaud et al. (2010), found several species of phytoplankton, zooplankton, and benthos as prey of fish based on the results of fish stomach dissections to determine trophic levels in several fish species in estuary areas.

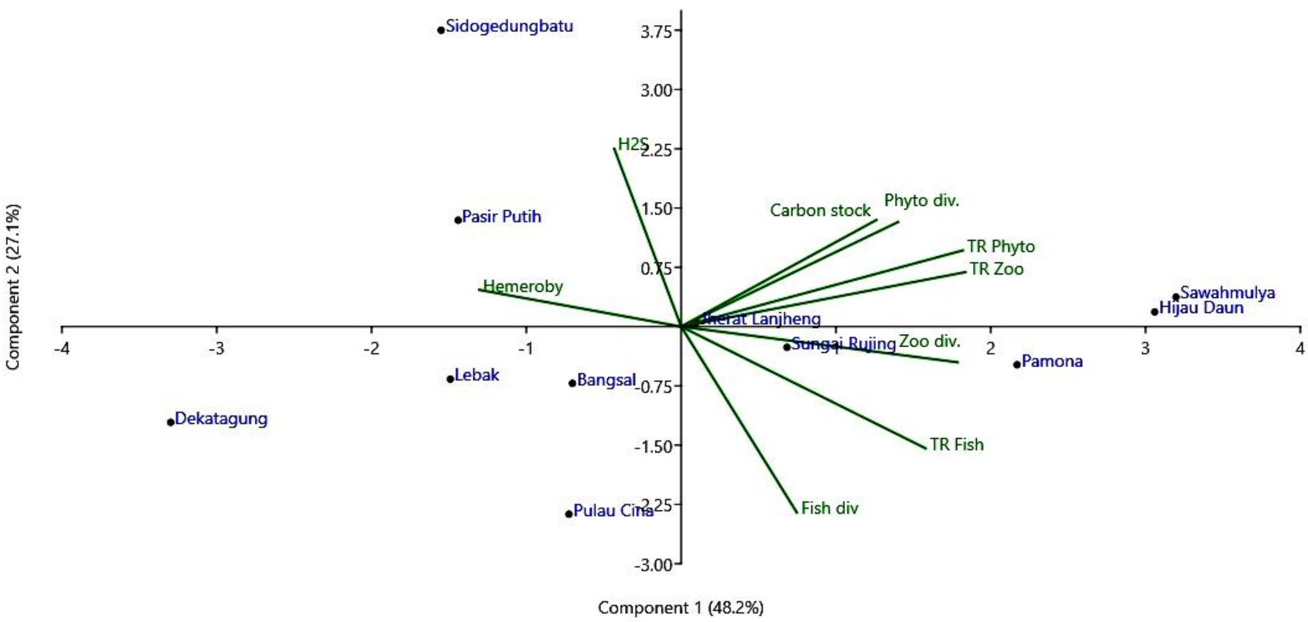

Figure 3. The grouping of mangrove ecosystem quality in Bawean Island, Gresik District, Indonesia based on human activity, diversity, and abundance of phytoplankton, zooplankton, fish, and carbon stock (Note: div: diversity; phyto: phytoplankton; TR: taxa richness; zoo: zooplankton)

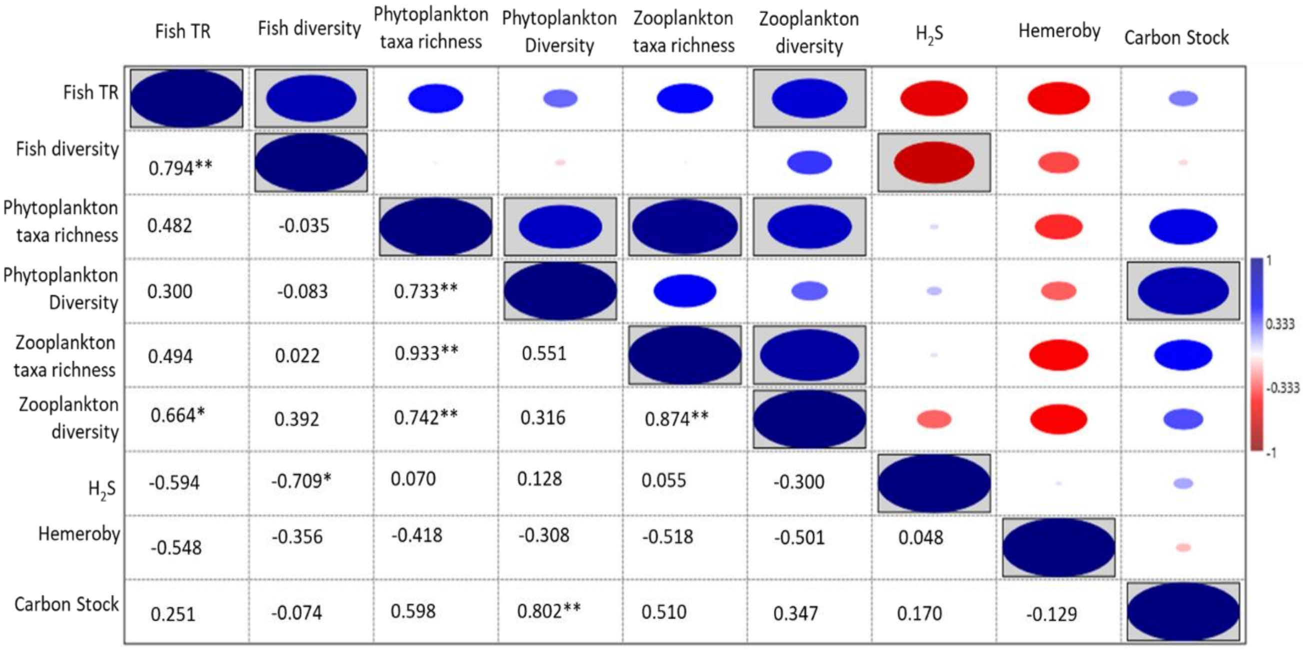

Figure 4. Correlation between carbon stock, water quality and diversity of some aquatic biota in the mangrove ecosystem on Bawean Island, Gresik District, Indonesia

Based on the results of this research, it can be concluded that some physicochemical water quality parameters in 11 locations of the mangrove ecosystem in Bawean Island, such as levels of dissolved oxygen/DO, dihydrogen sulfide (H_2S), nitrate, and orthophosphate, exceeded the quality standard values set by the Indonesian Government in PP RI No. 22 of 2021 (appendix VIII) concerning the living of marine biota and mangrove ecosystems. Meanwhile, pH, BOD, salinity, and dissolved Pb met the quality standards. Based on the hemeroby index, the mangrove ecosystem in Bawean Island had a level of human activity disturbance that was included in the β-mesoherobic to metahemerobic category. Moreover, the analysis results also showed that the higher level of human activity and H_2S in the waters will have a negative impact on carbon stock and the diversity and taxa richness of phytoplankton, zooplankton, and fish. High carbon stock in the mangrove ecosystem has a positive effect on the taxa richness and diversity of phytoplankton, zooplankton, and fish. Further, phytoplankton diversity and taxa richness have a positive effect on zooplankton diversity and taxa richness. Meanwhile, zooplankton diversity and taxa richness have a positive effect on fish diversity and taxa richness. However, phytoplankton diversity and taxa richness do not directly influence the diversity and taxa richness of fish. Based on the results of this research, to improve mangrove ecosystem services, it is necessary to increase the value of carbon stock through revegetation activities from various species of mangrove plants which in turn will also have an impact on increasing the diversity of phytoplankton, zooplankton and fish.

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