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# Water Quality Assessment Based on Meiofauna Diversity and Phosphate-Nitrate Distribution on the Losari Coast, Indonesia

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## ABSTRACT

Various anthropogenic activities in the Losari coastal area, Indonesia, generate and introduce waste by-products into the waters that can harm the surrounding organisms and ecosystems. This study aimed to assess water quality based on meiofauna diversity index and phosphate-nitrate content distribution along the coast, and then examine the relationship between the two pollution indicators. The study was conducted on Losari Coast, Makassar, Indonesia, with nine observation stations representing the objectives of the study. The observation stations are busy areas and there are many anthropogenic activities that have the potential to produce pollutants that will enter the water body. The observation samples were taken purposively, and the data collected were analyzed in a quantitative descriptive study. Ecological analysis was used to analyze biological parameters, while physico-chemical parameters of the aquatic environment were analyzed *in situ* and *ex situ*. Principal Component Analysis (PCA) was used to identify the correlation between phosphate-nitrate distribution and its effect on meifauna diversity on Losari Coast. With very low diversity index values, the coastal waters were classified as heavily polluted. Some species of meiofauna, especially those adaptable to such environments, were present in high abundance. The phosphate and nitrate contents exceeded the upper limit set by the government for the maximum allowable presence in coastal waters. Therefore, the area is at risk of eutrophication characterized by algae, algae and phytoplankton blooms that block sunlight from reaching underwater plants, causing dissolved oxygen depletion and death of various aquatic organisms. Phosphate levels were positively correlated and strongly influenced the diversity of local meiofauna, while the opposite was true for nitrate: it was negatively correlated and the effect was weak.

## INTRODUCTION

The coast is a transitional area that encompasses dynamic water and land ecosystems and contains natural resources extractable for community welfare improvement **(Jumaris *et al.*, 2024; Nikiforova *et al.*, 2024)**. The Losari coastal zone is a strategic area located in Makassar City, Sulawesi Selatan, Indonesia. Several anthropogenic activities in the surroundings dispose of waste byproducts into the water body, threatening biotic organisms and species diversity and substantially degrading water quality and ecosystems **(Yusal *et al.*, 2019c)**.

Prior scholars have described the condition of the coast as experiencing a decline in water quality due to contamination by heavy metals and other chemical compounds. **Duong**

**and Nhung (2024)** and **Hammoud and Aldhamin (2024)** stated that the coastal waters are heavily polluted with aquatic physical-chemical environmental parameters exceeding their highest allowable presence in seawater, as set in the Decree of the Ministry of Environment No. 51 of 2004. Additionally, the bioindicators observed show a high abundance of certain bottom-dwelling, or benthic, organisms that can adapt to what has been proven as a polluted environment. Furthermore, **Azzahra *et al*. (2025)** reported contaminations by heavy metals in the area, including lead (Pb), copper (Cu), and cadmium (Cd).

High nitrate:phosphate (N:P) ratios in waters are a prerequisite of eutrophication, a nutrient enrichment process that leads to excessive growth or blooms of algae and phytoplankton. With anthropogenically accelerated rate and extent, eutrophication leads to depletion of dissolved oxygen (DO) and induces some phytoplankton to secrete toxins; both conditions are extremely harmful and can result in the death of other aquatic organisms (e.g., by asphyxiation) **(Liri *et al*., 2023; Bouasria *et al*., 2025; Rahmai *et al*., 2025)**. Based on phosphate concentrations, waters can differentiate into three levels of fertility: low (total phosphate content = 0-0.02 mg/liter), moderate (0.021-0.05 mg/liter), and high (0.051-0.1 mg/liter) **(Hani *et al*., 2024; Doumi *et al*., 2025; Yusal *et al*., 2025)**.

Phosphate is one of the limiting factors for growth that influences marine life development **(Yusal *et al*., 2025)**. Its presence in seas and coastal waters is sourced inland, from which rivers transport waste and other substances containing this nutrient salt downstream. Therefore, higher concentrations are likely found in estuaries than river's lower courses. Phosphates naturally enter the food chain through absorption by phytoplankton, while anthropogenic phosphorus comes from industrial and domestic waste derived from detergents **(Stukalyuk *et al*., 2023; Fattah *et al*., 2025; Mohmed *et al*., 2025)**.

Nitrates in water act as a nutrient element in the growth of algal plants and constitute a significant component in the formation of amino acids as the structural units that make up proteins in the bodies of marine organisms. These highly soluble and stable compounds are produced by a complete oxidation process in waters and sourced from domestic and industrial waste, rainwater, and organic matters transported by rivers. In the nitrogen cycle, decomposing bacteria break down nitrates in the form of protein molecules in dead organisms to produce organic materials. Nitrates make up the soft tissues of plankton and play a part in the formation of protoplasm in the sea. If higher than 0.2mg/ liter, nitrates may indicate an evidence of eutrophication **( The Decree of the Ministry of Environment No. 51 of 2004; Hasyim *et al*., 2025)**.

Meiofauna is benthic organisms with an enormous ecological role for aquatic ecosystems because of these properties: 1) meiofauna can be used as an indicator of water quality; 2) meiofauna can recycle and decompose organic matters at the bottom of the waters into food sources; 3) meiofauna can be used as a water purifier; and 4) meiofauna can balance and create connections between material cycles and flows of energy in food webs in aquatic environments **(Yusal *et al*., 2019a; Yusal *et al*., 2019b; Yasser *et al*., 2022; Baiti *et al*., 2025)**. Therefore, this study was designed to assess water quality based on the meiofauna diversity index and the distribution of phosphate-nitrate content and to determine the relationship between the two indicators on the Losari Coast, Indonesia. In this context, **Hasyim *et al*. (2024)** suggested that benthos is a very potential organism as a bioindicator of water quality.

## MATERIALS AND METHODS

### 1. Study area

The research took place in the Losari coastal waters, Makassar, Sulawesi Selatan, Indonesia, with nine (9) observation stations. The nine research stations are shown in Table (1) and Fig. (1).

**Table 1.** Locations of the research stations

| Research station | Areal description |
|---|---|
| Station 1 | Around the Losari Beach (a tourist attraction), hotel buildings, restaurants, cafes, and restaurants (05°08’19.99” S; 119°24’18.57” E) |
| Station 2 | At the disposal outlets of wastewater from Stella Maris Hospital, household waste, and wastes generated in handicraft industries, gold crafting, supermarkets, and food stalls (05°08’40.59” S; 119°24’28.40” E) |
| Station 3 | The Losari Beach reclamation site (05°08’40.59” S; 119°24’08.51” E) |
| Station 4 | At the mouth of the Fort Rotterdam canal that drains a variety of household wastes and byproducts of gold crafting (05°08’09.62” S; 119°24’12.32” E) |
| Station 5 | Nearby the Soekarno Hatta International Airport (05°08’02.43” S; 119°24’10.34” E) |
| Station 6 | At the mouth of Jeneberang River (05°11’28.67” S; 119°22’50.27” E) |
| Station 7 | Around the Tanjung Merdeka Beach (a tourist attraction) (05°10’41.98” S; 119°22’50.27” E) |
| Station 8 | At the traditional Paotere Port (05°06’34.06” S; 119°25’13.71” E) |
| Station 9 | At the mouth of Tallo River (05°05’58.27” S; 119°26’19.84” E) |

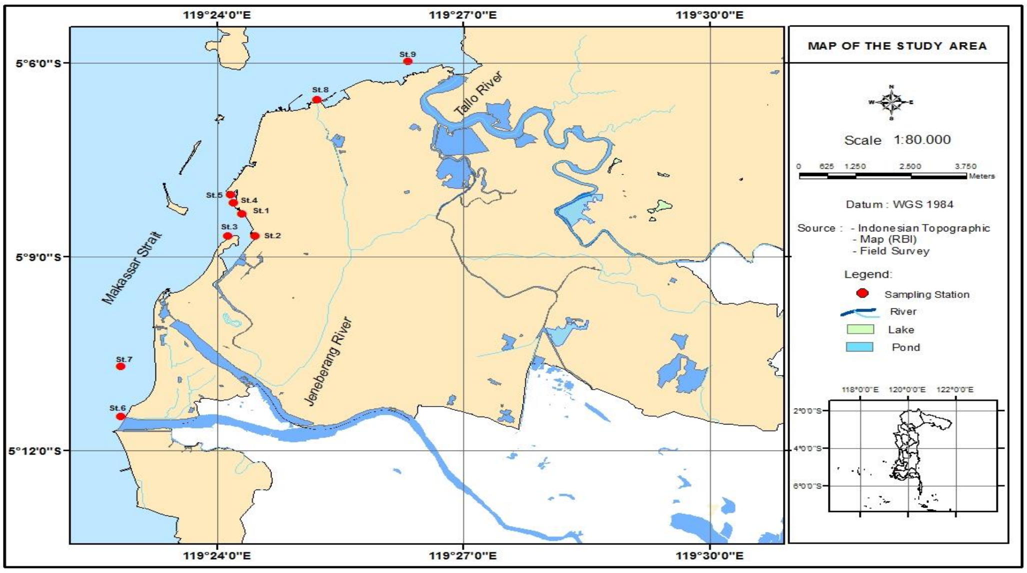


**Fig. 1.** The map of the research location and the nine observation stations distributed along the Losari Coast, Indonesia

## 2. Sampling method

The meiofauna observation sites were selected through purposive sampling, i.e., a sampling technique that is based on predetermined research objectives. Meiofauna sampling was conducted in August-October 2023 using the Ekman grab as the sediment sampler/trap and a 20-mesh screen (0.0362 inches, < 1 mm) to separate meiofauna samples from mud. Rose bengal solution was used in sample staining to facilitate observation under a binocular microscope. Meiofauna was identified using the *Introduction to the Study of Meiofauna* book by **Higgins and Thiel (1988)** as a reference. Phosphate and nitrate contents were measured *ex-situ* using the Greenan method **(Goos, 2013)**.

## 3. Statistical data analysis

The meiofauna abundance ($K$, in individuals/m$^2$) was calculated using the **Southwood and Henderson formula (2015)**, as shown in Eq. (1) below. It is a function of the number of meiofauna found per sample ($a$, individuals) and the opening size of the Ekman grab ($b$, 22.5 cm x 22.5 cm), with 10,000 as a conversion factor from cm$^2$ to m$^2$.

$$K = \frac{10000 x\, a}{b} \quad (1)$$

The diversity index ($H$) of meiofauna was based on the Shannon-Wiener index. As shown in Eq. (1) and (2) below, $H$ depends on the total number of individuals of all species ($N$) and the number of individuals per species ($ni$) **(Southwood & Henderson, 2015)**.

$$H = -\sum_{i=1}^{s} \left( pi \ln pi \right) \quad (2)$$

$$\text{where Pi} = \frac{ni}{N} \quad (3)$$

The diversity index analysis results were also used as a guide to determine water pollution severity (water quality status) in the research location. For this purpose, the index values were divided into four levels of diversity and water quality, as shown in Table (2) below **(Southwood & Henderson, 2015)**.

**Table 2.** Diversity levels and water qualities based on the Shannon-Wiener diversity index values

| Index values | Diversity | Water quality status |
|---|---|---|
| > 2.0 | High diversity | Unpolluted |
| 1.6-2.0 | Medium diversity | Lightly polluted |
| 1.0-1.59 | Low diversity | Moderately polluted |
| < 1.0 | Very low diversity | Heavily polluted |

Phosphate-nitrate contents were analyzed as water quality indicators per the Decree of the Minister of Environment No. 51 of 2004 on Guidelines for Determination of Water Quality Status. Then, Principal Component Analysis (PCA) was used to identify how phosphate-nitrate distribution correlated with and affected meiofauna diversity on the Losari coast.

## RESULTS

Fig. (2) shows some of the phyla meioufauna trapped during the study period.

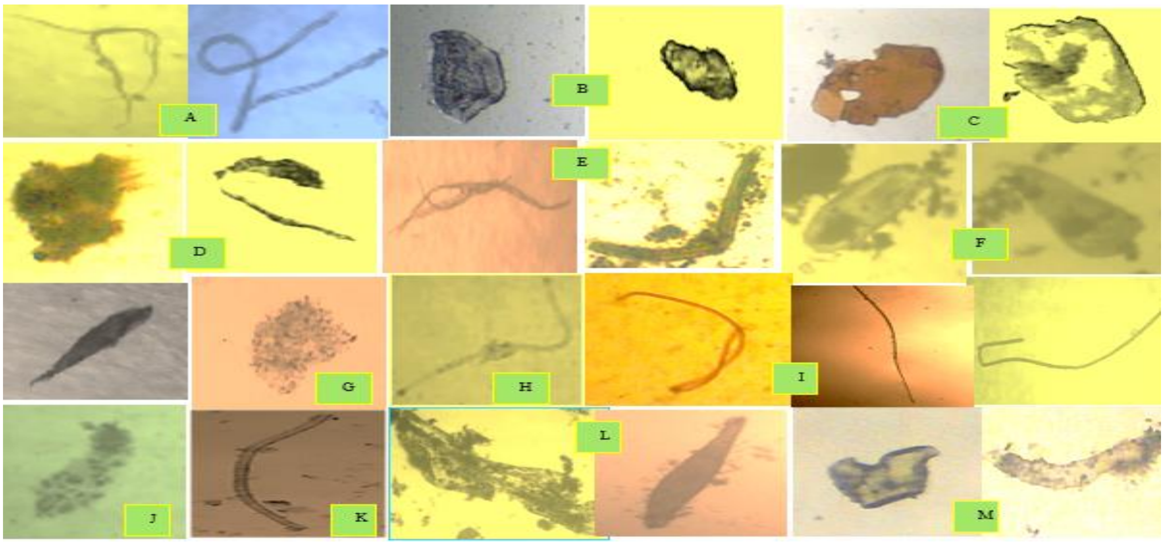


**Fig. 2.** The phyla of meiofauna in Losari Coast, Makassar Indonesia: A. Oligochaeta; B. Ostracoda; C. Sarcomastigophora; D. Ciliophora; E. Polychaeta; F. Turbellaria; G. Tunicata; H. Nemertina; I. Nematoda; J. Tardigrada; K. Aelosomatidae; L. Gastrotricha; M. Gnathostomulida

## 1. Meiofauna abundance on the Losari Coast, Indonesia

The total meiofauna abundance identified throughout the research on the Losari Coast was 193,436indv./ $m^2$ belonging to 13 phyla, which are shown in Table (3) and Fig. (2, 3). Ostracoda and Oligochaeta were the most highly abundant phyla found, with relative densities in the range of 27.36-46.58%. Sarcomastigophora, Ciliophora, Polychaeta, Tunicata, Turbellaria, and Nematoda occurred in the low abundance class; some had relative densities of 2.86-6.72%. Phyla with the lowest abundance, 0.02-0.76%, were Aelosomatidae, Gastrotricha, Gnathostomulida, Nemertina, and Tardigrada. In descending order of abundance, the meiofauna phyla were as follows: Ostracoda (90101 indv./$m^2$), Oligochaeta (52925 indv./$m^2$), Sarcomastigophora (12994 indv./$m^2$), Ciliophora (8953 indv./$m^2$), Polychaeta (8036 indv./$m^2$), Tunicata (5810 indv./$m^2$), Turbellaria (5529 indv./$m^2$), Nematoda (5396 indv./$m^2$), Gastrotricha (1468 indv./$m^2$), Nemertina (1150 indv./$m^2$), Gnathostomulida (756 indv./$m^2$), Aelosomatidae (278 indv./$m^2$), and Tardigrada (40 indv./$m^2$).

**Table 3.** Meiofauna abundance and relative densities on the Losari Coast, Indonesia

| Phyla | Abundance (indv./$m^2$) | | | | | | | | | | Relative densities |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | ST. I | ST. 2 | ST. 3 | ST. 4 | ST.5 | ST.6 | ST. 7 | ST.8 | ST. 9 | Σ | |
| Aelosomatidae | 0 | 80 | 198 | 0 | 0 | 0 | 0 | 0 | 0 | 278 | 0.14 |
| Ciliophora | 1226 | 1286 | 516 | 1386 | 556 | 614 | 714 | 892 | 1763 | 8953 | 4.63 |
| Gastroicha | 318 | 0 | 356 | 0 | 40 | 158 | 160 | 0 | 436 | 1468 | 0.76 |
| Gnathostomulida | 0 | 40 | 238 | 0 | 0 | 40 | 0 | 120 | 318 | 756 | 0.39 |
| Nematoda | 1798 | 0 | 1680 | 614 | 356 | 0 | 0 | 0 | 948 | 5396 | 2.79 |
| Nemertina | 40 | 40 | 198 | 0 | 0 | 318 | 158 | 0 | 396 | 1150 | 0.59 |
| Oligochaeta | 950 | 3143 | 7228 | 5375 | 2156 | 11494 | 6497 | 5631 | 10451 | 52925 | 27.36 |
| Ostracoda | 18279 | 7773 | 2575 | 6054 | 3348 | 17142 | 17648 | 6821 | 10461 | 90101 | 46.58 |
| Polychaeta | 1068 | 158 | 2294 | 635 | 455 | 1384 | 100 | 476 | 1466 | 8036 | 4.15 |
| Sarcomastigophora | 3162 | 2788 | 2334 | 556 | 1266 | 396 | 1502 | 436 | 554 | 12994 | 6.72 |
| Tardigrada | 0 | 0 | 40 | 0 | 0 | 0 | 0 | 0 | 0 | 40 | 0.02 |
| Tunicata | 0 | 40 | 2568 | 2094 | 316 | 158 | 80 | 0 | 554 | 5810 | 3.00 |
| Turbellaria | 634 | 3004 | 120 | 80 | 438 | 318 | 356 | 419 | 160 | 5529 | 2.86 |
| Σ | 27475 | 18352 | 20345 | 16794 | 8931 | 32022 | 27215 | 14795 | 27507 | **193436** | 100 |

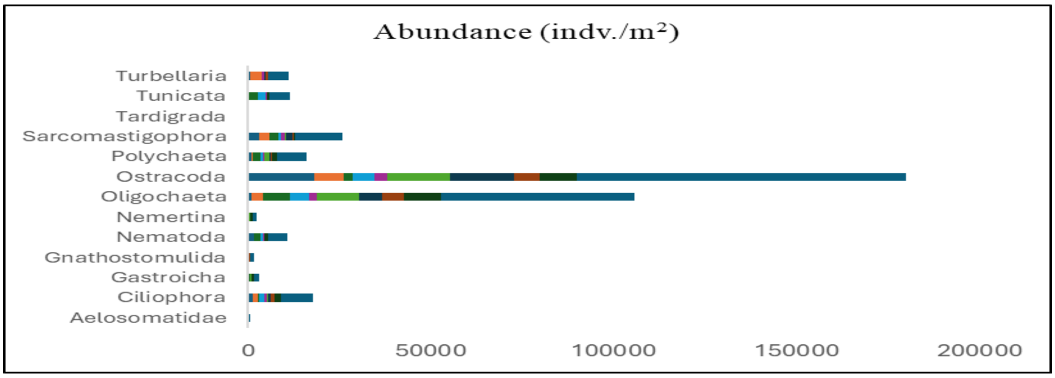


**Fig. 3.** Graph of meiofauna abundance on the Losari Coast, Indonesia

The meiofauna diversity index ranged from 0.008 to 0.3, with standard deviations of 0.005-0.092. Table (4) and Figs. (4, 5, 6) show very low index values, indicating a heavily polluted aquatic environment. Diverse human activities in the vicinity are the leading cause of declining water quality on the Losari Coast, as they generate and introduce waste into the water body, thus affecting various organisms on, above, and in the bottom sediments.

The research stations are located around coastal tourism sites, the disposal outlets of wastewater from Stella Maris Hospital, international and traditional ports, slum and densely populated housing, and household-scale industries. Also, some are at the outlets of soil and drain pipes that carry wastes from residential buildings, gold crafting industries, and hotels and sewage from cafes, restaurants, and food stalls in the surroundings, which are shown in Table (1) and Fig. (1). Morphologically, these stations are located at the estuaries of two large rivers (i.e., Jeneberang and Tallo) that flank the coast of Makassar City. Rivers, currents, and rainwater transport organic and inorganic particles or pollutants generated by anthropogenic activities in the lower course to the upper reaches of the estuaries.

## 2. Effects of phosphate-nitrate contents on meiofauna diversity on the Losari Coast, Indonesia

Table (5) shows that the seawater samples contained 0.02-2.24 mg/liter of phosphates and 0.001-0.0062 mg/liter of nitrates, while the sediment samples had 14.75-20.41 mg/liter of phosphates and 0.44-1.22 mg/liter of nitrates. According to the Decree of the Ministry of Environment No. 51 of 2004, the upper limits for phosphate and nitrate contents are 0.015 and 0.008 mg/liter. Elevated phosphate and nitrate levels potentially cause harm to the lives of various aquatic organisms. For instance, their high presence can trigger nutrient enrichment or eutrophication that, in turn, stimulates the rapid growth or blooms of algae and aquatic plants and leads to uncontrolled growth of phytoplankton that is very dangerous to other aquatic organisms **(The Decree of the Ministry of Environment No. 51 of 2004; Yusal *et al*., 2019c; Noor *et al*., 2025)**. Another detrimental impact of eutrophication is the depletion of dissolved oxygen (DO) in waters that might result in the death of various aquatic organisms (e.g., by asphyxiation). Similar data were reported in the studies of **Yusal and Nur (2023)** and **Nafea (2025)** elucidating that environmental factors have a wide influence on community structure and organism diversity.

**Table 4.** Diversity index values and standard deviations of meiofauna on the Losari Coast, Makassar

| Phyla | St.1 | | St.2 | | St.3 | | St.4 | | St.5 | | St.6 | | St.7 | | St.8 | | St.9 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | H | St.Dev. | H | St.Dev. | H | St.Dev. | H | St.Dev. | H | St.Dev. | H | St.Dev. | H | St.Dev. | H | St.Dev. | H | St. Dev. |
| Aelosomatidae | - | - | 0.02 | - | 0.05 | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Ciliophora | 0.01–0.10 | 0.041 | 0.02–0.11 | 0.033 | 0.01–0.03 | 0.007 | 0.01–0.10 | 0.032 | 0.02–0.11 | 0.032 | 0.01–0.02 | 0.005 | 0.01–0.06 | 0.021 | 0.01–0.10 | 0.047 | 0.01–0.10 | 0.032 |
| Gastrotricha | 0.01–0.04 | 0.018 | - | - | 0.01–0.04 | 0.018 | - | - | 0.02 | - | 0.02 | - | 0.01 | - | - | - | 0.02–0.06 | 0.034 |
| Gnathostomulida | - | - | 0.01 | - | 0.06 | - | - | - | - | - | 0.008 | - | - | - | 0.02 | - | 0.02–0.03 | 0.008 |
| Nematoda | 0.05–0.11 | 0.026 | - | - | 0.03–0.16 | 0.058 | 0.01–0.07 | 0.041 | 0.05–0.12 | 0.054 | - | - | - | - | - | - | 0.06–0.1 | 0.030 |
| Nemertina | 0.01 | - | 0.01 | - | 0.05 | - | - | - | - | - | 0.01–0.02 | 0.007 | 0.03 | - | - | - | 0.07 | - |
| Oligochaeta | 0.01–0.11 | 0.048 | 0.03–0.12 | 0.035 | 0.01–0.21 | 0.082 | 0.04–0.18 | 0.058 | 0.05–0.16 | 0.053 | 0.02–0.20 | 0.071 | 0.07–0.21 | 0.058 | 0.04–0.27 | 0.092 | 0.08–0.17 | 0.028 |
| Ostracoda | 0.02–0.25 | 0.058 | 0.01–0.18 | 0.042 | 0.01–0.19 | 0.056 | 0.01–0.18 | 0.052 | 0.02–0.14 | 0.032 | 0.008–0.23 | 0.070 | 0.01–0.18 | 0.038 | 0.02–0.20 | 0.066 | 0.01–0.22 | 0.059 |
| Polychaeta | 0.12 | - | 0.015–0.036 | 0.015 | 0.02–0.11 | 0.033 | 0.01–0.05 | 0.019 | 0.12 | - | 0.008–0.09 | 0.030 | 0.01 | - | 0.02–0.04 | 0.011 | 0.02–0.07 | 0.020 |
| Sarcomastigophora | 0.01–0.11 | 0.036 | 0.02–0.20 | 0.072 | 0.02–0.15 | 0.056 | 0.01–0.10 | 0.038 | 0.20–0.23 | 0.022 | 0.01–0.03 | 0.012 | 0.01–0.12 | 0.040 | 0.02–0.08 | 0.046 | 0.05 | 0.005 |
| Tardigrada | - | - | - | - | 0.01 | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Tunicata | - | - | 0.01 | - | 0.29 | - | 0.3 | - | 0.14 | - | 0.02 | - | 0.01 | - | - | - | 0.09 | - |
| Turbelaria | 0.01–0.05 | 0.023 | 0.02–0.17 | 0.059 | 0.01–0.02 | 0.008 | 0.03 | - | 0.02–0.11 | 0.037 | 0.008–0.20 | 0.006 | 0.01–0.05 | 0.032 | 0.01–0.03 | 0.006 | 0.02 | - |

H: Diversity Index; St. Dev.: Standard Deviation

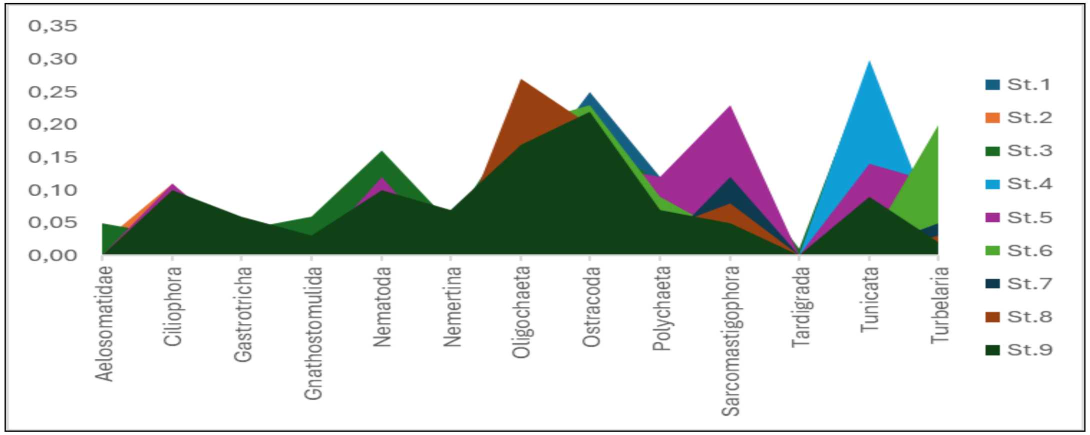


**Fig. 4.** Graph of the meiofauna diversity index at each research station on the Losari Coast, Indonesia

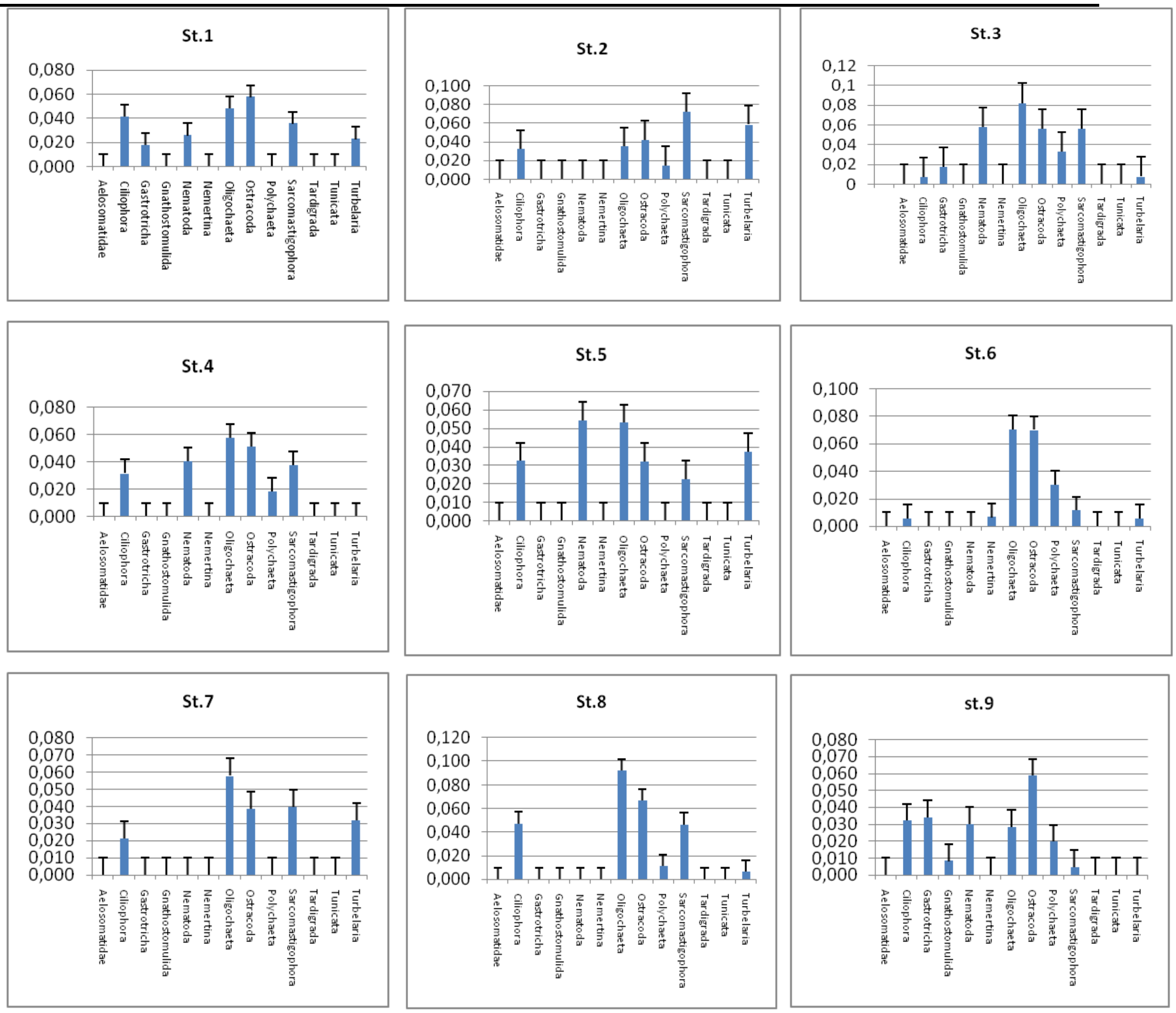


**Fig. 5.** The standard deviations of the meiofauna diversity index values at each research station

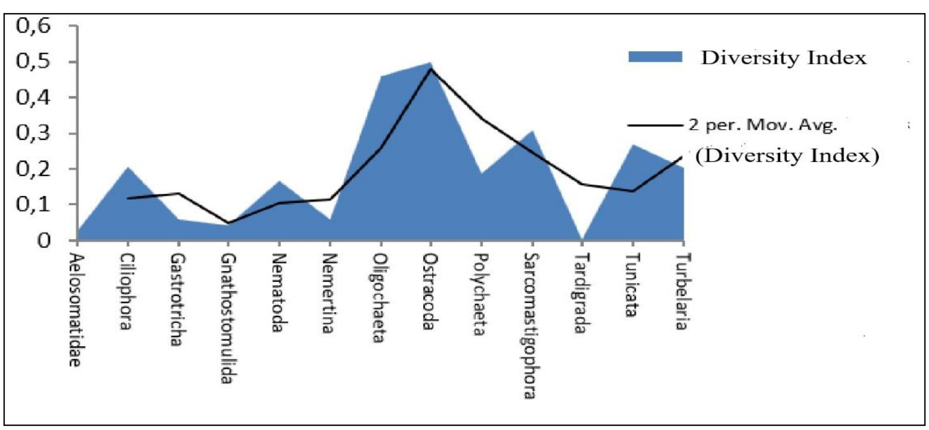


**Fig. 6.** Graph of the meiofauna diversity index (mean values) on the Losari Coast, Indonesia

**Table 5.** The physical-chemical parameter values of the aquatic environment at each research station on the Losari Coast

| Parameters | Stations | | | | | | | | | Upper limits* |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | |
| Salinity | 25 | 30 | 29 | 26 | 26 | 20 | 27 | 20 | 26 | 33-35 ppt |
| Ph | 4.8 | 5.6 | 5.4 | 4.98 | 5.2 | 5.6 | 4.54 | 4.8 | 5.4 | 7-8.5 |
| Temperature | 30 | 28 | 31 | 28 | 32 | 33 | 30 | 32 | 33 | 28-32 C |
| Depth | 3.2 | 2.4 | 6 | 2 | 3 | 4 | 2.6 | 4 | 3 | Natural |
| Current velocity | 0.03 | 0.068 | 0.3 | 0.4 | 0.65 | 0.59 | 0.32 | 0.42 | 0.64 | 0.1-0.9 m/s |
| Brightness | 2 | 2 | 3 | 1 | 1.5 | 3.5 | 2.5 | 3.4 | 1.5 | >3 m |
| DO | 4 | 3.4 | 5 | 3.2 | 4 | 4 | 5 | 3 | 3.5 | >5 mg/l |
| Phosphate-seawater | 0.81 | 0.8 | 0.13 | 0.81 | 0.33 | 0.02 | 0.01 | 2.24 | 0.08 | 0.015 mg/l |
| Phosphate-sediment | 17.25 | 16.85 | 20.41 | 18.63 | 17.25 | 16.52 | 14.75 | 19.63 | 17.52 | 0.015 mg/l |
| Nitrate-seawater | 0.0024 | 0.0032 | 0.0024 | 0.0051 | 0.0042 | 0.0021 | 0.0062 | 0.001 | 0.0024 | 0.008 mg/l |
| Nitrate-sediment | 0.89 | 1.22 | 0.85 | 0.69 | 0.85 | 1.02 | 0.86 | 0.47 | 0.44 | 0.008 mg/l |

**Table 6.** The correlation matrix (Spearman) between the physical-chemical variables and meiofauna abundance and diversity as derived from the Principal Component Analysis (PCA)

| Variables | Abundance | Diversity | Salinity | Temp. | Depth | Current Velocity | DO | Phosphate-seawater | Phosphate-sediment | Nitrate-seawater | Nitrate - sediment |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Abundance | **1** | -0.4167 | -0.1617 | 0.3390 | 0.2353 | -0.1333 | 0.4747 | **-0.5858** | -0.3849 | -0.2712 | 0.2678 |
| Diversity | -0.4167 | **1** | -0.0596 | -0.2627 | 0.1681 | -0.1167 | -0.4747 | **0.5219** | **0.5439** | -0.1695 | -0.0502 |
| Salinity | -0.1617 | -0.0596 | **1** | **-0.5455** | -0.4035 | -0.3831 | 0.2052 | -0.2650 | -0.0513 | **0.6147** | 0.2137 |
| Temp. | 0.3390 | -0.2627 | **-0.5455** | **1** | **0.6154** | **0.7289** | 0.5014 | -0.3660 | 0.0596 | **-0.6121** | -0.3447 |
| Depth | 0.2353 | 0.1681 | -0.4035 | **0.6154** | **1** | 0.0504 | 0.2578 | -0.0506 | 0.3587 | **-0.7864** | -0.0633 |
| Current Velocity | -0.1333 | -0.1167 | -0.3831 | **0.7289** | 0.0504 | **1** | 0.3286 | -0.2510 | 0.0335 | -0.1017 | **-0.5188** |
| DO | 0.4747 | -0.4747 | 0.2052 | 0.5014 | 0.2578 | 0.3286 | **1** | **-0.8800** | -0.3392 | 0.1486 | 0.1100 |
| Phosphate-seawater | **-0.5858** | **0.5219** | -0.2650 | -0.3660 | -0.0506 | -0.2510 | **-0.8800** | **1** | **0.5504** | -0.2383 | -0.2101 |
| Phosphate-sediment | -0.3849 | **0.5439** | -0.0513 | 0.0596 | 0.3587 | 0.0335 | -0.3392 | **0.5504** | **1** | -0.3490 | **-0.6849** |
| Nitrate-seawater | -0.2712 | -0.1695 | **0.6147** | **-0.6121** | **-0.7864** | -0.1017 | 0.1486 | -0.2383 | -0.3490 | **1** | 0.1106 |
| Nitrate-sediment | 0.2678 | -0.0502 | 0.2137 | -0.3447 | -0.0633 | **-0.5188** | 0.1100 | -0.2101 | **-0.6849** | 0.1106 | **1** |

*Values in bold are different from 0 with a significance level alpha = 0.15*

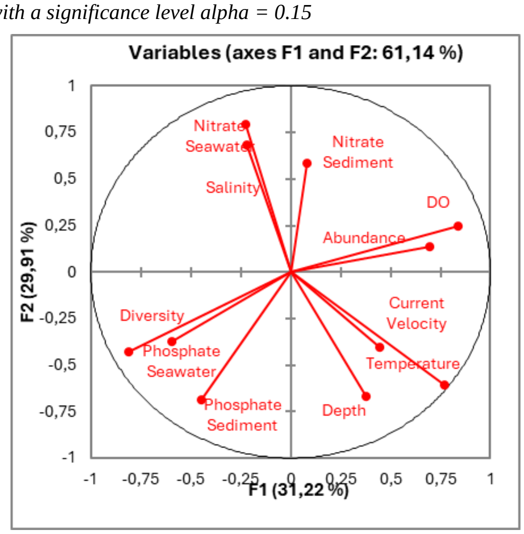


**Fig. 7.** The Principal Component Analysis (PCA) plot for physical-chemical variables and meiofauna abundance

## DISCUSSION

True meiofauna constituted the majority (96.04%) of the meiofauna abundance in the coastal environment; only a small portion was temporary meiofauna (3.60%). The former included Oligochaeta, Ostracoda, Sarcomastigophora, Polychaeta, Turbellaria, Nematodes, Gastrotricha, Gnathostomulida, Tardigrada, and Aelosomatidae, while the latter consisted of Nemertina and Tunicate. True meiofauna is benthic organisms that spend their entire life as meiofauna, whereas temporary meiofauna starts off as meiofauna but transforms into macrofauna in the adult stage.

As summarized in Table 3, Ostracoda and Oligochaeta had high abundance levels compared to the other phyla. Both live in coarse and fine sandy and muddy substrates and have high adaptability to diverse water conditions to a point where their species, which are bisexual or parthenogenetic, can even breed in heavily contaminated waters. Similarly, **Yusal *et al*. (2019a)** reported that these meiofaunas have varying patterns of adaptation to polluted waters because their various types of digestions allow them to feed on different micro-sized and meiofauna organisms in water substrates. In general, Ostracoda and Oligochaeta are detritus eaters, which obtain nutrients by consuming carcasses of decomposing organisms, with herbivorous and carnivorous diets and predatory feeding behavior. They ingest food sources by filter-feeding, sucking, and trapping mechanisms. Other forms of adaptation are setae and cilia formation in response to oxygen deficiency (anoxic), slender body shape to facilitate locomotion, and adhesive yarns to anticipate heavy currents at the bottom of waters. Both Ostracoda and Oligochaeta also create deep burrows in bottom substrates to avoid predation **(Yusal *et al*., 2019b; Zedam *et al*., 2024; Mercader *et al*., 2025; Pary *et al*., 2025)**.

Ostracoda and Oligochaeta have a high tolerance to various unfavorable water conditions, including the presence of pollutants. Several adaptation methods have developed, namely (1) morphological adaptation: a slender body shape and adhesive yarns to attach to water substrates in extreme water currents, (2) anatomical adaptation: various types of digestions that allow both phyla to ingest any usable food sources at the bottom by trapping, filter-feeding, and sucking, (3) physiological adaptation: setae and cilia formation in oxygen-deprived water substrates (anoxic) and efficient reproductive strategies in unpredictable environments, namely hermaphrodism, bisexuality, or parthenogenesis, and (4) behavioral adaptation: deep burrowing in bottom sediments to avoid predation **(Yusal *et al*., 2019a)**.

Sarcomastigophora, Ciliophora, Polychaeta, Tunicata, Turbellaria, and Nematoda were present in low abundance because of several factors. (1) Some have incredible capacities to migrate and move to other habitats suitable for their survival despite their high adaptability to unfavorable environments. (2) Species belonging to each phylum tend to prefer habitats containing substantial amounts of oxygen despite their high adaptability to anoxic environments. (3) Some prefer habitats rich in food sources, e.g., vegetated habitats or environments with vegetation associated with other benthic organisms. (4) Some like to grow in bottom substrates composed of coarse sand or coarse mud with high concentrations of organic matter; meanwhile, several locations on the Losari Coast have fine mud substrates **(Higgins & Thiel, 1988; Yusal *et al*., 2019b; Khairunnisa *et al*., 2025)**.

Aelosomatidae, Gastrotricha, Gnathostomulida, Nemertina, and Tardigrada were found at very low abundance levels because these phyla prefer aquatic habitats that are not contaminated with waste or other pollutants. **Yusal *et al*. (2019c)** also state that Aelosomatidae, Gastrotricha, Gnathostomulida, and Tardigrada live on the bottom sediments of the water body (epibenthic) and are thereby found in high abundance in clean sandy habitats. Some show patterns of highly active migration in search of suitable habitats, while some others are groups of species that are particularly abundant in freshwater with low tolerance to high-salinity environments **(Yusal *et al*., 2019a; Yunus *et al*., 2022; Hasyim *et al*., 2024)**.

A low diversity index value was also followed by a high abundance of meiofauna that could tolerate contaminations by various waste and pollutants, e.g., species of Ostracoda and Oligochaeta which can be seen in the Table (3). These benthic organisms have developed morphological, anatomical, physiological, and behavioral adaptation strategies to deal with unfavorable conditions. These results are consistent with those of **Hasyim *et al*. (2025)** who confirmed that, the declining water quality in the Losari coastal area has reached the status of highly polluted. In this condition, organisms as bioindicators of water quality exist in very low diversity, and several physical-chemical parameters have exceeded their respective upper limits, as determined by the Indonesian government. Similarly, **Duong and Nhung (2024)** reported that the coast has very low meiofauna diversity and poor water quality, and true meiofauna phyla are particularly abundant. Stable water quality in an aquatic environment creates a habitat for all benthic organisms that are evenly distributed on the bottom sediments, as evidenced by the discovery of true and temporary meiofauna in similar or even compositions.

As seen in Table (5), the DO and pH values were smaller than their lower limits, exacerbating the risk of eutrophication at several research stations on the Losari Coast. This is in line with the study of **Nugroho *et al*. (2024)**, who postulated that several physical-chemical parameters are outside the ranges of their respective acceptable values, i.e., higher than the upper limits or smaller than the lower limits, thus endangering various organisms in the vicinity. Similarly, **Azzahra *et al*. (2025)** reported that this coastal area is contaminated with hazardous metals, such as lead (Pb), copper (Cu), cadmium (Cd), zinc (Zn), mercury (Hg), and arsenic (As).

Table (6) and Fig. (7) show that the phosphates on the Losari coast positively correlated with and significantly/strongly affected meiofauna diversity; the opposite is true for nitrates, i.e., negative correlation and insignificant/weak influence. Phosphate contents of seawater and sediment positively correlated with meiofauna diversity, meaning that elevated (lowered) phosphate concentrations will increase (decrease) the diversity index values. In both seawater and sediment samples, phosphates have a significant influence on this parameter. Meanwhile, the nitrate concentrations negatively correlate with meiofauna diversity, meaning that elevated (decreased) nitrate levels will result in low (high) diversity index values. Contrary to phosphates, nitrates have an insignificant effect on this parameter. These findings are consistent with the outcomes of **Yusal *et al*. (2019a)** and **Stukalyuk *et al*. (2023)**, who successfully correlated several physical and chemical parameters of an aquatic environment with meiofauna abundance on the Losari Coast.

## CONCLUSION

The meiofauna diversity index categorizes the coastal waters of Losari, Indonesia, as heavily polluted with meiofauna species that have high adaptability to contaminated aquatic environments and are found in high abundance. The phosphate and nitrate contents have exceeded the upper limits set by the Indonesian government, indicating declining water quality and increased risk of eutrophication that can result in depleted dissolved oxygen and eventually the death of various aquatic organisms (asphyxiation). Furthermore, eutrophication triggers hydrophytic (aquatic plants), algal, and phytoplankton blooms, damaging the entire aquatic ecosystems. Based on the seawater and sediment sample analyses, phosphate contents positively correlate with and strongly influence the diversity of meiofauna on the Losari Coast. The opposite is true for nitrate levels: negative correlation and weak/insignificant effects.

## CONFLICT OF INTERESTS

The authors declare that they had no conflict of interest during the manuscript preparation and completion.

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