

# Effect of moon phase during tides on variation of aquatic biodiversity in a tropical coastal lake of Anak Laut Lake, Aceh, Indonesia

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**Abstract.** Muhtadi A, Leidonald R, Rohim N, Firdaus M. 2025. Effect of moon phase during tides on variation of aquatic biodiversity in a tropical coastal lake of Anak Laut Lake, Aceh, Indonesia. *Biodiversitas* 26: 810-823. Anak Laut Lake, Aceh, Indonesia, is a coastal lake whose water dynamics are influenced by sea tides. It serves as a vital environment for marine life in Singkil and surrounding waters, functioning as a nursery and feeding grounds for prawns and fish larvae. This study was conducted from March to April 2023 at Anak Laut Lake in Gosong Telaga Barat Village, North Singkil District, Aceh Singkil District, Aceh Province, Indonesia. Sampling was conducted on four occasions during the tidal cycle: the new moon, first quarter, full moon, and last quarter. Aquatic biota samples were collected during both high and low tides. A Principal Component Analysis (PCA) multivariate analysis was performed using Microsoft Excel 2016 and Minitab. The nekton in Anak Laut Lake exhibited variations in space and time during high and low tides, with 29 families and 55 species identified. Benthic organisms included 26 species, classified into four distinct classes and 23 families. The abundance of phytoplankton was higher than that of zooplankton, reaching 90.96-95.30% of the plankton community. The larvae and juveniles discovered in Anak Laut Lake predominantly consisted of fish species from marine environments that reproduce in estuaries and seas and are transported into the lake by tidal currents. Fish population and diversity were higher during high tide due to the availability of habitats and the influx of marine fish. The tidal dynamics influenced the presence, abundance, and diversity of aquatic organisms in the lake. The new and full moon phases greatly affected the dynamics of the water quality and biodiversity of the lake due to the pronounced tidal ranges produced.

**Keywords:** Estuarine, fish, plankton, tidal phenomenon, tide

## INTRODUCTION

Indonesia is known as a world biodiversity hotspot. Indonesia, as a country with the nickname mega biodiversity, is ranked second after Brazil, with the highest biodiversity wealth in the world. Fish is one of Indonesia's biodiversity contributions, reaching 12.1% of the total species wealth in the world (Butler 2016). Froese and Pauly (2024) estimate that there are at least 5,000 species of fish found in Indonesian waters. Froese and Pauly (2024) indicate, these species of fish consist of +3,860 species of brackish and marine fish, and the rest are freshwater fish (Allen 2020; Allen and Erdmann 2024; Froese and Pauly 2024). In addition to fish, there are several groups of aquatic organisms found in brackish and sea waters, including crustaceans, mollusks, and microscopic organisms, such as plankton (Leidonald et al. 2019a; Muhtadi et al. 2023a; Palomares and Pauly 2024). Indonesia's marine crustacean resources recorded more than 783 species (81 families) from 9,280 identified crustacean species in the world (Wardiatno 2018). Meanwhile, the wealth of mollusks in Indonesia has not been widely reported, whereas the wealth of mollusks in the world is reported to reach ~86,600 accepted species (MolluscaBase 2025). In addition, the wealth of plankton certainly cannot be reported in detail in Indonesia and even in the world. Therefore, taxonomists estimate that there are still hundreds of species of fish, crustaceans, and mollusks

in Indonesia that have not been discovered and described. Thus, one of the efforts of researchers and academics in Indonesia is to continue to research the identification of types and geographical and temporal distributions related to aquatic organisms in Indonesia. This effort is important as part of the effort to document and describe types as part of Indonesia's efforts to manage biodiversity. Anak Laut Lake is one of the unique aquatic habitats because the lake waters are salty (Leidonald et al. 2023, et al. 2024).

Anak Laut Lake, located in Indonesia, is a tropical coastal lake influenced by the tides of the Indian Ocean, making it unique among similar water bodies. Anak Laut Lake has an area of 11.26 km<sup>2</sup> at high tide and 9.84 km<sup>2</sup> at low tide, with an average depth ranging from 2.61-3.57 m (Leidonald et al. 2023). Therefore, Anak Laut Lake is classified as a tidal lake (Muhtadi et al. 2017, et al. 2020a). The tidal type of the Singkil waters is a mixed tide prevailing semidiurnal, resulting in two high and two low tides daily, with different periods and heights (Leidonald et al. 2023). The tides in this lake originate from tidal propagation in the double-type Indian Ocean, which reaches the west coast of Sumatra Island (Wyrcki 1961). Furthermore, this lake serves multiple purposes, including fishing activities involving floating net cage cultivation, tourism for nearby communities, and supporting surrounding land use such as settlements, fish landing bases, and palm oil plantations (Muhtadi et al. 2023a; Leidonald et al. 2024).

The tidal influence of the Indian Ocean directly affects the water level dynamics (Leidonald et al. 2023) and water quality (Leidonald et al. 2024) of Anak Laut Lake. This tidal interaction also affects the composition and distribution of aquatic biota as found in other coastal lakes (Fernández-Alfás et al. 2020; Leidonald et al. 2019a; Pérez-Ruzafa et al. 2019; Muhtadi et al. 2020b, et al. 2022, et al. 2023b; Yulianda et al. 2020; Muhtadi and Leidonald 2024). The lake's edge is surrounded by mangroves dominated by the *Rhizophora* species, and its predominantly consists of brackish and marine organisms. These organisms include both permanent residents and migratory species. Anak Laut Lake hosts diverse aquatic biota, including golden sea cucumbers (*Stichopus herrmanni*), seahorses (*Hippocampus come* and *H. kuda*) classified as vulnerable status, tap rays (*Maculabatis gerrardi*), and sand sea cucumbers (*Holothuria scabra*) listed as Endangered (EN) species (Muhtadi et al. 2023a).

Numerous studies have explored aspects of Anak Laut Lake, including its morphology and hydrodynamics (Leidonald et al. 2023), water quality status and profiles (Leidonald et al. 2024), and aquatic biodiversity, including fish, crustaceans, mollusks, and plankton (Muhtadi et al. 2023a,b,c). However, further research is needed to focus on the relationship between lake biodiversity and water quality. Previous research has reported the relationship between water quality and aquatic biodiversity in the tidal Siombak Lake (North Sumatra, Indonesia) (Muhtadi and Leidonald 2024; Muhtadi et al. 2024). These findings highlighted a correlation between water quality and biodiversity, particularly during the full moon phase. This study aims to investigate the relationship between tidal variations (tidal cycles include the new moon, first quarter, full moon, and last quarter) and the presence, abundance, and diversity of aquatic biota in coastal lakes. This study will review in detail how tides affect the population of

aquatic organisms, both micro (plankton and larvae) and macro (fish, crustaceans, and benthic organisms).

## MATERIALS AND METHODS

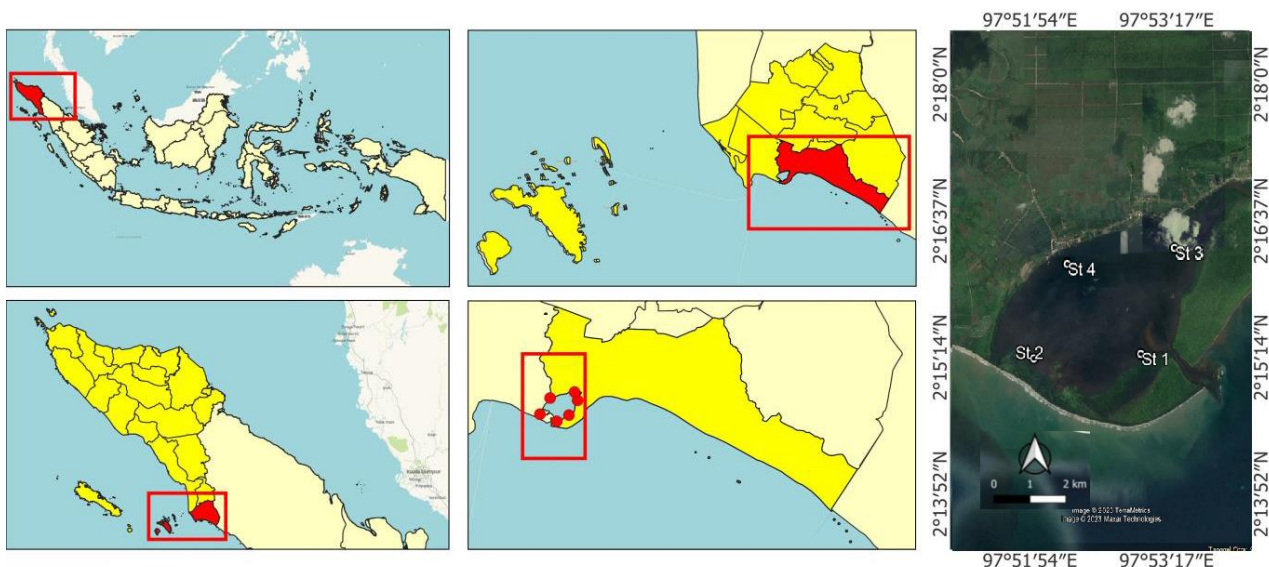
### Study area

This study was conducted from March to April 2023 at Anak Laut Lake, Gosong Telaga Barat Village, North Singkil District, Aceh Singkil District, Aceh Province, Indonesia. Sampling was conducted at four distinct locations (Figure 1 and Table 1). Aquatic biota samples were identified at the Aquatic Environment Laboratory, which is part of the Aquatic Resource Management Study Program at the Universitas Sumatra Utara, Indonesia. Sampling occurred on four occasions in accordance with the tidal cycle: during the new moon, first quarter, full moon, and last quarter. Aquatic biotas were sampled during both high and low tides.

### Procedures

#### Plankton sampling and identification

Plankton sampling was performed using a plankton net with a mesh size of 30 microns. The sampling was conducted using the vertical approach, in which a plankton net was dropped directly downwards from the boat to the 2-4 m and then gradually hauled back towards the boat. Water samples collected in the collecting tube on the plankton net were transferred into a sample vial. Sampling was conducted once during both the high- and low-tide periods at four designated locations. The plankton samples were then preserved using a 4% Lugol solution prior to identification (APHA 2017; Muhtadi et al. 2020b; Hasani et al. 2022). Plankton identification was carried out using a microscope (Olympus CX33, Olympus Corporation, Japan), with each sample observed three consecutive times. Plankton identification refers to Yamaji (1979).



**Figure 1.** Location of Anak Laut Lake, Aceh Singkil District, Aceh Province, Indonesia

**Table 1.** Sampling locations and area descriptions

Location	Coordinate	Description
Station 1	2°15'14.93"N 97°53'4.46"E	Station 1 is the inlet and outlet area of the lake. This location is close and directly connected to sea waters. The water that enters is seawater at high tide. The water that comes out at low tide is sea water mixed with a little fresh water. Station 1 is also a "gateway" for fishing boats to and from the open sea (Indian Ocean). Around Station 1, there are mangrove forests and pine trees. Station 1 is a fishing area, especially for sea cucumbers.
Station 2	2°15'18.13"N 97°51'26.61"E	Station 2 is located in the western part of Anak Laut Lake. Around this point, there are many mangroves. This location is a fishing area.
Station 3	2°16'4.89"N 97°53'33.70"E	Station 3 is the inlet area of the river/paluh originating from the settlement of Gosong Telaga Village. The incoming water is brackish. At this station, many mangrove trees are found. This location is also a fishing location and a transportation route for the community to and from the Indian Ocean.
Station 4	2°16'12.80"N 97°52'0.99"E	Station 4 is a location close to settlements, tourist activities, and fishing ports. At station 4 there is also a channel connected to the oil palm plantation.

#### *Larvae sampling and identification*

Larval specimens were collected using a specialized net designed to capture larvae. A boat was used to draw the larval net horizontally over a distance of 50 m at a depth of approximately 1-2 m. The specimens collected using the bongo net were subsequently placed in sample vials containing a 90% alcohol solution. The specimens obtained were then identified using an identification book Miller and Kendall (2009) as a reference. Larvae with zooplankton are distinguished based on references from Miller and Kendall (2009); they are temporary forms of fish or other aquatic organisms after hatching from eggs, which are characterized by imperfect forms, while zooplankton has their study (previous sub-chapter), which are holoplankton from the rotifera, cladocerans, etc. groups.

#### *Nekton sampling and identification*

Nekton collection was conducted using fish trap, gill nets, and purse seines during both high and low tides in the lake. Fish trap with a size of 30x30 cm with a mesh size of 2 inches. Gill net with a length of 50 m and a height of 2 m with a mesh size of 1 inch. Purse seine with a total length of 100 m and a mesh size of 2 inches. Subsequently, the captured nektons were transferred to a container filled with 96% alcohol. The samples obtained were then identified using a nekton identification book (Carpenter and Niem 1998, 1999; White et al. 2013).

#### *Macrozoobenthic sampling and identification*

Sampling was systematically conducted at four predetermined sites. Sampling was conducted twice daily during tidal cycles. During low tide, a 1x1 m Parallon pipe was used as a transect for capturing and photographing the biota. During high tide, sampling was conducted using a diving method with an Ekman grab. Identification of macro zoobenthos refers to Carpenter and Niem (1998).

#### *Water quality*

Water quality data were acquired from a previous study by Leidonald et al. (2024). There are 14 water quality parameters measured/analysed in this study. These parameters consist of: water transparency, turbidity,

temperature, Total Suspended Solids (TSS), Total Dissolved Solids (TDS), water level, current, Dissolved Oxygen (DO), pH, Biological Oxygen Demand (BOD), Nitrate (NO<sub>3</sub>), Phosphate (PO<sub>4</sub>), salinity, and total coliform.

#### **Data analysis**

##### *Plankton density*

Plankton abundance (N) was estimated using the method described by the American Public Health Association (APHA 2017) as follows:

$$N = n \times \frac{A}{a} \times \frac{v}{vc} \times \frac{1}{V}$$

Where,

- N : Plankton abundance (cells. L<sup>-1</sup>)
- n : Number of plankton counted (cells)
- a : Area of one field of view (1000 mm<sup>2</sup>)
- v : Volume of concentrated water (100 mL)
- A : Cover glass area (1000 mm<sup>2</sup>)
- vc : Volume of water under the cover glass (1 mL)
- V : Volume of filtered water (L)

##### *Abundance of larval nekton*

Larval nekton abundance refers to the number of fish larvae per unit volume in a sample region. Larval abundance was calculated using the method described by the APHA (2017) as follows:

$$N = n/V_{tsr}$$

Where,

- N : Abundance of larval nekton (ind.m<sup>-3</sup>)
- n : Number of larvae obtained (ind)
- V<sub>tsr</sub> : Filtered water volume (V<sub>tsr</sub> = l × t × v)
- l : Mouth opening area of the bongo net (m<sup>2</sup>)
- t : Length of towing time (min)
- v : Towing speed (meters. min<sup>-1</sup>)

### Amount of benthic organisms

The number of organisms was determined using the following formula provided by Krebs (2014):

$$D_i = n_i / A$$

Where,

$D_i$  : Number of individuals of the  $i^{\text{th}}$  species (ind.m<sup>-2</sup>)

$n_i$  : Number of  $i^{\text{th}}$  individuals obtained

$A$  : Total area of the sampling area

### Relationship between water quality and aquatic biodiversity

A Principal Component Analysis (PCA) multivariate analysis was conducted using Microsoft Excel 2016 and Minitab software. Principal Component Analysis is a descriptive statistical method that aims to reveal the maximum information contained in a data matrix in a graphical form. The matrix data consists of water disclosure variables as individuals (rows) and water physicochemical parameter variables as quantitative variables (columns). Principal Component Analysis can provide an easy-to-read or interpret picture of the data structure by extracting important information. This Principal component analysis results will show the correlation between parameters in each tidal cycle. Principal Component Analysis can also divide or group environmental parameter similarities in a data matrix (Muhtadi et al. 2020b, et al. 2024; Muhtadi and Leidonald 2024).

## RESULTS AND DISCUSSION

### Aquatic biodiversity

Based on our observations, nektons in Anak Laut Lake showed variations in both space and time, with differences observed during high and low tides. A total of 29 families and 55 species of nekton were identified (Table 2). The nekton found in Anak Laut Lake are marine organisms, similar to those found in Teluk Belukar Lake (Hasudungan et al. 2008). However, Siombak Lake still contains freshwater fish, as reported by Leidonald et al. (2019a) and (Muhtadi et al. 2023b). Throughout both high and low tides, the new moon phase exhibited the highest nekton abundance, with 378 ind.m<sup>-2</sup> during high tide and 266 ind.m<sup>-2</sup> during low tide. In the first quarter, nekton abundance was at its lowest, with 138 ind.m<sup>-2</sup> at high tide and 80 ind.m<sup>-2</sup> at low tide. Researchers have discovered a similar pattern in Siombak Lake, where fish abundance was higher during high tide compared to low tide. Additionally, fish abundance was found to be greater during spring tide than during neap tide (Muhtadi et al. 2023b; Muhtadi and Leidonald 2024). *Gerres filamentosus*, *Aurigequula fasciata*, and *Charybdis japonica* were the most abundant nekton in Anak Laut Lake, accounting for 22.20%, 16.93%, and 13.18% of the catch, respectively.

Research conducted at Anak Laut Lake also revealed a diverse, plankton composition consisting of nine classes and 62 genera. The total plankton abundance was 17,325

individuals per litre at high tide and 13,360 individuals per litre at low tide (Table 3). The plankton species were predominantly from the class Bacillariophyceae, with included 41 genera (57%) (Figure 2). Other classes represented were Crustacea and Dinophyceae (five genera each) (7%), Ciliata (four genera), Cyanophyceae (three genera), and Chlorophyceae, Euglenophyceae, Eurotatoria, and Appendicularia (one genus each). The findings in this study were lower compared to Siombak Lake, where 66 genera (54 genera of phytoplankton and 12 genera of zooplankton) from 10 classes (three phytoplankton and seven zooplankton) were found (Figure 3). The number of phytoplankton species at each station ranged from 34 to 49, while the number of zooplankton species ranged from 4 to 10 (Muhtadi et al. 2023a). In comparison to other studies, the plankton abundance in Anak Laut Lake was greater than that in Teluk Belukar Lagoon (Nias, Indonesia) with 28 genera (Hasudungan et al. 2008), the Baja California coastal lagoon (México) with 47 genera (Gracia-Escobar et al. 2014), and Ebony Lake (Jakarta-Indonesia) with 48 species (Pratiwi et al. 2018). These findings reflect the varying plankton diversity in different coastal ecosystems. In subtropical regions like Turkey, the plankton species diversity was lower, with only 32 species observed in Kamil Abdus Lagoon, Turkey (Yilmaz et al. 2018).

The larvae discovered in Anak Laut Lake were identified as belonging to 10 different genera (Table 3), representing 10 distinct families (as much as 14% of all plankton groups). The larval population density was 10,849 ind.100m<sup>-3</sup> at high tide and 10,477 ind.100m<sup>-3</sup> at low tide (Table 2). *Parapenaopsis* larvae were the most abundant, comprising 43.64% (4,734 ind.100m<sup>-3</sup>) during high tide and 34.54% (3,619 ind.100m<sup>-3</sup>) during low tide. Estuaries, which include tidal lakes, serve as breeding grounds for crustaceans, as demonstrated by research conducted by Gómez-Ponce et al. (2018) and Puspasari and Aisyah (2018). The larvae and juveniles discovered in Anak Laut Lake mostly comprised fish larvae and juveniles originating from maritime environments, which were transported into the lake by tidal currents (Jaxion-Harm and Speight 2017; Berkström et al. 2020).

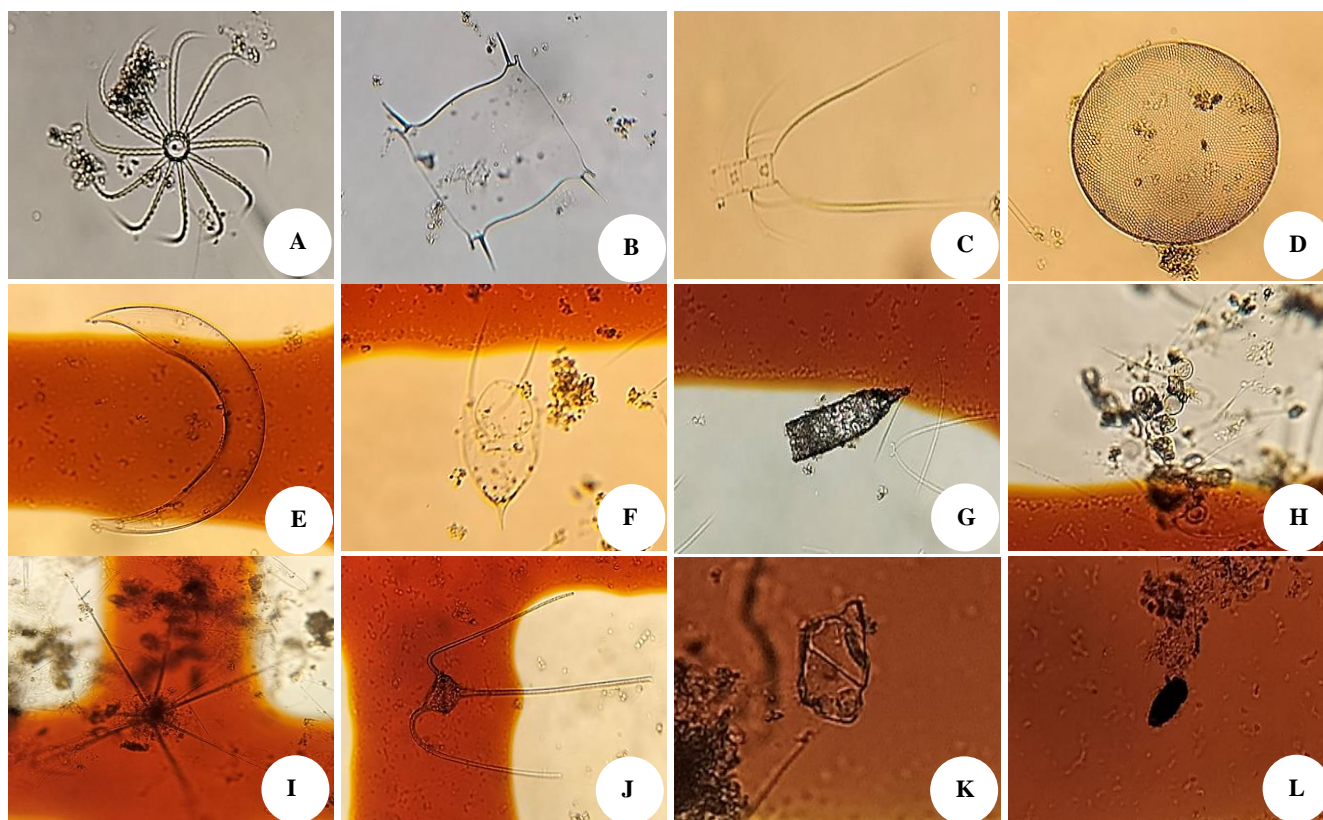
The benthic organisms discovered in Anak Laut Lake comprised a total of 26 species, categorized into four distinct classes and 23 families (Table 2). The benthos density was higher during low tide (332 ind.m<sup>-2</sup>) than during high tide (115 ind.m<sup>-2</sup>). Benthos discovered in Anak Laut Lake comprised marine organisms, including Echinodermata, such as sea urchins and sea cucumbers, which are commonly found in marine environments with a salinity range of 30.4-32.3 parts per thousand (%). Echinoidea exhibit a higher tolerance to brackish water than other invertebrates. The presence of these organisms in Anak Laut Lake is consistent with findings from Belukar Bay Lake, indicating the lake's benthic community was marine in nature (Hasudungan et al. 2008). Nevertheless, the benthic organisms in Anak Laut Lake differed significantly from those in Siombak Lake, where the benthic community was predominantly composed of invasive clams, and the Echinodermata group was notably absent, as reported by Yulianda et al. (2020).

**Table 2.** Nekton and benthos species observed at Anak Laut Lake, Aceh, Indonesia

Family	Species	Common name	Categories	Populations		IUCN status*
				High tide	Low tide	
<b>Fish</b>						
Ambassidae	<i>Ambassis urotenia</i>	Banded-tail glassy perchlet	Resident fish	11	7	LC
Apogonidae	<i>Yarica hyalosoma</i>	Humpbacked cardinalfish	Migratory species	15	5	LC
Belonidae	<i>Strongylura leiura</i>	Banded needlefish	Migratory species	14	22	NE
	<i>Tylosurus crocodilus</i>	Hound needlefish	Migratory species	4	6	LC
Carangidae	<i>Alepes vari</i>	Herring scad	Migratory species	9	0	LC
	<i>Caranx ignobilis</i>	Giant trevally	Migratory species	1	0	LC
	<i>Caranx papuensis</i>	Brassy trevally	Migratory species	1	0	LC
	<i>Carangoides praeustus</i>	Brownback trevally	Migratory species	85	101	LC
	<i>Caranx sexfasciatus</i>	Bigeye trevally	Migratory species	2	0	LC
	<i>Scomberoides lysan</i>	queenfish,	Migratory species	1	0	LC
	<i>Scomberoides tala</i>	Barred queenfish	Migratory species	1	0	NE
	Dasyatidae	<i>Maculabatis gerrardi</i>	Whitespotted Whipray	Migratory species	1	0
<i>Taeniura lymma</i>		Ribbontail stingray	Migratory species	2	0	LC
Engraulidae	<i>Stolephorus indicus</i>	Indian anchovy	Migratory species	25	13	LC
Ephippidae	<i>Platax teira</i>	Longfin batfish	Migratory species	1	0	LC
Gerreidae	<i>Gerres erythrourus</i>	Deep-bodied mojarra	Migratory species	23	22	LC
	<i>Gerres filamentosus</i>	Whipfin silver-biddy	Migratory species	169	210	LC
	<i>Gerres longirostris</i>	Strongspine silver-biddy	Migratory species	15	17	LC
Hemiramphidae	<i>Hyporhamphus quoyi</i>	Quoy's garfish	Resident fish	17	23	LC
Leiognathidae	<i>Aurigequula fasciata</i>	Striped ponyfish	Migratory species	131	158	LC
	<i>Eubleekeria splendens</i>	Splendid Ponyfish	Migratory species	4	6	LC
Lutjanidae	<i>Lates calcarifer</i>	Barramundi	Migratory species	3	1	LC
	<i>Lutjanus argentimaculatus</i>	Mangrove red snapper	Migratory species	5	3	LC
	<i>Lutjanus carponotatus</i>	Spanish flag snapper	Migratory species	2	3	LC
	<i>Lutjanus russellii</i>	Russell's snapper	Migratory species	2	0	LC
Mugilidae	<i>Lutjanus xanthopinnis</i>	Yellowfin snapper	Migratory species	4	5	DD
	<i>Planiliza subviridis</i>	Greenback mullet	Migratory species	53	81	LC
	<i>Crenimugil seheli</i>	Bluespot mullet	Migratory species	21	24	LC
Mullidae	<i>Upeneus vittatus</i>	Yellowstriped goatfish	Migratory species	11	0	LC
Nemipteridae	<i>Nemipterus japonicus</i>	Japanese threadfin bream	Migratory species	2	1	LC
	<i>Nemipterus gracilis</i>	Raceful threadfin bream	Migratory species	3	5	LC
Ostraciidae	<i>Lactoria cornuta</i>	Longhorn cowfish	Migratory species	2	0	NE
Platycephalidae	<i>Grammoplites scaber</i>	Rough flathead	Migratory species	2	0	NE
Scatophagidae	<i>Scatophagus argus</i>	Spotted scat	Migratory species	17	21	NE
	<i>Siganus fuscescens</i>	Mottled spinefoot	Migratory species	11	7	LC
Scombridae	<i>Scomberomorus commerson</i>	Narrow-barred Spanish mackerel	Migratory species	2	0	NT
	<i>Rastrelliger kanagurta</i>	Indian mackerel	Migratory species	5	2	DD
	<i>Rastrelliger brachysoma</i>	Short mackerel	Migratory species	4	0	DD
Serranidae	<i>Cephalopholis formosa</i>	Bluelined hind	Migratory species	5	1	LC
	<i>Epinephelus areolatus</i>	Areolate grouper	Migratory species	3	0	LC
Siganidae	<i>Siganus canaliculatus</i>	White-spotted spinefoot	Migratory species	2	0	LC
Sillaginidae	<i>Sillago sihama</i>	Silver sillago	Migratory species	66	94	LC
Sphyaenidae	<i>Sphyaena barracuda</i>	Great barracuda	Migratory species	1	0	LC
	<i>Sphyaena putnamae</i>	Sawtooth barracuda	Migratory species	11	7	NE
Syngnathidae	<i>Hippocampus comes</i>	Tiger tail seahorse	Resident fish	2	0	VU
	<i>Hippocampus kuda</i>	Spotted seahorse	Resident fish	3	0	VU
Terapontidae	<i>Terapon jarbua</i>	Tiger perch	Resident fish	18	33	LC
Tetraodontidae	<i>Lagocephalus spadiceus</i>	Half-smooth golden pufferfish	Migratory species	5	7	LC
Tetrarogidae	<i>Chelonodon patoca</i>	Milkspotted puffer	Migratory species	7	8	NE
	<i>Tetraroge barbata</i>	Bearded roguefish	Migratory species	1	3	LC
<b>Crustacea</b>						
Cancriidae	<i>Cancer pagurus</i>	edible crab	Migratory species	8	0	NE
Matutidae	<i>Ashtoret lunaris</i>	yellow moon crab	Migratory species	47	24	NE
Penaecidae	<i>Parapenaecopsis coromandelica</i>	coromandel shrimp	Resident	213	75	NE
	<i>Penaeus merguensis</i>	Banana prawn	Migratory species	155	47	NE
Portunidae	<i>Charybdis japonica</i>	Asian paddle crab	Migratory species	148	77	NE
	<i>Portunus Sanguinolentus</i>	three-spot swimming crab	Migratory species	57	25	NE
	<i>Scylla serrata</i>	Mangrove crab	Resident	35	13	NE

<b>Echinodermata</b>						
Clypeasteridae	<i>Arachnoides placenta</i>	Cake sand dollar	Resident	12	148	NE
Diadematidae	<i>Diadema setosum</i>	Long-spined Sea urchin	Resident	11	1	NE
Holothuriidae	<i>Holothuria scabra</i>	Sand fish	Resident	2	0	EN
	<i>Holothuria atra</i>	Lollyfish	Resident	0	17	LC
Laganidae	<i>Laganum laganum</i>	Sand dollar	Resident	5	3	NE
Luidiidae	<i>Luidia quinaria</i>	Spiny sand seastar	Resident	0	4	NE
Stichopodidae	<i>Stichopus herrmanni</i>	Curryfish	Resident	0	2	VU
<b>Arthropoda</b>						
Balanidae	<i>Amphibalanus amphitrite</i>	Striped barnacle	Resident	5	0	NE
<b>Gastropoda</b>						
Buccinidae	<i>Babylonia spirata</i>	Spiral babylon	Resident	0	1	NE
Cerithiidae	<i>Cerithium corallium</i>	Coral cerith	Resident	7	73	LC
Melongenidae	<i>Pugilina cochlidium</i>	Spiral melongena	Resident	16	0	NE
Nassariidae	<i>Nassarius olivaceus</i>	Olivaceous nassa	Resident	4	5	NE
Neritidae	<i>Nerita planospira</i>	Flat-spire nerite snail	Resident	0	8	NE
Pachychilidae	<i>Faunus ater</i>	Black devil snail	Resident	6	10	LC
Potamimididae	<i>Teleskopium telescopium</i>	The telescope snail	Resident	1	5	NE
	<i>Terebralia palustris</i>	Giant mangrove whelk	Resident	28	28	NE
Strombidae	<i>Strombus canarium</i>	The dog conch	Resident	2	3	NE
<b>Bivalvia</b>						
Arcidae	<i>Anadara antiquata</i>	Antique ark	Resident	2	3	NE
Cyrenidae	<i>Corbicula javanica</i>	Basket clams	Resident	0	6	NE
Lasaeidae	<i>Kellia suborbicularis</i>	Holteschelpje	Resident	1	0	NE
Lucinidae	<i>Fimbria fimbriata</i>	basket lucina	Resident	0	1	NE
Myidae	<i>Mya arenaria</i>	Steamers	Resident	0	2	NE
Mytilidae	<i>Septifer bilocularis</i>	Ledge mussel	Resident	0	1	NE
Pinnidae	<i>Pinna muricata</i>	Prickly pen shell	Resident	11	0	NE
	<i>Atrina pectinata</i>	Pen shells	Resident	1	0	NE
Veneridae	<i>Mactra grandis</i>	Radiate mactra	Resident	1	10	NE
	<i>Dosinia contusa</i>	West Indian dosinia	Resident	0	1	NE

\*IUCN (2025); NE: Not Evaluated; DD: Data Deficient; LC: Least Concern; NT: Near Threatened; VU: Vulnerable; EN: Endangered



**Figure 2.** Phytoplankton commonly found in Anak Laut Lake, Aceh, Indonesia (A. *Bacteriastrum*; B. *Biddulphia*; C. *Chaetoceros*; D. *Coscinodiscus*; E. *Closterium*; F. *Favella*; G. *Tintinnopsis*; H. *Anabaena*; I. *Trichodesmium*; J. *Ceratium*; K. *Peridinium*; L. *Trachelomonas*)

**Table 3.** Plankton and larvae genus collected from Anak Laut Lake, Aceh, Indonesia

Genus	Abundance (cell.L <sup>-1</sup> )	
	High tide	Low tide
<b>Bacillariophyceae</b>		
<i>Amphiprora</i>	260	159
<i>Amphora</i>	431	292
<i>Asterionella</i>	52	16
<i>Bacillaria</i>	121	65
<i>Bacteriastrium</i>	647	638
<i>Biddulphia</i>	140	47
<i>Campylodiscus</i>	102	46
<i>Chaetoceros</i>	8372	6250
<i>Coscinodiscus</i>	317	153
<i>Cyclotella</i>	219	49
<i>Cymbella</i>	23	15
<i>Cylindrotheca</i>	215	116
<i>Ditylum</i>	104	14
<i>Entomoneis</i>	24	7
<i>Fragillaria</i>	388	441
<i>Guinardia</i>	83	30
<i>Gyrosigma</i>	46	15
<i>Hemiaulus</i>	71	38
<i>Isthmia</i>	108	61
<i>Lauderia</i>	145	51
<i>Leptocylindrus</i>	110	38
<i>Meuniera</i>	39	17
<i>Mostogloia</i>	93	47
<i>Navicula</i>	149	78
<i>Nitzschia</i>	353	448
<i>Odontella</i>	69	6
<i>Palmeria</i>	46	41
<i>Pleurosigma</i>	83	52
<i>Proboschia</i>	141	205
<i>Pseudo-nitzschia</i>	127	89
<i>Rhizosolenia</i>	228	134
<i>Skeletonema</i>	206	248
<i>Stenopterobia</i>	57	30
<i>Stephanopyxis</i>	12	0
<i>Surirella</i>	36	41
<i>Synedra</i>	457	339
<i>Thalassionema</i>	303	363
<i>Thalassiosira</i>	284	199
<i>Thalassiothrix</i>	243	295
<i>Trachyneis</i>	38	0
<i>Triceratium</i>	21	4
<b>Chlorophyceae</b>		
<i>Closterium</i>	50	0
<b>Ciliata</b>		
<i>Codonellopsis</i>	11	18
<i>Favella</i>	40	0
<i>Tintinnopsis</i>	140	119
<i>Eutintinnus</i>	5	3
<b>Cyanophyceae</b>		
<i>Anabaena</i>	239	134
<i>Oscillatoria</i>	270	229
<i>Trichodesmium</i>	310	190
<b>Dinophyceae</b>		
<i>Ceratium</i>	62	57
<i>Cystodinium</i>	14	3
<i>Dinophysis</i>	11	8
<i>Peridinium</i>	108	24
<i>Protoperdinium</i>	35	15
<b>Euglenophyceae</b>		
<i>Trachelomonas</i>	449	315

<b>Crustaceae</b>		
<i>Acartia</i>	36	31
<i>Balanus</i>	18	13
<i>Calanus</i>	209	404
<i>Nauplius</i>	200	381
<i>Tigriopus</i>	95	221
<b>Rotifera</b>		
<i>Asplanchna</i>	41	6
<b>Urochordata</b>		
<i>Oikopleura</i>	19	12
<b>Larvae (Ind/100 m<sup>3</sup>)</b>		
<i>Epinephelus</i> sp.	71	65
<i>Gerres</i> sp.	357	279
<i>Aurigequula</i> sp.	1238	1936
<i>Strongylura leiura</i>	1	2
<i>Caranx</i> sp.	262	139
<i>Planiliza</i> sp.	3002	2720
<i>Upeneus vittatus</i>	67	35
<i>Portunus</i> sp.	50	9
<i>Parapenaeopsis</i> sp.	4734	3619
<i>Penaeus</i> sp.	1053	1655

A wide range of Endangered (EN) aquatic species have been identified in this lake (Figure 4), including tap ray (*M. gerrardi*) and sand cucumber (*H. scabra*). Other species whose status is in the Vulnerable (VU) category are the golden sea cucumber (*S. herrmanni*) and seahorse (*H. comes* and *H. kuda*). Narrow-barred Spanish mackerel (*Scomberomorus commerson*) is included in the Near Near Threatened (NT) category (Table 2 and Figure 4). The protection status of EN and VU species in the lake is around 6%, where in general the most are still in the Least Concern (LC; 46%) and Not Evaluated (NE; 43%) status. The presence of these species underscores the lake's importance as a critical habitat for marine life in Singkil and surrounding areas. This lake plays a vital role as a nursery and feeding ground, as indicated by the abundance of prawns and fish larvae. Coastal lakes, like Anak Laut Lake, are important habitats for the reproduction and early development of marine species. This finding is supported by a study conducted by El-Regal et al. (2024), which similarly found that fish species from the Red Sea reproduced in coastal lakes around the Red Sea.

Previous research has demonstrated that larval abundance in Anak Laut Lake remains greater than that in Siombak Lake. The larval population in Siombak Lake was 2263 individuals per 100 m<sup>2</sup> during high tide and 2701 individuals per 100 m<sup>2</sup> during low tide. Nevertheless, the larval diversity in Siombak Lake was higher, encompassing 11 taxa comprising six families of fish, two families of crustaceans, and one family of Cnidaria (Muhtadi 2022). Siombak Lake serves as a breeding ground for Penaeidae (crustacean) and Ulmaridae (jellyfish). Larval and juvenile biodiversity in Anak Laut Lake was lower than that observed in comparable tidal or coastal lakes elsewhere. In Tamiahua Lagoon, located in Veracruz, Mexico, a study conducted by Ocaña-Luna and Sánchez-Ramírez (2016) identified 40 species, 37 genera, and 19 fish families of fish larvae and juveniles. Machado et al. (2021) detected 18 taxa in Laguna de Roca, Uruguay. According to Jaxion-

Harm and Speight (2017), nine families were discovered in Oyster Bed Lagoon, located in Honduras.

### Water quality

According to previous research (Leidonald et al. 2023, et al. 2024), the tides in Anak Laut Lake exhibit a mixed pattern, with two high and two low tides occurring on a single day. These tides exhibit variations in both period and height. Variations in water level led to variations in the hydro-morphometry of the lake. The waters of Anak Laut Lake exhibit remarkable dynamism and fluctuation, mirroring the intricate patterns of the tidal cycle in the Indian Ocean. During the last quarter phase, a noticeable increase was observed in the concentrations of organic matter, Biological Oxygen Demand (BOD) and nutrients ( $\text{NO}_3$  and  $\text{PO}_4$ ), along with an increase in total coliform levels. This coincided with a period of low water inflow into the lake, as shown in Table 4. Previous studies conducted at Siombak Lake in Medan, Indonesia, found that water quality conditions varied significantly in accordance with the tidal cycle, with the exception of temperature and pH (Leidonald et al. 2019b; Muhtadi et al. 2020b, et al. 2023c). Coastal lakes influenced by tidal cycles frequently exhibit fluctuating water quality parameters, as demonstrated studies conducted by Sahu et al. (2014), Elshemy and Khadr (2015), Sajinkumar et al. (2017) and Ratnayake et al. (2018).

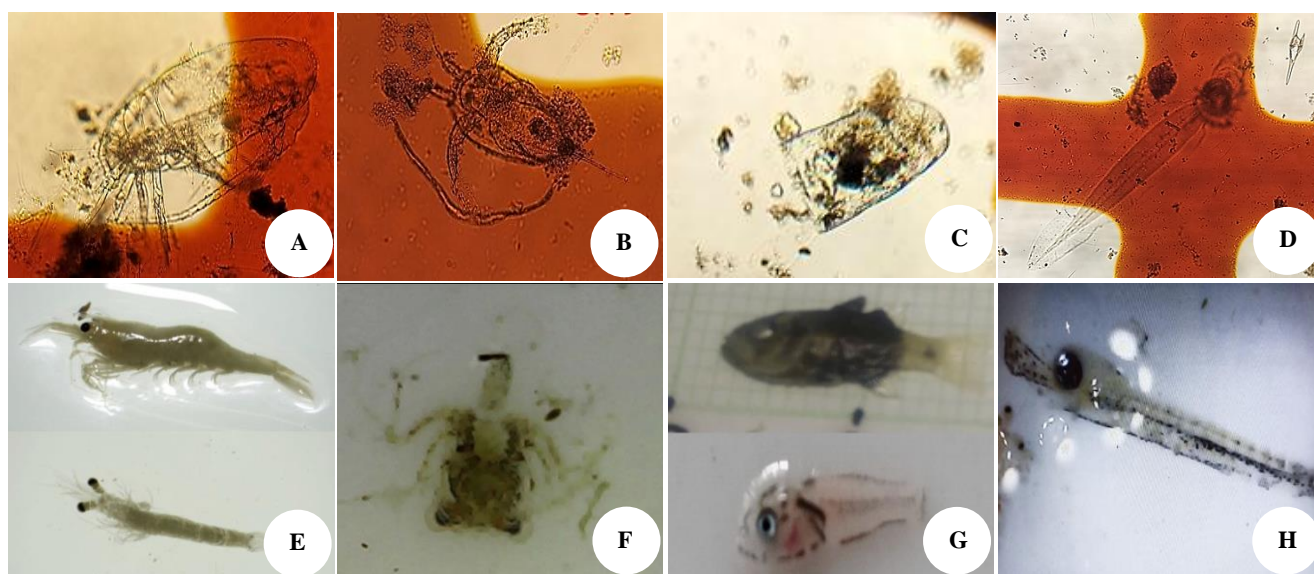
### Discussion

#### *Existence and diversity of aquatic biodiversity based on moon phase during tides*

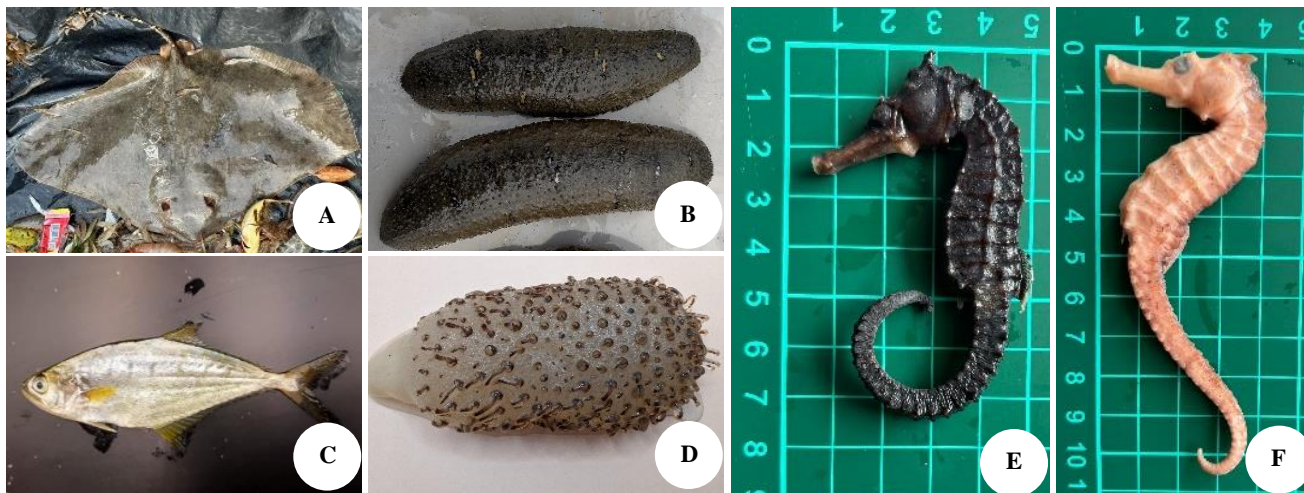
Plankton composition and abundance are often influenced by salinity. Previous research conducted in Siombak Lake, where salinity levels were lower, found that the Chlorophyceae class was the most prevalent (Muhtadi et al. 2020a). In coastal lakes with higher salinity levels,

Bacillariophyceae and Dinophyceae were the predominant phytoplankton types. This has been confirmed in several studies, such as those by Hasudungan et al. (2008), Srichandan et al. (2015a,b), Sahu et al. (2016), Mukherjee et al. (2018), Yilmaz et al. (2018), and Cutrim et al. (2019) in coastal lakes, and Ajibare et al. (2019) in coastal seas. Plankton in the Yangtze Estuary (China) exhibited variability due to the highly dynamic estuarine waters. During the rainy season, Chlorophyta and Bacillariophyta classes were prevalent, whereas Cyanophyta were abundant in the summer (Yang et al. 2019). *Chaetoceros* had the highest plankton concentration, with 14.62 million cells per cubic meter, accounting for 47.65% of the total. *Chaetoceros* and *Peridinium* were the dominant species in Belukar Bay, which was characterized by high salinity levels (>25 ppt), according to Hasudungan et al. (2008). Studies by Hasani et al. (2022) and Hadi et al. (2023) found that species of the genus *Chaetoceros* tend to exhibit high abundance values. *Chaetoceros*, a genus of diatoms, is commonly found in large quantities in marine environments. In coastal lakes with lower salinity levels (<5 ppt), Ebony Lake in Jakarta (Pratiwi et al. 2018) was dominated by *Merismopedia* sp. and *Cyclotella* sp., whereas Siombak Lake (Muhtadi et al. 2020a) was dominated by *Geminella*.

The abundance of plankton exhibited temporal fluctuations, with the highest levels during the new moon phase and the lowest during the full moon phase (Figure 5). During the new moon, plankton abundance reached 4771 cells/L during high tide and 5524 cells/L during low tide. These levels were lower than those in other brackish/coastal lakes in Indonesia. For instance, the plankton abundance in Siombak Lake was 18.61 million cells. $\text{m}^{-3}$  during high tide and 18.20 million cells. $\text{m}^{-3}$  during low tide (Muhtadi et al. 2020a).



**Figure 3.** Zooplankton (A. *Calanus*; B. *Nauplius*; C. *Asplanchna*; D. *Oikopleura*) and larvae (E. *Penaeus* (above) and *Parapenaeopsis* (under); F. *Megalopa* (Portunidae); G. *Gerres* sp. and *Planiliza* sp.; H. *Strongylura leiura*) are commonly found in Anak Laut Lake, Aceh, Indonesia



**Figure 4.** Threatened species found in the lake. Endangered: A. *Maculabatis gerrardi*; B. *Holothuria scabra*. Near Threatened: C. *Scomberomorus commerson*. Vulnerable: D. *Stichopus herrmanni*; E. *Hippocampus kuda*; F. *Hippocampus comes*.

Comparatively, the abundance in Laguna Teluk Belukar, Nias reached 33 million cells.m<sup>-3</sup> (Hasudungan et al. 2008), and in Ebony Lake, Jakarta, up to 1800 million cells.m<sup>-3</sup> (Pratiwi et al. 2018). However, Anak Laut Lake had higher plankton abundance than Chilika Lake (India), where it only reached 2.3 million cells.m<sup>-3</sup> (Srichandan et al. 2015a,b; Sahu et al. 2016; Sahu and Das 2021). Significant differences in phytoplankton abundance are caused by various factors, including the availability of nutrients in the form of the Nitrogen and Phosphorus (NP) ratio (Gamito et al. 2019; Gophen 2019; Yang et al. 2019; Muhtadi et al. 2020a), ammonia availability (Pratiwi et al. 2018), temperature and salinity (Srichandan et al. 2015a,b; Muhtadi et al. 2020a) and light availability (Yang et al. 2019). Additionally, residence time is also a key factor controlling the dynamics of phytoplankton in coastal lakes (Obolewski et al. 2018; Gophen 2019), whereas zooplankton dynamics are greatly influenced by temperature, salinity, and pH (Muhtadi et al. 2020a).

Regarding nekton larvae, the highest abundance was observed during the full moon phase (581 ind.100 m<sup>-3</sup> during high tide and 454 ind.100 m<sup>-3</sup> during low tide), while the lowest abundance occurred during the new moon phase (110,581 ind.100 m<sup>-3</sup> at high tide and 53,581 ind.100 m<sup>-3</sup> during low tide) (Figure 6). Shima and Swearer (2019) discovered that moonlight significantly enhances the daily growth rate of fish larvae, along with temperature (positive effect) and cloud cover (negative effect), likely influencing foraging efficiency and predator avoidance (Shima and Swearer 2019; Shima et al. 2021; Xia et al. 2023).

The benthic population in Anak Laut Lake also exhibited higher values during the full moon phase than during other phases (Figure 7). The benthos density during a full moon reached 109,581 ind.m<sup>-2</sup> at low tide and 34 ind.m<sup>-2</sup> during high tide. This pattern contrasts with larvae and fish abundance, which was higher during high tide. Benthos, being sessile, tend to be more captured during low tide, while they were less affected by tidal changes during high tide. Similarly, in Siombak Lake, benthos density was significantly higher during low tide (Yulianda et al. 2020).

In contrast, the abundance of fish found in Anak Laut Lake was greater during high tide than during low tide (Figure 8). This could be due to the availability of more habitats or niches for fish communities during high tide. In addition, high tides push marine fish into the lake, which could be attributed to the larger body of water caused by high tides (Xia et al. 2023; Muhtadi and Leidonald 2024). Furthermore, the fish population and diversity were typically higher during the spring tide (full moon and new moon phase) than during neap tide (first and final quarters) (Paperno et al. 2018; Muhtadi and Leidonald 2024). Fish in lakes directly connected to the sea experience varying migration patterns depending on location and time. The difference in abundance between high and low tides was attributed to the influx of fish carried by tidal currents into the lake during high tide, as well as their tendency to avoid ebb currents by staying in the lake's water bodies (Lee et al. 2014; Eggertsen et al. 2016). This behavior occurs because estuarine lake areas provide suitable growth conditions for these fish (Kimball et al. 2015; Paperno et al. 2018).

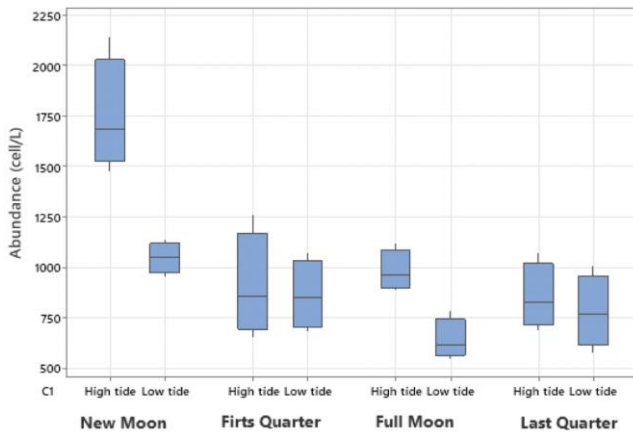
#### *Correlation moon phase during tides on aquatic biota communities*

PCA analysis of water quality and fish population in Anak Laut Lake showed that during the new moon, the high tide phase was dominant, whereas the low tide phase was dominated by both new and full moon phases. This is not surprising because the new and full moon phases are characterized by high and low tides, resulting in a significant tidal range compared to the first and final quarter phases. This result aligns with previous research in Anak Laut Lake, which showed that spring tides (full and new moons) produce a significantly greater tidal range (0.62-1.92 m) compared to neap tides (0.5-1.0 m) (Leidonald et al. 2023). A similar phenomenon was observed in Siombak Lake, where the fish population was more abundant during spring tide compared to neap tide due to the water level higher during spring tide (Muhtadi and Leidonald 2024).

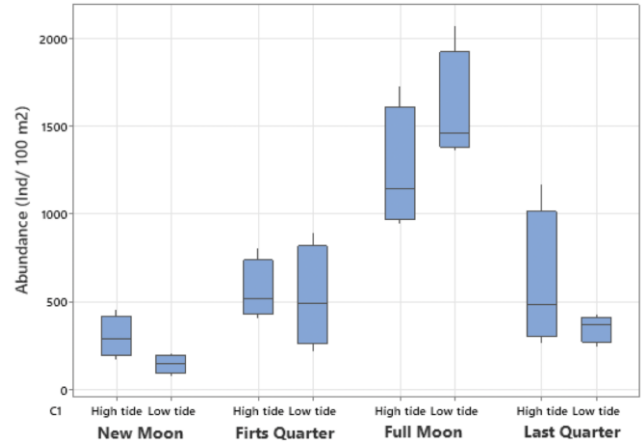
**Table 4.** Water quality characteristics of Anak Laut Lake, Aceh, Indonesia

Parameter	Unit	Moon phase during tides*							
		New moon		First quarter		Full moon		Last quarter	
		High tide	low tide	High tide	low tide	High tide	low tide	High tide	low tide
Water transparency	(m)	1.0-5.6	0.5-2.7	0.6-4.1	0.4-3.0	1.1-4.3	0.7-2.9	0.6-5.2	0.5-4.5
Turbidity	(NTU)	0.16-6.75	0.22-8.20	3.70-5.52	3.64-8.50	1.15-11.22	2.79-14.59	0.94-2.31	2.14-3.75
Temperature	(°C)	30.3-33.5	30.1-31.1	29.6-32.0	29.9-33.9	29.3-30.5	30.0-30.7	29.1-30.0	30.3-31.0
TSS	(mg. L <sup>-1</sup> )	9-12	7-15	7-11	7-11	3-9	7-8	7-10	8-9
TDS	(mg. L <sup>-1</sup> )	4,804-10,269	3,750-8,940	2,810-9,290	2,485-8,155	3,940-9,866	3,628-8,277	4,728-9,809	3,910-8,819
Water level	(m)	1.6-6.6	0.8-3.0	1.5-5.8	1.0-2.6	2.0-7.0	1.1-3.5	1.7-6.4	1.2-4.8
Current	(m.s <sup>-1</sup> )	0.09-0.15	0.06-0.13	0.07-0.10	0.01-0.05	0.07-0.16	0.02-0.14	0.05-0.12	0.02-0.10
DO	(mg. L <sup>-1</sup> )	5.3-5.9	5.3-5.5	5.3-5.6	5.0-5.5	5.2-5.8	5.2-5.7	5.4-5.9	5.1-5.6
pH		8.1-8.5	7.9-8.4	7.8-8.3	7.7-7.9	7.9-8.3	7.7-8.0	7.7-8.3	7.7-8.1
BOD	(mg. L <sup>-1</sup> )	3.8-5.3	3.6-7.2	3.7-4.1	3.2-6.3	3.6-4.6	3.5-5.2	8.1-13.1	6.3-17.5
NO <sub>3</sub>	(mg. L <sup>-1</sup> )	1.6-4.8	3.3-8.3	0.3-2.5	0.6-3.1	0.3-3.6	0.3-3.9	1.9-8.1	0.3-4.8
PO <sub>4</sub>	(mg. L <sup>-1</sup> )	0.02-0.12	0.02-0.04	0.02-0.15	0.02-0.06	0.03-0.07	0.02-0.09	0.02-1.43	0.02-0.05
Salinity	(ppt)	29-34	28-31	27-31	25-30	27-32	27-31	28-31	26-30
Total Coliform	(MPN.100mL <sup>-1</sup> )	7-23	17-47	40-90	18-20	2-18	15-45	47-1,600	39-1,700

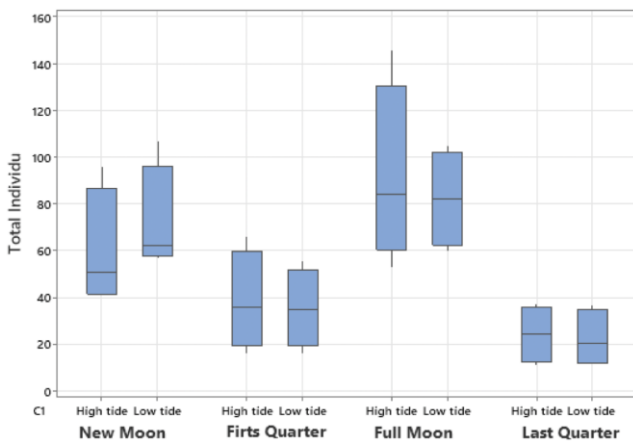
Notes: TSS: Total Suspended Solids; TDS: Total Dissolved Solids; DO: Dissolved Oxygen; BOD: Biological Oxygen Demand; ppt: part per thousand; NTU: Nephelometric Turbidity Unit; MPN: Most Probable Number. \*Adapted from (Leidonald et al. 2024)



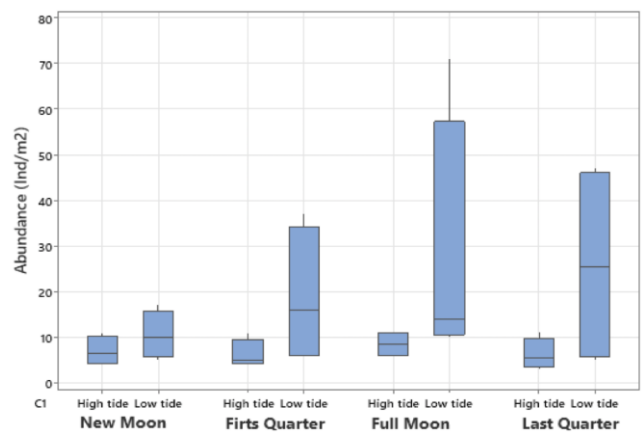
**Figure 5.** Plankton abundance reported in Anak Laut Lake, Aceh, Indonesia, based on Moon Phase During Tides



**Figure 6.** Larvae abundance reported in Anak Laut Lake, Aceh, Indonesia, based on Moon Phase During Tides



**Figure 7.** Benthos abundance reported in Anak Laut Lake, Aceh, Indonesia, based on Moon Phase During Tides

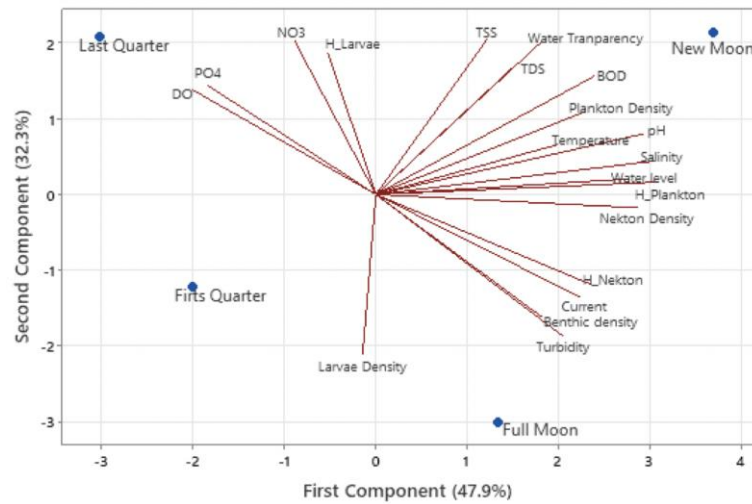


**Figure 8.** Nekton abundance reported in Anak Laut Lake, Aceh, Indonesia, based on Moon Phase During Tides

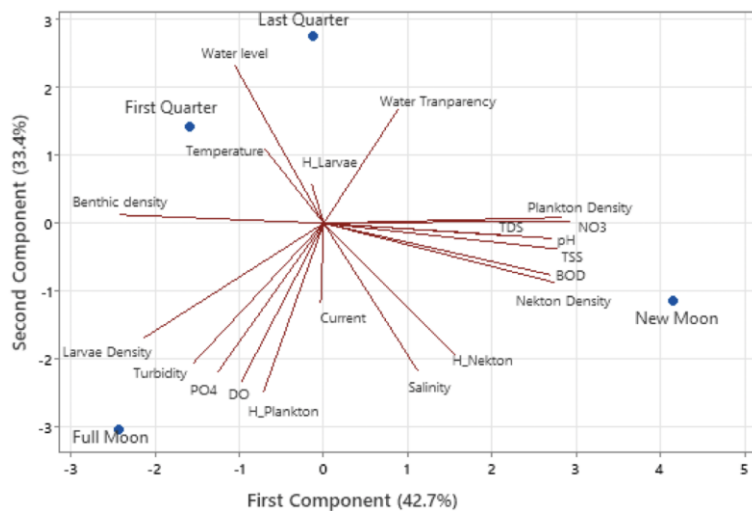
During high tide (Figure 9) and the new moon phase, water quality is primarily characterized by parameters such as salinity, water transparency, Total Suspended Solid (TSS), temperature, and water level, whereas the biological community is characterized by the abundance and diversity of plankton. In contrast, during the full moon phase, water quality is characterized by its flow and turbidity, while the biological aspect is characterized by the presence of nekton and benthos. The final and first quarter phases were characterized by nutritional levels, as well as the abundance and diversity of larvae. During low tide (Figure 10), the new moon phase, water quality was characterized by parameters including salinity, total dissolved solids (TDS), TSS, pH, and Biological Oxygen Demand (BOD), while its biological community was defined by the abundance of nekton and plankton. Conversely, during the full moon phase, water quality was characterized by turbidity, luminosity, and currents, whereas the biological community was characterized by larval abundance. The presence of significantly high tides during spring tide (full

and new moon phases) results in a large volume of water, causing currents that transport materials such as TDS and salinity, as well as aquatic organisms such as plankton and nekton. These findings align with those of a study conducted in Siombak Lake, which highlighted the crucial role of salinity dynamics in coastal lake waters in determining fish population distributions. In high-salinity conditions, marine fish dominate, whereas in low-salinity conditions, freshwater fish were more prevalent (Muhtadi et al. 2023b; Muhtadi and Leidonald 2024).

Fish species entering the lake during high tide often search for food, as estuarine area, including the coastal lakes, serves as a feeding ground for larger fish (Muhtadi et al. 2023b). The fish found in this lake are generally migratory species that utilize estuarine and coastal lakes as feeding grounds. This indicates that Anak Laut Lake also serves as a feeding ground for marine fish. Furthermore, brackish lakes are strongly suspected to serve as nurturing environments (Paperno et al. 2018; Pérez-Ruzafa et al. 2019; Berkström et al. 2020; Muhtadi 2022).



**Figure 9.** Relationship between water quality and biodiversity based on moon phase during high tide in Anak Laut Lake, Aceh, Indonesia



**Figure 10.** Relationship between water quality and biodiversity based on moon phase during low tide in Anak Laut Lake, Aceh, Indonesia

In this study, the most frequently caught fish were from the families Gerreidae, Mugilidae, and Ambassidae and were predominantly in the juvenile and subadult stages. These fish species are associated with mangrove forests during their juvenile phase; however, as adults, they tend to form schools along the coastline adjacent to mangrove forests (Guimarães et al. 2014; Hartz et al. 2019). Several fish species, such as Gerreidae, Leiognathidae, and Mugilidae, dominate fish communities in estuarine and mangrove waters. The captured fish populations mostly comprised juveniles or young individuals. This is because mangroves and estuarine ecosystems serve as critical nursery and feeding grounds due to their abundant food resources (Muhtadi et al. 2020a, et al. 2022, et al. 2023b; Yulianda et al. 2020). Consequently, most of the fish samples obtained were juvenile or adolescent sizes, particularly migratory species (Berkström et al. 2020;

Muhtadi et al. 2023b; Muhtadi and Leidonald 2024).

This study investigated the relationship between tidal variations and the presence, abundance, and diversity of aquatic biota in coastal lakes. We concluded that the tidal dynamics influenced the presence, abundance, and diversity of aquatic organisms in the lake. The new and full moon phases greatly affected the dynamics of the water quality and biodiversity of the lake due to the pronounced tidal ranges produced.

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