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Research Article

Zoo Benthic Biodiversity as a Bioindicator in the Bengawan Solo Estuary

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Abstract

As key aquatic organisms, benthos are a reliable indicator of water quality owing to their relatively fixed habitats, limited mobility, and residence at the bottom of the water. This study aimed to analyze benthos' biodiversity and community structure as bioindicators in the waters of the Bengawan Solo estuary that important for fishery activities conducted by local fishermen community. A descriptive analysis method was employed, involving identifying and analyzing benthos in density, biological indexes, and principal component analysis (PCA). The macrobenthos species composition consisted of Gastropoda, Bivalvia, Maxillopoda, Malacostraca, Polychaeta, and Clitellata while meiobenthos comprised Foraminifera, Bivalvia, Gastropoda, and Polychaeta. Macrobenthos density was 288 ind./m2, whereas meiobenthos density was 16 ind./10 cm2. Both macrobenthos and meiobenthos exhibited a moderate diversity index and a medium evenness index, although evenness values tended to be higher in macrobenthos. The dominance index for both macrobenthos and meiobenthos showed moderate values. PCA analysis revealed that macrobenthos, Bivalvia, Gastropoda, and Clitellata density was influenced by brightness and turbidity, Malacostraca and Maxillopoda density by salinity, and Polychaeta density by dissolved oxygen. In meiobenthos, Gastropoda and Foraminifera density was influenced by salinity, whereas Bivalvia and Polychaeta density was affected by brightness and turbidity. Density and biological index results indicate that the Bengawan Solo estuary is relatively stable.

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1. Introduction

The Bengawan Solo River, the longest river in Java, flows from the Sewu Mountains in Central Java into the Ujungpangkah Waters in East Java. This river and its estuaries are critical for local aquaculture activities, providing essential resources for both the economy and ecology of the region. The confluence between the Bengawan Solo River and Ujungpangkah Waters forms three Bengawan Solo Estuaries: Muara Slewean, Muara Pucuk, and Muara Kaliumum. Given its length, the Bengawan Solo River basin experiences high rainfall (Widyastuti *et al*., 2018), intensifying river erosion as rainwater erodes the soil surface into suspended particles, which are carried by river flow and accumulate in waters with diminished velocities, such as river estuaries (Sulaxono *et al*., 2020). The estuaries of the Bengawan Solo River play a critical role in the local economy, particularly for the fisheries sector and aquaculture. These areas provide essential water supplies for fishponds and contribute significantly to the livelihoods of local communities (Hasan *et al*., 2023; Marhaento *et al*., 2021).

An estuary, where fresh river water mixes with seawater, is a repository for suspended particles from river flow (Tendean *et al*., 2012). The accumulation of suspended particles causes sedimentation in the estuary (Jiyah *et al*., 2017), and the community uses this sedimentation as traditional ponds (Setyaningrum and Laily, 2022). However, high sedimentation has adverse effects on aquaculture. For example, excessive sedimentation can impede respiration in cultivated shrimp and fish, potentially covering gill surfaces (Hasniar, 2014). Historically, estuary wetlands have been preferred locations for human activity, such as high-intensity fishing and aquaculture activities, that could affect the health status of the estuary area (Jiang *et al*., 2023; Leung *et al*., 2024; Li *et al*., 2022). Moreover, the reduction in human activities can impact the water quality of estuaries based on physicochemical and biological parameters (Hartiningsih *et al*., 2024). Previous studies, including Barrotut (2015), used the STORET index to categorize water quality in the Bengawan Solo estuary, placing it in Class D, which indicates poor water quality and significant pollution. This study will build on these findings by analyzing how poor water quality, as measured through bioindicators like benthic community health, impacts aquaculture practices. Deteriorating water conditions will markedly impact aquaculture production in the area.

The fluctuating salinity and high sedimentation levels in the Bengawan Solo River estuary directly impact the health of aquatic organisms, particularly in aquaculture. This study aims to analyze how these factors influence water quality and benthic community composition, using bioindicators to assess their suitability for aquaculture activities. Therefore, understanding water suitability for aquaculture activities is imperative. This involves analyzing water quality using bioindicators, with benthos as one possible indicator given their relatively fixed habitat, individual size, limited mobility, and benthic residence (Nangin *et al*., 2015). Moreover, benthos plays a vital role in organic matter decomposition, thereby sustaining the growth and development of other organisms, such as phytoplankton and zooplankton (Syafarina *et al*., 2018). In general, current speed can directly or indirectly influence the condition of the bottom substrate which is a determining factor in the composition of benthic animals, wave movements can increase the amount of oxygen in the water and influence the particles that make up the bottom substrate which is a determining factor in the benthic community (Ruswahyuni, 2010). Recent studies have shown that macrobenthos, due to their fixed habitat and role in organic matter decomposition, can be effective bioindicators of water quality in estuarine environments (Li *et al*., 2022). These organisms play a critical role in the aquatic food web, and their health reflects the overall environmental conditions, particularly in aquaculture settings. By independently different sources of the environmental variables, the researcher could conclude the main effects of human activities on the macrobenthic community (Pei *et al*., 2024). Rozirwan *et al*. (2021) suggested that lower water quality could the directly affect the diversity of microbenthic and community survival. Therefore, benthic community structure can reflect water conditions. Benthic community structure has been reported in some estuaries in Krueng cut Banda Aceh (Irham *et al*., 2020), Cimandiri river and estuary (Ibrahim *et al*., 2023), mangrove estuary Brebes (Zallesa *et al*., 2020), and Gorontalo water (Kadim *et al*., 2022). However, research on benthic community structure in the Bengawan Solo River and Ujungpangkah Waters remains limited; thus, data and information updates are necessary, given the constantly changing conditions in these environments. This study addresses this knowledge gap by analyzing the biodiversity and community structure of benthos serving as bioindicators in the Bengawan Solo estuary waters. The objective of this study is to identify the diversity and community structure of benthic as a bioindicator in determining the level of environmental pollution in the Bengawan Solo River estuary and Ujungpangkah Waters and analyze the diversity of benthic using principal component analysis (PCA).

2. Materials and Methods

2.1 Materials

The materials used in this study are 4% formaldehyde, water, sediment samples, and water samples. The equipment used in this study includes a pH meter, YSI Pro 20, refractometer, secchi disc, Van Veen Grab (25 × 45 cm), bucket, sample bottles, zip lock bags, stereo microscope, petri dishes (6 cm diameter), dropper pipettes, tweezers, tiered sieves (1.0 mm² and 0.1 mm²), styrofoam box, sediment corer (PVC pipe with a diameter of 2.6 cm and a length of 14 cm), camera, and GPS.

Table 1. Stations and sampling points at the study location.

Station	Point	Location	Coordinate
Fresh water	3	Bengawan Solo River branching	S: 6°52’38.7372” E: 112°33’20.5632”
	5	Bengawan Solo River branching	S: 6°55’13.242” E: 112°34’56.9172”
Brackish water	1	Slewean estuarine	S: 6°51’34.4988” E: 112°31’49.242”
	2	Pucuk estuarine	S: 6°51’04.0248” E: 112°32’56.6088”
	4	Kaliumum estuarine	S: 6°53’30.4368” E: 112°36’29.2896”
Sea water	6	Ujungpangkah waters	S: 6°51’21.3588” E: 112°31’39.4932”
	7	Ujungpangkah waters	S: 6°50’37.6836” E: 112°34’47.1216”
	8	Ujungpangkah waters	S: 6°53’11.652” E: 112°37’15.0708”

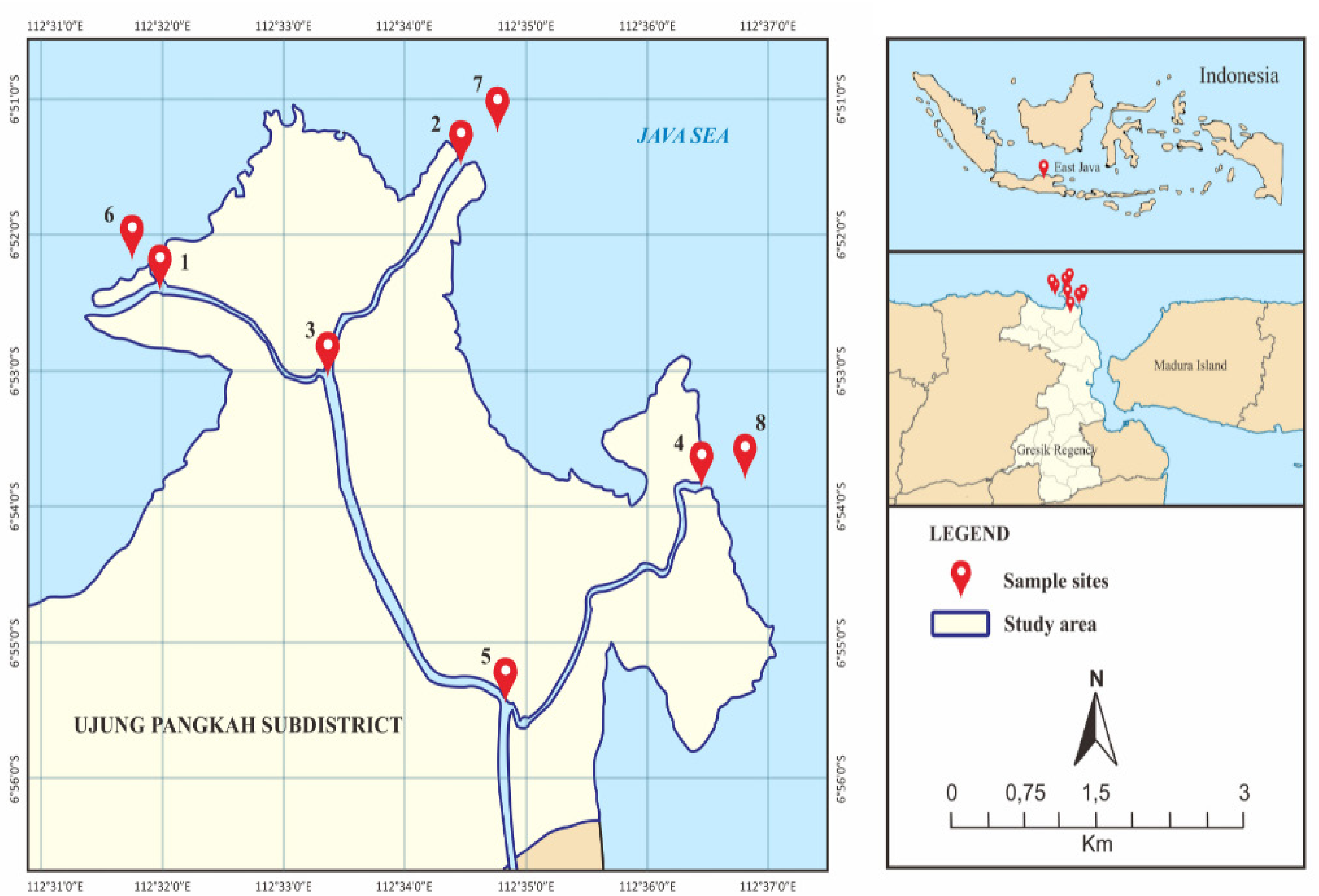

Figure 1. Study location of the Bengawan Solo River, which discharges into the Ujungpangkah Waters, Gresik, East Java.

2.1.1 Ethical approval

This study does not require ethical approval because it does not use experimental animals.

2.2 Study Area

The study was conducted over four months (March, May, July, and September 2022), with monthly sampling conducted in the Bengawan Solo River, discharging into the Ujungpangkah Waters, Gresik, East Java. Sampling occurred at eight stations, each comprising three sampling points determined based on the salinity gradient at the site (Table 1) (Figure 1). Sample analysis was performed at the Anatomy and Aquaculture Laboratory, Faculty of Fisheries and Marine Sciences, Airlangga University. Turbidity analysis was conducted at the Aquatic Productivity and Marine Sciences, Airlangga University. Turbidity analysis was conducted at the Aquatic Productivity and Environment Laboratory, Department of Aquatic Resources Management, IPB University.

2.3 Methods

2.3.1 Physical–chemical parameter sampling

Parameters affecting macrozoobenthos viability were measured *in situ* [temperature were measure using thermometer, dissolved oxygen (DO) was measured using a digital DO meter, salinity was measured using hand refractometer, water transparency was measured using a secchi disk, and pH was evaluated using hand pH meter] and *ex-situ* (turbidity was measure using a digital turbidimeter).

2.3.2 Benthos sampling

Sampling collections were conducted using a Van Veen Grab with a wide opening of 0.1125 m^2. Meiobenthos samples were collected using a sediment corner (d = 5.3 cm^2) inserted into the sediment samples. Macrobenthos samples were collected from all obtained sediments. Macrobenthos and meiobenthos samples underwent separation from substrates using 1.0- and 0.1-mm sieves, respectively. Subsequently, they were preserved in a 4% formaldehyde solution in sample bottles and analyzed in the laboratory. Benthos identification was performed using standard Benthos identification books (Bunjamin, 2005; Kenneth and Gosner, 1971) and the WoRMS (World Register of Marine Species) website database.

2.4 Analysis Data

2.4.1 Benthos density

Benthos density was analyzed using the Shannon–Wiener Index (Odum, 1993) based on the following formula:

$$\mathrm{Di} = \frac{\mathrm{Ni}}{\mathrm{A}}$$

Where:

Di = Benthos density (macrobenthos: individuals (ind.)/m^2; meiobenthos: ind./10 cm^2)

Ni = Number of individuals of the *i* species (macro benthos: ind.; meiobenthos: ind.)

A = Total number of individuals (macrobenthos: m^2; meiobenthos: cm^2).

2.4.2 Diversity index (H')

Benthos diversity was analyzed using the Shannon–Wiener Index (Odum, 1993) based on the following formula:

$$\mathrm{H}' = -\sum pi.\log_2.pi$$

Where:

H' = Diversity index

Pi = Proportion of the *i* species (*Ni/A*)

Diversity index categories included low diversity ($H' \leq 1$), moderate diversity ($1 < H' \leq 3$), and high diversity ($H' > 3$).

2.4.3 Evenness index (E)

Benthos evenness was analyzed using the Pielou Evenness Index (Odum, 1993) based on the following formula:

$$\mathrm{E} = \frac{\mathrm{H}'}{\mathrm{H_{max}}}$$

Where:
E = Evenness index
H' = Diversity index
H_{max} = Maximum diversity (Log_2.pi)

Evenness index categories, according to Krebs (1989), included tertiary communities ($0 < E \leq 0.5$), less-stable communities ($0.5 < E \leq 0.75$), and stable communities ($0.75 < E \leq 1$).

2.4.4 Dominance index (C)

Benthos dominance was analyzed using Dominance of Simpson (Odum, 1993) based on the following formula:

$$\mathrm{C} = \sum \left(\frac{\mathrm{ni}}{\mathrm{N}}\right)^2$$

Where:

Ni = Number of individuals of the *i* species

A = Total number of individuals

Dominance index categories, according to Krebs (1989), included low dominance ($0 < C < 0.5$), moderate dominance ($0.5 < C < 0.75$), and high dominance ($0.75 < C \leq 1.0$).

2.4.5 Principal component analysis (PCA)

PCA, describing the relationship between benthos density and water quality parameters, was performed using PAST 4.03.exe software.

3. Results and Discussion

3.1 Results

In this study, the macrobenthic composition consisted of Gastropoda (11 genus), Bivalvia (6 genus), Maxillopoda (1 genus), Malacostraca (1 genus), Polychaeta (1 genus), and Clitellata (1 genus) (Table 2). Meiobenthos exhibited a species composition comprising Foraminifera (13 genera), Bivalvia (1 larval stage), Gastropoda (1 larval stage), and Polychaeta (1 genus) (Table 3).

Bivalvia dominated macrobenthos across all research stations (Figure 2a), whereas Foraminifera was the dominant meiobenthos group (Figure 2b). Macrobenthos distribution at each station in the study area exhibited an increasing trend in seawater species and a decreasing trend in freshwater species each month (Figure 3). Conversely, meiobenthos in the same area comprised solely seawater meiobenthos.

Macrobenthos density (Di) was 288 ind./m2. At all stations, the density of macrobenthos was highest in July, coinciding with the dry season (Figure 4a).

Table 2. Macrobenthos found in the Bengawan Solo estuary.

Taxa	March			May			July			September		
	A	B	C	A	B	C	A	B	C	A	B	C
Bivalvia												
Anodonta	62	231	62	200	54	80	40	39	95	71	89	48
Gafrarium	0	30	0	0	0	15	0	27	6	0	12	0
Anadara	0	0	0	0	0	0	0	9	9	0	0	0
Tellina	14	101	9	23	36	62	5	130	133	9	33	12
Perna	0	3	3	5	3	15	9	18	15	0	9	6
Pilsbryoconcha	0	0	0	0	3	0	0	6	0	0	0	0
Gastropoda												
Brotia	5	71	0	5	30	9	0	74	3	0	3	0
Terebra	0	18	0	0	0	3	5	36	0	0	3	0
Cerithium	0	6	0	0	0	0	0	30	0	0	24	0
Nassarius	0	3	0	0	3	0	0	12	9	0	3	0
Pila	0	0	0	0	3	0	0	3	0	0	0	0
Gyraulus sp.	0	0	0	0	3	0	0	0	0	0	0	0
Telescopium	0	0	0	0	0	0	0	39	3	0	0	0
Clithon	0	0	0	0	0	0	0	9	0	0	6	0
Tarebia	0	0	0	0	0	0	0	36	0	0	3	0
Thiara	0	24	0	0	21	0	0	0	0	0	0	0
Sulcospira	31	45	0	0	9	6	0	44	0	0	12	0
Maxillopoda												
Balanus	14	18	38	9	47	0	0	36	33	0	6	53
Clitellata												
Lumbricus	0	0	0	0	12	0	0	9	9	0	0	0
Polychaeta												
Nereis	0	3	0	0	3	3	0	0	3	36	18	0
Malacostraca												
Grandidierella	0	0	0	0	0	0	0	0	110	0	0	0
TOTAL	**126**	**553**	**112**	**242**	**227**	**193**	**59**	**557**	**428**	**116**	**221**	**119**

Description: (A) Fresh water; (B) Brackish water; (C) Sea water.

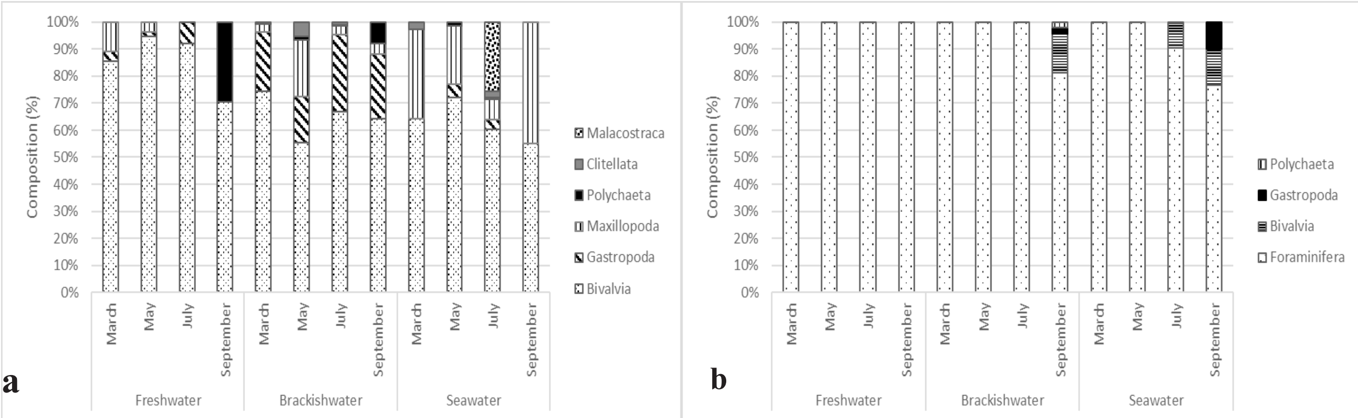

Figure 2. Compositions of macrobenthos (a) and meiobenthos (b) in the Bengawan Solo estuary.

Table 3. Meiobenthos found in the Bengawan Solo estuary.

Taxa	Mach			May			July			September		
	A	B	C	A	B	C	A	B	C	A	B	C
Foraminifera												
Ammonia	5	4	3	4	2	2	3	2	4	4	2	3
Amphistegina	1	1	1	0	0	0	1	0	0	1	0	0
Calcarina	2	1	0	1	0	0	1	0	0	0	0	0
Ellipsonodosaria	0	0	0	1	0	0	0	0	1	0	0	0
Elphidium	1	2	5	1	1	1	2	1	0	1	0	1
Globigerina	4	8	11	6	10	19	4	15	15	4	10	9
Rotalia	1	2	2	1	1	0	1	0	1	0	1	0
Lagena	0	0	0	0	0	0	0	0	0	0	0	0
Cibicides	1	0	1	1	1	0	1	0	0	1	0	2
Eggrella	1	0	0	0	0	0	0	0	0	0	0	0
Milliamina	0	0	0	0	0	0	1	0	0	1	0	0
Streblus	1	1	0	1	1	1	0	0	0	1	1	1
Textularia	0	0	1	1	1	0	1	1	1	1	1	0
Bivalvia												
Larval stage	0	0	0	0	0	0	0	0	1	0	1	2
Gastropoda												
Larval stage	0	0	0	0	0	0	0	0	0	0	0	2
Polychaeta												
Nereis	0	0	0	0	0	0	0	0	0	0	1	0
TOTAL	**17**	**19**	**24**	**17**	**17**	**23**	**15**	**19**	**23**	**14**	**17**	**20**

Meiobenthos density (Di) was 16 ind./10 cm2. This density was stable between March and September across all stations (Figure 5b). Results from each station showed that the highest macrobenthos density was found at the brackish water station (Figure 4b). In contrast, the highest meiobenthos density was observed at the seawater station (Figure 5b).

Diversity index values, (H') were obtained based on observation time, with the highest values observed in May for macrobenthos (Figure 6a) and September for meiobenthos (Figure 8a). In contrast, the lowest diversity values occurred in September (Figure 6a) for macrobenthos and July for meiobenthos (Figure 8a). Based on the analysis of observation stations, the highest diversity values were found in brackish water stations for macrobenthos (Figure 7a) and freshwater stations for meiobenthos (Figure 9a). In contrast, the lowest values were observed at freshwater stations for macrobenthos (Figure 7a) and seawater stations for meiobenthos (Figure 9a). Both macrobenthos and meiobenthos exhibited moderate H' values (1 < H' < 3).

Evenness index values (E) were obtained based on observation times, with the highest evenness values observed in March for both macrobenthos and meiobenthos (Figure 6b and Figure 8b), and the lowest values observed in July for both macrobenthos and meiobenthos (Figure 6 and Figure 8b). Based on the analysis of observation stations, the highest evenness values were found at brackish water stations for macrobenthos (Figure 7b) and freshwater stations for meiobenthos (Figure 9b). In contrast, the lowest evenness values were found at freshwater stations for macrobenthos (Figure 7b) and seawater stations for meiobenthos (Figure 9b). Evenness values indicated that macrobenthos displayed moderate evenness that tended toward high values (0.75 < E ≤ 1), whereas meiobenthos showed moderate evenness (0.5 < E ≤ 0.75).

Dominance index values (C) were obtained based on observation times, with the highest dominance values observed in September for macrobenthos (Figure 6c) and March for meiobenthos (Figure 8c), and the lowest dominance values observed in July (Figure 6c) for macrobenthos and March for meiobenthos (Figure 8c). According to observation station analysis, the highest dominance values were found at freshwater stations for macrobenthos (Figure 7c) and seawater stations for meiobenthos (Figure 9c). In contrast, the lowest dominance values were observed at brackish water stations for macrobenthos (Figure 7c) and freshwater stations for meiobenthos (Figure 9c). Both macrobenthos and meiobenthos exhibited moderate dominance values that tended toward low dominance (0 < C ≤ 0.5).

The outcomes of water quality assessments at the study site are presented in Table 4. The influence of water conditions on benthic community structure was evaluated through key water quality measurements, including salinity, turbidity, DO, temperature, brightness, and pH. These parameters were compared against the KEPMEN LH No. 51 standards of 2004 concerning Seawater Quality Standards for Marine Biota. Salinity measurements across all stations exhibited an increasing trend from March to September, impacting the distribution of benthic species. Turbidity measurements indicated a continuous decline from March to September. The recorded turbidity value surpassed the quality standard of <5 NTU. DO, temperature and pH measurements revealed a stable trend each month, aligning with quality standards for marine biota (DO > 5 mg/L; temperature: 28-32°C; pH 7.0–8.5). Brightness increased from March to July, followed by a decrease in September.

PCA was applied to determine the relationship between the two principal components, namely Benthos density and water quality parameters. Regarding macrobenthos, the density of Bivalvia, Gastropoda, and Clitellata was positively correlated with brightness and turbidity at brackish water stations (Figure 10a). The macrobenthos density of Malacostraca and Maxillopoda was positively correlated with salinity at the seawater station (Figure 10a). Furthermore, the density of macrobenthos in Polychaeta was positively correlated with DO at the freshwater station (Figure 10a). Regarding meiobenthos, the density of Gastropoda and Foraminifera was positively correlated with salinity at the seawater station (Figure 10b). Additionally, the density of meiobenthos in Bivalvia and Polychaeta was positively correlated with brightness and turbidity at the brackish water station (Figure 10b).

3.2 Discussion

3.2.1 Composition and density of benthos

Macroinvertebrates or macrobenthos play an essential role in ecosystem trophic transfer by supporting an energy flow from lower to upper trophic-level organisms (Ndhlovu *et al.,* 2024). Bivalvia dominated macrobenthos across all research stations, whereas Foraminifera was the dominant meiobenthos group. Both benthic organism groups can adapt to environmental changes, explaining their dominance. Bivalvia have adapted by sediment burrowing activity to adapt to complex aquatic sediment conditions (Islami, 2015). Foraminifera have unique characteristics in the composition and morphology of their shells to adapt to their environment (Supardi and Rahmawati, 2022).

The presence of benthos is related to water conditions, which are influenced by factors such as rainfall and benthic substrate habitats. Benthic observations revealed the density of macrobenthos peaking from May to July and meiobenthos was stable between March and September across all stations. Despite reduced rainfall in these months, accumulated turbidity from the previous month, containing organic matter as benthic food, and increased salinity and temperature, they are supported by enhanced benthic productivity (Aurícht *et al.,* 2018; Dominici *et al.,* 2019). Additionally, the existence of benthos is influenced by the research location's

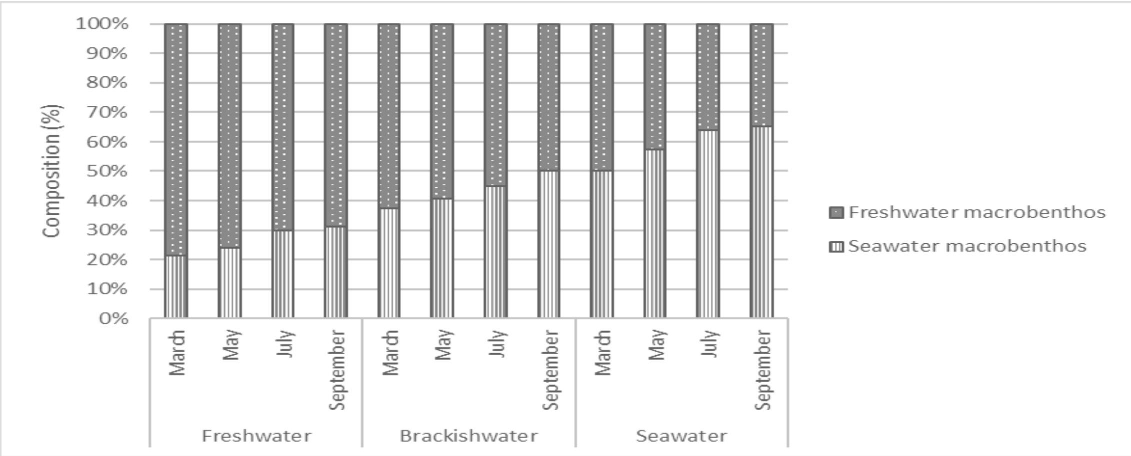

Figure 3. Macrobenthos distribution based on habitat in the Bengawan Solo estuary.

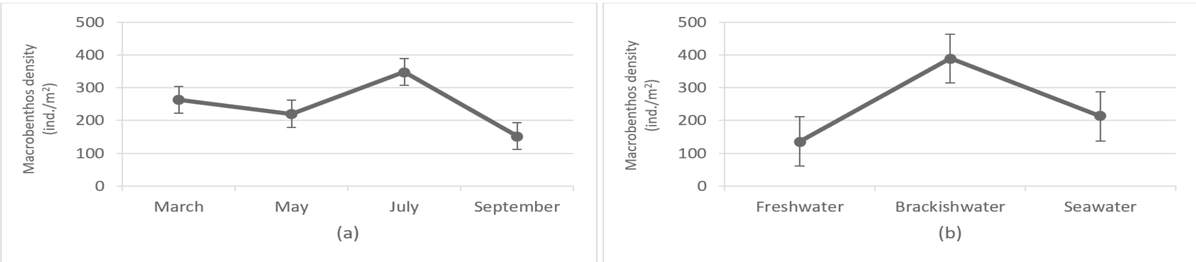

Figure 4. Macrobenthos density based on month (a) and station (b) in the Bengawan Solo estuary.

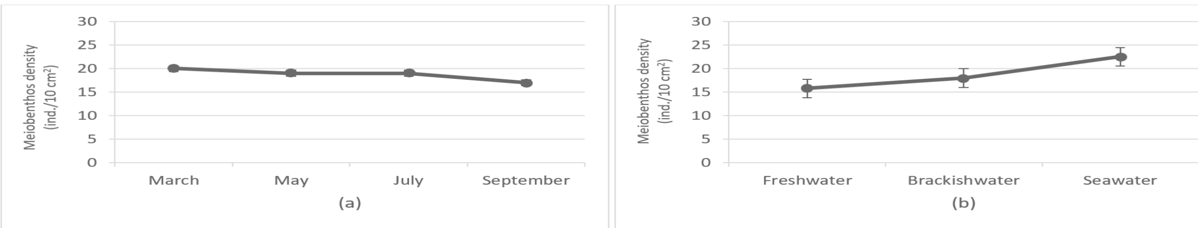

Figure 5. Meiobenthos density based on month (a) and station (b) in the Bengawan Solo estuary.

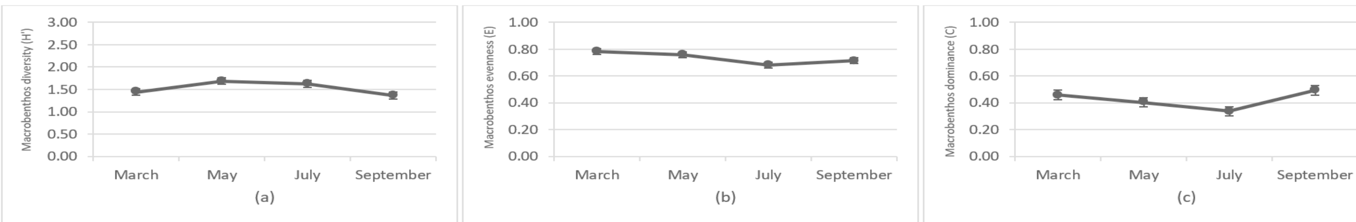

Figure 6. Diversity (*H'*), evenness (*E*), and dominance (*C*) indexes of macrobenthos across four months in the Bengawan Solo estuary.

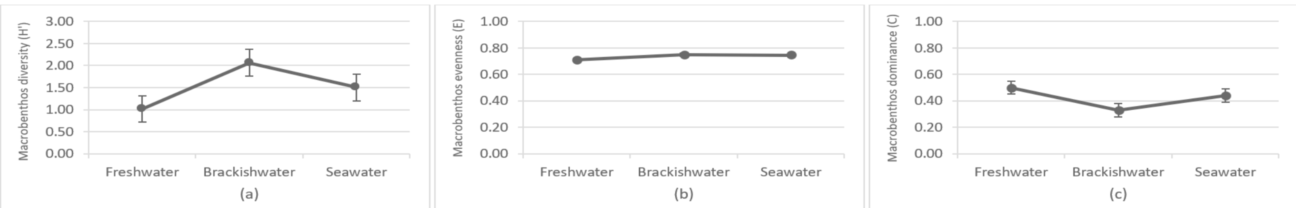

Figure 7. Diversity (*H'*), evenness (*E*), and dominance (*C*) indexes of macrobenthos across three stations in the Bengawan Solo estuary.

condition, i.e., a confluence of seawater and freshwater with natural ecosystem pressures, such as salinity gradients and seasonal variations (Medeiroz *et al.,* 2016).

Macrobenthos distribution at each station in the study area exhibited an increasing trend in seawater species and a decreasing trend in freshwater species each month. Salinity emerged as the primary factor influencing macrobenthos species distribution. High rainfall reduces salinity due to increased freshwater supply from the upstream river, promoting abundant freshwater macrobenthos. Conversely, decreased rainfall allows seawater to enter estuaries, elevating salinity and promoting the presence of marine macrobenthos (Barus, 2002). Lowe *et al.* (2022) suggested that macrobenthos density and species dominance are affected by seasonal changes, which demonstrates the critical role of freshwater infiltration. Agreed with the study reported by Tian *et al.,* (2023), macroinvertebrates such as Gastropods, Bivalvia, Polychaeta, and Amphipoda widely distributed in mudflats, and some genera still could attach to rocks.

Meiobenthos distribution at each station in the study area comprised solely seawater meiobenthos. The substrate of the water's bottom markedly influenced meiobenthos species distribution. The primary substrate at the study site is mud, which has high organic matter

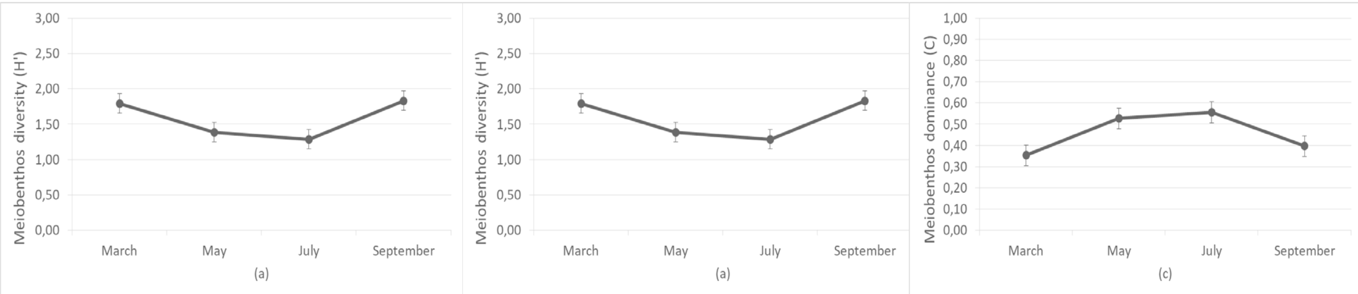

Figure 8. Diversity (H'), evenness (E), and dominance (C) indexes of meiobenthos across four months in the Bengawan Solo estuary.

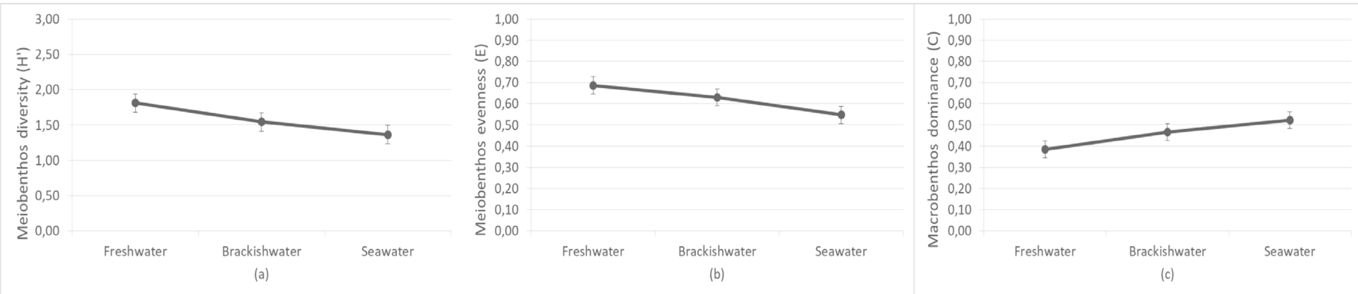

Figure 9. Diversity (H'), evenness (E), and dominance (C) indexes of meiobenthos across three stations in the Bengawan Solo estuary.

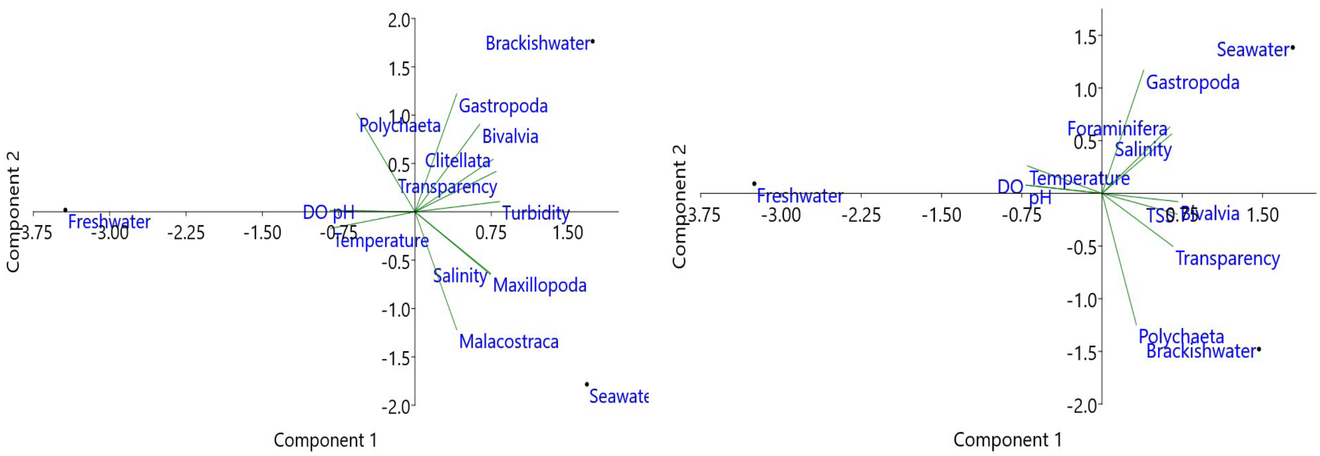

Figure 10. Relationships between water quality parameters and the density of macrobenthos (a) and meiobenthos (b) in the Bengawan Solo estuary.

Table 4. Water quality parameters in the Bengawan Solo estuary.

Station	Month	Salinity (ppt)	Turbidity (NTU)	Transparency (cm)	DO (mg/L)	Temperature (°C)	pH
Fresh water	March	0.0 ± 0.0	331 ± 60	7.5 ± 3.5	6.2 ± 0.4	29.5 ± 0.6	7 ± 0.1
	May	0.0 ± 0.0	156 ± 71	17.5 ± 3.5	4.3 ± 0.3	28.8 ± 0.1	7 ± 0.1
	July	0.0 ± 0.0	100 ± 42	41.0 ± 4.2	6.0 ± 0.2	29.5 ± 0.4	7 ± 0.1
	September	10.0 ± 5.7	73 ± 25	40.0 ± 0.0	9.8 ± 1.0	31.5 ± 0.7	8 ± 0.2
Brackish water	March	0.0 ± 0.0	653 ± 158	7.3 ± 0.6	5.7 ± 0.4	29.0 ± 0.1	7 ± 0.1
	May	2.0 ± 2.7	97 ± 70	24.7 ± 7.1	4.7 ± 0.6	28.8 ± 0.2	7 ± 0.1
	July	12.0 ± 6.1	70 ± 45	36.3 ± 3.5	4.7 ± 0.5	28.6 ± 0.2	6 ± 0.5
	September	21.3 ± 6.4	52 ± 31	29.0 ± 5.2	6.1 ± 2.6	30.4 ± 1.0	8 ± 0.2
Sea water	March	0.0 ± 0.0	728 ± 201	6.0 ± 1.7	5.7 ± 0.3	28.9 ± 0.1	7 ± 0.1
	May	7.0 ± 7.0	50 ± 17	33.0 ± 1.7	4.7 ±0.5	29.3 ± 0.3	7 ± 0.1
	July	24.3 ± 4.0	40 ± 16	43.7 ± 24.7	4.4 ±0.8	28.4 ± 0.3	6 ± 0.1
	September	23.7 ± 7.8	32 ± 14	31.3 ± 12.3	6.2 ± 1.0	30.5 ± 0.9	8 ± 0.2

content but low oxygen levels (Zarkasyi *et al.,* 2016). Therefore, the identified meiobenthos originate from organisms adapted to live in mud substrates and can survive in low-oxygen environments. In contrast, freshwater meiobenthos typically inhabits sandy bottom substrates with abundant oxygen distribution in sediment due to air pores, facilitating mixing with the water above (Silver, 2002).

At all stations, the density of macrobenthos was highest in July, coinciding with the dry season. This is attributed to turbidity accumulation, which collects during the rainy season owing to heightened rainfall. Macrobenthos capitalizes on the accumulated turbidity during the dry season, benefiting from elevated water temperature and salinity resulting from heightened productivity (Auricht *et al.,* 2018; Dominici *et al.,* 2019). This notion is supported by the increased salinity and water temperature observed during the study period.

This density was stable between March and September across all stations. The availability of food sources in sediments primarily affects meiobenthos density. The basic sediment at the study site, mud, originates from mainland turbidity accumulation via river currents containing organic matter used by microorganisms, such as bacteria, which represent a crucial food source for meiobenthos (Saravankumar *et al.,* 2007). This notion was supported in the present study by water temperature values, which increased and stabilized each month. Indeed, Abrar (2013) found that increased temperature enhances the metabolism and growth of microorganisms, including bacteria.

Results from each station showed that the highest macrobenthos density was found at the brackish water station. In contrast, the highest meiobenthos density was observed at the seawater station. The former result is attributed to complex and fluctuating conditions, abundant nutrients, and high stability and heterogeneity of bottom sediments (Wang *et al.,* 2021). In contrast, euryhaline meiobenthos species in streams are rare, with most meiobenthos in estuaries being marine species, contributing to their higher density at seawater stations (Coul, 1999).

3.2.2 Diversity, evenness, and dominance indexes

Both macrobenthos and meiobenthos exhibited moderate diversity. According to the study reported by Rozirwan *et al.* (2021), the macrobenthic diversity and community structure in the Musi Estuary tend to increase offshore and decrease towards the river due to increasing freshwater availability. High human activities in the Bengawan Solo estuary area hypothetically caused this study's moderate diversity status. In another study, benthic macroinvertebrate density was presented as moderate upstream of the Karnaphuli River due to less human disturbance upstream (Farukuzzaman *et al.,* 2023).

The obtained benthic diversity index values suggest ecosystem instability due to the environment's low heterogeneity of organism types (Krebs, 1989). Low heterogeneity implies that environmental conditions favor the survival of only one species, indicating ecological instability. This instability affects community structure, potentially leading to species' emergence or disappearance, leaving the most robust species to survive (Sandika, 2021). Conversely, a balanced environment is characterized by an environmental carrying capacity that supports all living organisms with sufficient biological resources.

The obtained benthic diversity index values indicate low species competition, supported by a high evenness index and low dominance values. A high evenness index denotes minimal competition for space and food, and a low dominance index indicates that no single species has influence or control over other organisms (Hardiyanti *et al.,* 2019; Putra *et al.,* 2022). Competition typically manifests when certain types dominate compared with other types (Katili *et al.,* 2020). Environmental conditions supporting the survival of a single species lead to minimal competition for resources and the lack of dominance of specific species, indicating a potential ecological imbalance.

3.2.3 Water quality parameteres

Salinity measurements across all stations exhibited an increasing trend from March to September, impacting the distribution of benthic species. This was demonstrated via the macrobenthos found at each research station, which exhibited differing distributions influenced by benthos tolerance to environmental changes, especially salinity (Remane and Schlieper, 1971; Coul, 1999). Turbidity measurements indicated a continuous decline from March to September. The recorded turbidity value surpassed the quality standard of <5 NTU. Elevated turbidity results from substantial inputs of inorganic materials (sand and mud) and organic matter (plankton and microorganisms) suspended in the water (Djunaidah *et al.,* 2017). These materials serve as a food source for macrobenthos and meiobenthos, contributing to their increased density (Pohan *et al.,* 2020; Wang *et al.,* 2021). DO, temperature and pH measurements revealed a stable trend each month, aligning with quality standards for marine biota. Brightness increased from March to July, followed by a decrease in September. There is no standard water brightness quality value for estuarine–marine biota. Although brightness does not directly affect benthos, it can influence other water quality parameters, such as temperature. Increased brightness elevates water temperature, triggering the metabolism of organisms, including benthic organisms and the phytoplankton and bacteria they rely on as food (Dominici *et al.,* 2019). However, owing to the marginal variations in parameter values, these four parameters do not markedly impact community structure.

3.2.4 Relationship between benthos and water quality parameters

Regarding macrobenthos, the density of Bivalvia, Gastropoda, and Clitellata was positively correlated with brightness and turbidity at brackish water stations. Turbidity and brightness exhibited an inverse relationship; as brightness decreased, turbidity increased. The heightened turbidity results from substantial inputs of suspended inorganic and organic matter (Djunaidah *et al.,* 2017), serving as food for mollusks, including bivalves and gastropods, both suspension feeders. Additionally, the suspended material later settles on the substrate, becoming a food source for ciliates.

The macrobenthos density of Malacostraca and Maxillopoda was positively correlated with salinity at the seawater station. Malacostraca and Maxillopoda belong to the subphylum Crustacea, the members of which have metabolisms strongly influenced by water salinity levels (Whiteley *et al.,* 2001). Furthermore, the density of macrobenthos in Polychaeta was positively correlated with DO at the freshwater station. The amount of DO is one of the most crucial factors in determining the water quality, which plays a role in the living of biotic organisms in the water ecosystem (Farukuzzaman *et al.,* 2023). Polychaeta is a group known for its tolerance to hypoxic environments; however, their survival and population resilience depend on DO content in the water (Llansó, 1991). The correlation between the diversity and density of macrobenthos with water quality parameters is indicated by dissolved oxygen and temperature, determined at the station towards the sea (Rozirwan *et al.,* 2021).

Regarding meiobenthos, the density of Gastropoda and Foraminifera was positively correlated with salinity at the seawater station. According to Maia and Coutinho (2016), Gastropoda density in estuarine environments is influenced by several factors, including competition, predation, temperature, rainfall, and salinity. Similarly, the density of Foraminifera is affected by salinity, as Foraminifera relies on seawater salinity as an ion source to form shells and undergo biomineralization processes (Iglikowska and Pawowska, 2015). Additionally, the density of meiobenthos in Bivalvia and Polychaeta was positively correlated with brightness and turbidity at the brackish water station. The inverse relationship between turbidity and brightness remained consistent; reduced brightness corresponded with elevated turbidity. Like macrobenthos, turbidity is related to suspended inorganic and organic matter that serves as food for the suspension-feeding meiobenthos group, including Bivalvia and Polychaeta.

4. Conclusion

The finding of this study revealed an density and biological index results indicate that the Bengawan Solo estuary is relatively stable. Moreover, the corresponding water quality parameters strongly influenced the density of each benthic group studied. Based on the research result, continuous research to determine temporal changes in benthic density over a long period of time. Additional data are also needed to support information regarding factors that influence the distribution of benthos, such as the type of bottom water substrate.

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Authors' Contributions

The contributions of each author were as follows: Elva, Mr. Shofy, Mr. Sulistiono, Firman, and Prima collected the data; Elva, Mr. Shofy, Mr. Annur, Mrs. Nina and Mrs. Juni drafted the manuscript, devised the main conceptual ideas, and critically revised the article. All authors discussed the results and contributed to the final manuscript.

Conflict of Interest

The authors declare that they have no competing interests.

Declaration of Artificial Intelligence (AI)

The author(s) affirm that no artificial intelligence (AI) tools, services, or technologies were employed in the creation, editing, or refinement of this manuscript. All content presented is the result of the independent intellectual efforts of the author(s), ensuring originality and integrity.

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