JEE Journal of Ecological Engineering

Journal of Ecological Engineering 2024, 25(1), 303–319
https://doi.org/10.12911/22998993/175365
ISSN 2299–8993, License CC-BY 4.0

Received: 2023.10.31
Accepted: 2023.11.20
Published: 2023.12.04

Ecological Risk Assessment of Heavy Metal Contamination in Water, Sediment, and Polychaeta (*Neoleanira Tetragona*) from Coastal Areas Affected by Aquaculture, Urban Rivers, and Ports in South Sumatra

Rozirwan[1*], Shahnaz Ajeng Fatimah Az-Zahrah[1], Nadila Nur Khotimah[2], Redho Yoga Nugroho[2], Wike Ayu Eka Putri[1], Fauziyah[1], Melki[1], Fitri Agustriani[1], Yusni Ikhwan Siregar[3]

[1] Department of Marine Science, Faculty of Mathematics and Natural Sciences, Universitas Sriwijaya, 30862 Indralaya, Indonesia

[2] Environmental Management Study Program, Graduate Program, Universitas Sriwijaya, 30139 Palembang, Indonesia

[3] Department of Marine Science, Faculty of Fisheries and Marine Science, Universitas Riau, 28293 Pekanbaru, Indonesia

* Corresponding author's e-mail: rozirwan@unsri.ac.id

ABSTRACT

Industrial activities in coastal areas can produce pollutant substances that are detrimental to the ecological environment. This study aimed to assess the ecological risks of heavy metal pollution in water, sediments, and polychaeta (*Neoleanira tetragona*) affected by aquaculture, urban rivers, and ports. Water parameters such as temperature, DO, pH, and salinity were measured in situ at fifteen observation stations. Samples were taken at three locations around the aquaculture area, namely the Barong River, the Musi River Estuary as an urban river area, and Tanjung Api-api port in South Sumatra, Indonesia. Analysis of sediment grain size and substrate types using the method of Shepard's triangle Heavy metal concentrations were measured by graphite furnace atomic absorption spectrometry. Then, the data were analyzed using one-way analysis of variance (ANOVA) and post-hoc Tukey statistical analysis. Ecological risk assessment uses the bioconcentration factor (BCF), index geoaccumulation (Igeo), contamination factor (Cf), and pollution load index (PLI). Based on the results, the concentration of heavy metal Pb in water was not detected until 0.625 mg/L, and Cu was not detected. Furthermore, Pb in sediments was 1.261–11.070 mg/kg, Cu was 0.193–19.300 mg/kg, Pb polychaeta was not detected until 0.0044 mg/kg, and Cu ranged from 0.0003–0.0014 mg/kg. Ecological risk assessment for BCF showed that the level of accumulation of polychaeta (N. tetragona) was categorized as an excluder (BCF < 1). Igeo and Cf indicate uncontaminated pollution levels (Igeo < 0) and low contamination (Cf < 1). Meanwhile, the Pollution Load Index is included in the non-polluted category (PLI <0). Based on the results, the quality of the ecological environment affected by aquaculture, urban rivers, and ports is still classified as safe for ecological risk assessment; further studies are needed regarding the relationship between pollution levels and the physiological response of biota.

Keywords: copper, ecological risk assessment, lead, Polychaeta (*Neoleanira tetragona*), sediment, water.

INTRODUCTION

Pollutants in coastal environments around the world have now become a global concern because of their impact on ecosystems [Yuan et al., 2020]. In recent years, the growth of anthropogenic activities such as agriculture, mining, aquaculture, ship transportation, and urbanization along coastal areas has led to the degradation of coastal ecosystems, which ultimately affect both living and non-living organisms (Almaniar et al., 2021; Dan et al., 2022; Shimod et al., 2022). Organisms that live on the coast, such as mangrove groups, annelids, gastropods, cephalopods, and fish, have an important role in maintaining ecosystem sustainability (Fitria et al., 2023; Rozirwan et al., 2023). Heavy metals are considered pollutants that carry many ecological risks due to their high toxicity, non-degradability, bioaccumulation, and biomagnification (Oluwagbemiga et al., 2019; Taslima et al., 2022). Heavy metals are divided into essential and non-essential categories (Slobodian et al., 2021). Essential metals function as protein cofactors in various biological processes but can be toxic if the concentration exceeds a certain threshold (Smethurst and Shcherbik, 2021; Jomova et al., 2022). Non-essential metals have no biological function and are toxic to organisms, even in small amounts (Ali et al., 2019; Romero-Estévez et al., 2023).

Both essential and non-essential metals in high amounts can cause adverse health effects [Wang et al., 2020]. Exposure to toxic environments is very concerning, such as from aquaculture activities, urban rivers, and ports where increased levels of toxic metals such as lead (Pb) and copper can be detected even far from their sources [Purwiyanto et al., 2020]. Heavy metal pollutants that end up in aquatic ecosystems will continuously settle to the bottom of the waters and accumulate in the biota (Elfidasari et al., 2020; Melake et al., 2023). Different biota may respond differently to metal toxicity due to adaptation to their local environment [Ghosh et al., 2021]. For example, metal concentrations influenced by industrial activities may exhibit more toxic effects than in relatively natural and conservation environments (Liu, Y. et al., 2020; Su et al., 2022; Rozirwan et al., 2022). Sediments were identified as the main reservoir of heavy metal pollutants, which are the main habitat for biota, especially in benthic species groups (molluska, crustaceans, and polychaeta), fish, and shrimp [Pandiyan et al., 2021]. In the food chain system, this occurs due to the biomagnification of heavy metal pollutants, causing various types of health problems in humans and other animals (Singh et al., 2023). Heavy metals can cause damage to various organs, including the nervous system, liver, lungs, kidneys, stomach, skin, and reproductive system [Hama Aziz et al., 2023].

The benthic macroinvertebrate community is one of the most effective bioindicators of environmental health because of its importance as a major food source for many fish, birds, and mammals, as well as its effect on sediment stability and geochemical composition (Rozirwan et al., 2021; Delgado et al., 2023; Rozirwan et al., 2023a). The main habitat of benthic macroinvertebrate species is sediment, which may have a high level of contamination with heavy metals [Bendary et al., 2023]. They live in sediments for long periods, and their current feeding strategy involves consuming sediment particles, resulting in maximum contaminant exposure in both sediment and pore water. The characteristics can enable macrobenthic invertebrates to indicate environmental pollution and offer the possibility of being used as a bioindicator of pollution in coastal areas (Mangadze et al., 2019; Eriksen et al., 2021). Among all benthic taxa, polychaetes are often the most abundant taxonomic group in estuarine ecosystems and are key elements in estuarine and coastal diets [Nogueira et al., 2023].

This study aims to assess the ecological risk of Cu and Pb heavy metal concentrations in water, sediment, and polychaeta in coastal areas affected by aquaculture, urban rivers, and ports. The choice of Cu and Pb for water analysis is influenced by their potential environmental impact and their relevance to human health. These metals are commonly monitored in water quality assessments due to their toxicity and potential to contaminate water sources. Lead, in particular, is known for its harmful effects on the nervous system and other organs, especially in high concentrations. This assessment uses a geochemical approach such as the bioconcentration factor (BCF), geoaccumulation index (Igeo), contamination factor (CF), and pollution load index (PLI), which function for quality interpretation and evaluation of anthropogenic influences on sediments and biota [Mugoša et al., 2016]. The author wants to emphasize the fact that this type of research on water quality, sediment, and biota at three different locations based on pollution sources was conducted for the first time in South Sumatra. A combination of ANOVA statistical methods and various geochemical approaches is used to assess the distribution of heavy metals, which can later be applied to other similarly contaminated coastal areas.

MATERIALS AND METHOD

Study area and sampling

This research was carried out from July to December 2021. Water, sediment, and polychaeta were taken at three locations with five different stations from around the industrial area:

the Banyuasin coast of South Sumatra, which includes the Barong River, Musi River Estuary, and Tanjung Api-api port (Figure 1). Stations 1 to 5 were affected by aquaculture activities in the Barong River area and were also included in the Sembilang National Park conservation area (Rozirwan et al., 2022). Stations 6 to 10 were affected by urban rivers with various activities such as air transportation, fishing areas, agricultural activities, and community organizations around the Musi River Estuary (Saputra et al., 2022; Rozirwan et al., 2021a). Stations 11 to 15 were affected by port activities such as ship services, handling of loading and unloading of crates, embarkation and disembarkation of passengers, and stacking services (Rozirwan et al., 2022a; Rebai et al., 2022; Rozirwan et al., 2023b).

Water samples were taken at each station and preserved by adding nitric acid (HNO_3) until the pH was <2. Sediment and polychaeta were taken using a grab pipe (30×10 cm) weighing as much as 250 g (Rozirwan et al., 2021b). The samples that had been taken were then stored in the coolbox. Sample identification has been carried out at the Marine Bioecology Laboratory. Sample preparation and destruction have been carried out at the Oceanography and Marine Instrumentation Laboratory, Department of Marine Science, FMIPA, Sriwijaya University, and analysis for concentrations of Pb and Cu has been carried out at the UPTD of the South Sumatra Provincial Land and Environment Service.

Environmental parameters

Water quality measurements were carried out in situ with three repetitions consisting of temperature, salinity, dissolved oxygen (DO), and pH. Grain size analysis was carried out using the sieve shaker method [Romano et al., 2017]. In determining the type of sedimentary substrate, including sand, gravel, silt, and clay, using Shepard's triangle analysis with Microsoft Excel V.2019 (EpiGear Intl, Queensland, Australia)[Kusumaningtyas, 2023].

Sample preparation and destruction

The water sample preparation stage was carried out by filtering using 0.45 μm Whatman paper [Agasti, 2021]. Meanwhile, sediment preparation was done by cleaning it from foreign objects, drying it in an electric oven at 60°C for 30 minutes, grinding it into powder until it had fine particles, and storing it in a polyethylene bottle [Smeds et al., 2022]. Next, the polychaeta samples were cleaned and crushed using a pestle and mortar [Rapi et al., 2020]. Destruction that has been carried out using wet destruction refers to (Gao et al., 2021; Rizk et al., 2022). Put 50 mL of the water

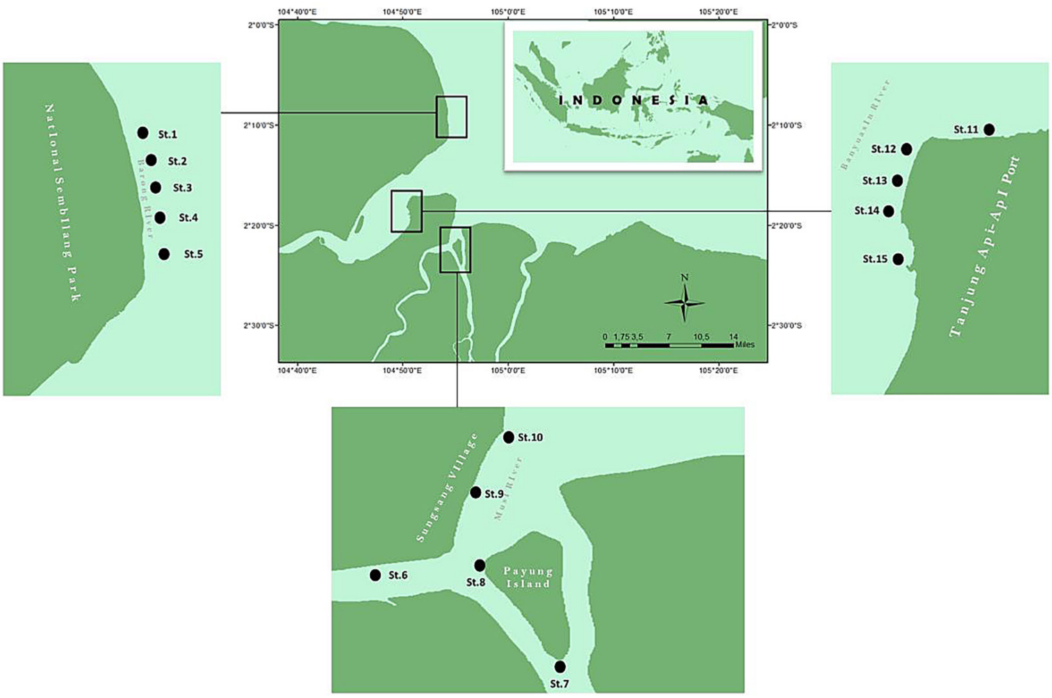

Figure 1. Map of sampling locations

sample into the Erlenmeyer and add 5 mL of HNO_3, then heat it with a C-MAG HS 7 hotplate stirrer until the water sample reaches 15–20 mL. Furthermore, the sediment is destroyed by acid by putting ± 3 g of sample into the Erlenmeyer and adding 25 ml of distilled water to be heated on a hotplate at a temperature of 105–120°C. Mix 5 mL of HNO_3 and wait until the volume reaches 10 mL. After removing and cooling, add 5 ml of concentrated HNO_3 and 1 ml of $HClO_4$. The sample was heated again until white smoke appeared and was clear, followed by heating for 30 minutes. After cooling, it was filtered using quantitative filter paper with a pore size of 8.0 μm.

The destruction of polychaeta samples was carried out by wet destruction to determine heavy metal elements [Moltedo et al., 2019]. The sample that was weighed is put into an Erlenmeyer, and HNO_3 (5–10 ml) and H_2O_2 (2 ml) are added. Digestion is carried out by setting up a microwave program. The digests were transferred to 50 mL vials with ultra-distilled water and stored in polyethylene containers at room temperature until further measurement.

Atomic absorption spectroscopic measurement

Measurement of the concentration of heavy metals Pb and Cu using an atomic absorption spectrophotometer (Shimadzu AA-7000) with a wavelength of 283.3 nm for Pb and 324.7 nm for Cu (Zhong et al., 2016; Susilowati et al., 2022).

DATA ANALYSIS

Quality standards

The concentrations of heavy metals in water, sediment, and polychaeta obtained from the analysis results were further compared with the quality standard values (Table 1).

ECOLOGICAL RISK ASSESSMENT

Bioconcentration factor (BCF)

Metal absorption by biota from sediments occurs through a process known as bioaccumulation. The BCF value is used to determine metal bioaccumulation in polychaeta from sediments [Almahasheer, 2019].

$$Bioconcentration\ factor\ (BCF) = \frac{Concentration\ of\ biota}{Concentration\ of\ sediment} \quad (1)$$

where: BCF < 1 implies that polychaeta is an excluder; BCF = 1 implies that polychaeta is an indicator; and BCF > 1 implies that polychaeta is a hyperaccumulator.

Geoacumulation index (I_{geo})

Igeo quantitatively evaluates the extent of heavy metal contamination and assigns pollution levels according to the classification criteria (Zhang et al., 2021; Xie et al., 2022b).

$$\text{I geo} = \text{Log 2} \left(\frac{Concentration\ heavy\ metals\ in\ sediment}{1.5.Background}\right) \quad (2)$$

where: Igeo value criteria: Igeo < 0 = not polluted; 0 < Igeo < 1 = slightly polluted; 1< Igeo < 2 = moderately polluted; 2 < Igeo 3 = severely polluted; 3 < Igeo < 4 = severely polluted; 4 < Igeo < 5 = extremely polluted; Igeo > 5 = extremely severely polluted (Xie et al., 2022b).

Contamination factor (Cf)

A contamination factor is a condition in which something is polluted by another element that has a certain effect [Antoniadis et al., 2019].

$$Contamination\ facktor\ (Cf) = \frac{Concentration\ of\ heavy\ metals\ in\ sediment}{Background} \quad (3)$$

where: contamination Factor criteria according to [Shaheen et al., 2017]: Cf <1 = low level of contamination; 1<Cf< 3 medium level

Table 1. Heavy metal quality standards

Sample	Pb	Cu	References
Water (mg/L)	0.0044	0.0013	[ANZECC and ARMCANZ, 2000]
Sediment (mg/kg)	50	65	[ANZECC and ARMCANZ, 2000]
Polychaeta (mg/kg)	0.12	3.28	(IAEA, 2003)

of contamination; 3<Cf<6 = enough level of contamination; Cf>6 = contamination level is very high.

Pollution load index (PLI)

The pollution load index is used to determine the quality of pollution. The pollution load index value uses the formula (Shaheen et al., 2019; Singh et al., 2020).

$$\text{Pollution load index (PLI)} = [Cf_1 \times Cf_2 \times Cf_3 ... \times Cfn]^{1/n} \quad (4)$$

where: criteria for pollution load index (PLI): PLI<0 = not polluted; PLI 0–2 = not polluted to slightly polluted; PLI 2–4 = moderately polluted; PLI 4–6 = severely polluted; PLI 6–8 =severely polluted; PLI 8–10 = extremely polluted.

Statistical analysis

The data were tested for homogeneity of variance with the Levene test and for normality of distribution with the Shapiro-Wilk test. Significant differences within each region by pollution source were assessed by one-way analysis of variance (ANOVA), followed by a post-hoc Tukey test if the conditions were met (Dolagaratz et al., 2018). The level of significance was $p < 0.05$. All statistical analyses were performed using the IBM SPSS V.26 application.

RESULTS

Environmental parameters

The results of measuring the quality of the aquatic environment at three different locations have various values (Table 2). The DO and pH values at the study sites varied quite a lot, with a range of 4.67–7.34 mg/L and 6.35–8.10 categorized as normal and evenly distributed across all observation stations. Salinity values varied, with a range between 0 and 25 PSU. Based on the results, the lowest salinity value was found at station 6, namely 0 PSU, and the highest salinity was found at station 2, which was 25.0 PSU. The temperature measurement results obtained ranged from 24.35 to 30.3 °C. The results of determining the type of substrate at three locations with the highest percentage of sediment fraction at each station were dominated by clay.

The chemical physics of the aquatic environment plays an important role in the survival of fish, invertebrates, and all organisms in the water. Anthropogenic-induced release of inorganic nutrients impacts water quality and affects macroinvertebrate communities [Duque et al., 2022]. Dissolved oxygen, pH, salinity, and temperature have varied measurements at each observation station, which are influenced by aquaculture, urban river, and port activities. Dissolved oxygen in the study area is still relatively good as a place for aquatic organisms to live. Bozorg-Haddad et

Table 2. Water environment quality parameters

Stations	Dissolved oxygen (mg/L)	Acidity	Salinity (PSU)	Temperature (°C)	Substrate type
1	7.34 ± 0.05	7.93 ± 0.06	24.67 ± 0.58	28.07 ± 0.12	Clay
2	6.87 ± 0.15	8.10 ± 0.10	25.00 ± 0.50	28.8 ± 0.20	Sand
3	6.81 ± 0.02	7.90 ± 0.01	23.33 ± 0.58	29.17 ± 0.29	Clay
4	5.88 ± 0.08	7.87 ± 0.15	21.33 ± 1.15	29.3 ± 0.61	Clay
5	5.86 ± 0.06	8.07 ± 0.12	20.67 ± 0.58	30.3 ± 0.61	Clay
6	4,81 ± 0.10	6.47 ± 0.03	0	24.38 ± 0.04	Clay
7	5.15 ± 0.03	6.35 ± 0.09	1.10 ± 0.10	24.43 ± 0.05	Clay
8	6.75 ± 0.09	7.10 ± 0.07	0.90 ± 0.10	24.35 ± 0.12	Sand
9	5.99 ± 0.14	6.99 ± 0.15	5.00 ± 0.30	25.19 ± 0.04	Clay
10	6.58 ± 0.52	6.98 ± 0.14	5.53 ± 0.15	25.41 ± 0.04	Sand
11	5.11 ± 0.25	6.85 ± 0.04	1.80 ± 0.00	24.38 ± 0.04	Clay
12	5.11 ± 0.25	6.85 ± 0.04	1,80 ± 0.00	24.43 ± 0.05	Clay
13	5.11 ± 0.25	6.85 ± 0.04	1.80 ± 0.00	24.35 ± 0.12	Clay
14	4.67 ± 0.33	6.77 ± 0.06	1.80 ± 0.00	25.19 ± 0.04	Clay
15	6.02 ± 0.10	6.81 ± 0.09	1.80 ± 0.00	25.41 ± 0.04	Clay

al. (2021) reported that most aquatic plants and animals require oxygen to survive and cannot survive in water with dissolved oxygen less than 5 mg/L. The higher the DO level, the more the macrozoobenthos can carry out their biological and physiological functions properly so that they can grow and develop (Duque et al., 2022; Bonifazi et al., 2023). The high and low pH were influenced by the fluctuations of oxygen and carbon dioxide in the waters. The area affected by port activity at stations 11–15 has a lower pH because it is influenced by Bangka Strait water input. This is consistent with [Rugebregt and Nurhati, 2020] The pH is increasing toward the open sea.

The lowest salinity value is in the port area. According to (Rozirwan et al., 2022) that the salinity around the area varies. This is because the influence of fresh water and seawater is very fluctuates depending on conditions at high and low tides. Water temperature values tend to be high in aquaculture areas. This is related to the infiltration of sunlight into the surface and deeper layers and the movement of water masses (Sui et al., 2022; Li et al., 2022). The distribution of polychaeta can be affected by changes in salinity in the estuary area, which will result in a decrease in the number of macrobenthos (Liu et al., 2023). The clay substrate is the type of substrate favored by polychaeta. According to Ryabchuk et al., (2020) clay is a substrate that strongly supports the life of polychaeta. The smooth substrate has a stronger ability to bind organic matter compared to the coarser substrate (Chenot et al., 2017; Rizqydiani et al., 2018; Huang and Gu, 2019). The smoother the sediment, the greater the strength to bind heavy metals [Özşeker et al., 2022].

Description of polychaeta

The polychaeta species found in the field is Neoleanira tetragona (Figure 2). Polychaetes-Polychaetes found in the field are morphologically characterized by segmented bodies (metamer), which are red, antennae on their heads, and many legs all over their bodies (chaetae).

Polychaeta found at observation stations live in and on the surface of the sediments. The research location is domiciled in a mangrove forest community with a mud substrate type [Fitria et al., 2023]. At this research location, birds were also found looking for food in the form of polychaeta (Rozirwan et al., 2022). The diversity of polychaeta is highest and most abundant in marine or estuarine habitats and decreases in freshwater habitats (Quirós-Rodríguez et al., 2023; Kohlenbach et al., 2023). Polychaeta also has an important role in determining environmental fertility and is also used as biomonitoring of marine health for indicators of organic pollution (Qu et al., 2016; Kies et al., 2020). Phylum Annelida inhabits marine, freshwater, and terrestrial habitats, ranging in size from microscopic to several

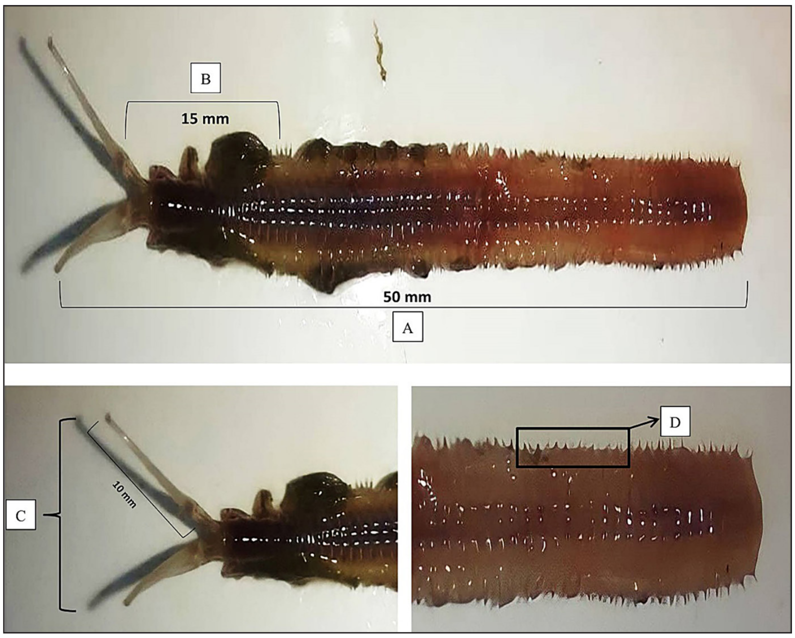

Figure 2. Morphology of polychaeta (*Neoleanira tetragona*). (a) body parts (50 mm size), (b) head parts (15 mm size), (c) Antenna (10 mm size), (d) Chaeta

meters, and includes highly motile swimmers or crawlers as well as tube-dwelling and tube-dwelling species [Schulze, 2023]. In particular, polychaetes were commonly used in ecotoxicological studies because of their abundance, easy capture, and assimilation of heavy metals from sediments through their skin and gut (Dolagaratz et al., 2018).

Heavy metals concentration

The concentrations of heavy metals Pb and Cu in water, sediment, and polychaeta from three areas affected by aquaculture, urban rivers, and ports are summarized in Figure 3. The concentration of the heavy metal Pb in water ranged from

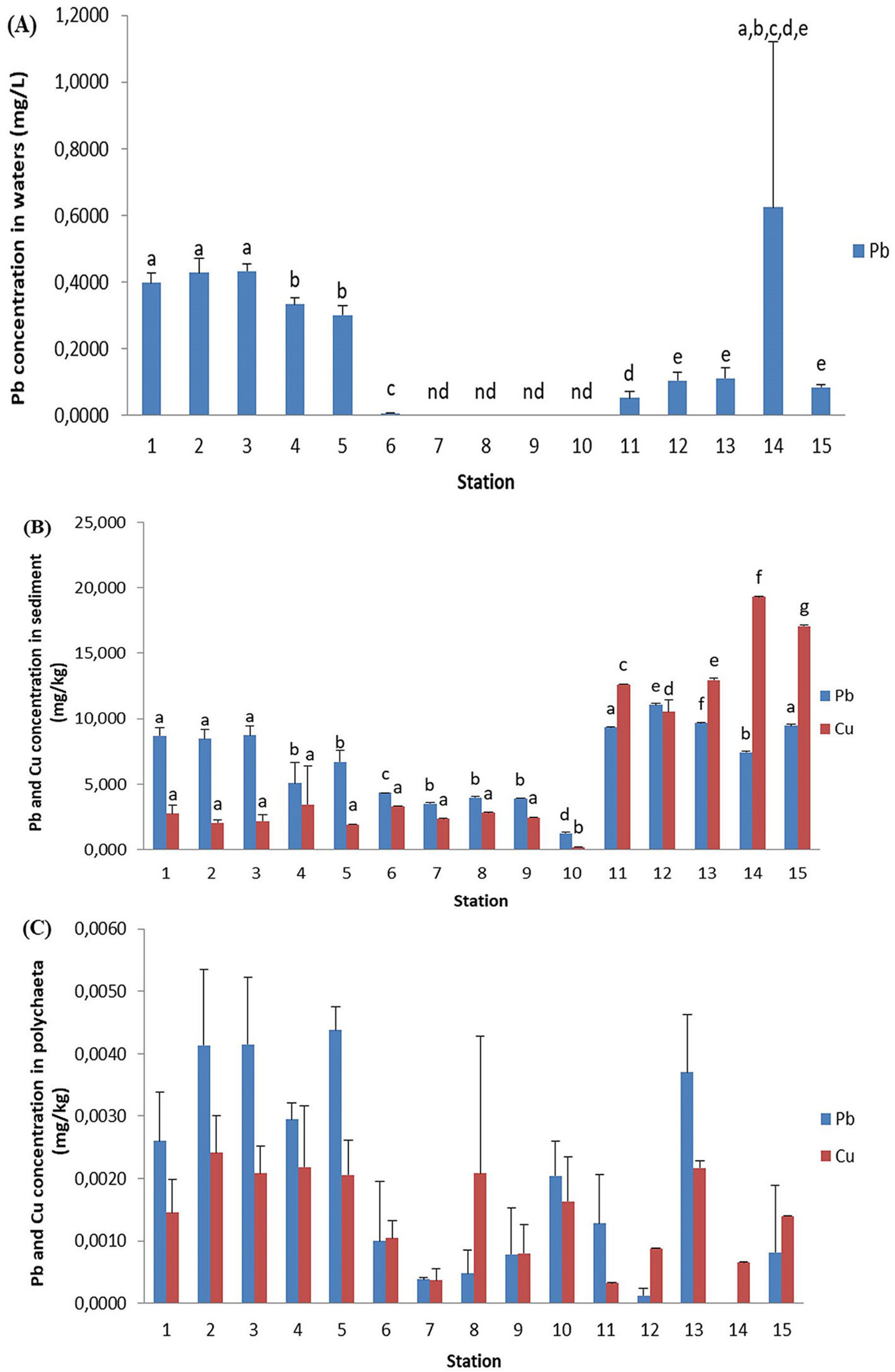

Figure 3. Heavy metal concentrations of Pb and Cu (median with min and max, n = 3), A: Water, B. Sediment, C. Polychaeta (*Neoleanira tetragona*). Significant differences among affinity groups are represented with different letters ($p < 0.05$). nd: not detected

not detectable to 0.625 mg/L. Meanwhile, the concentration of Cu heavy metal in the water of each area was not detected. The concentration of heavy metal Pb in sediments ranges from 1,261 to 11,070 mg/kg. The lowest concentrations were found at stations 10 and 12. The concentration of Cu heavy metal in the sediment ranged from 1.930–19.30 mg/kg. The concentration of heavy metal Pb in polychaeta ranged from not being detected to 0.0044 mg/kg, while the concentration of heavy metal Cu ranged from 0.0003 to 0.0024 mg/kg. The differences in each area statistically using ANOVA and post hoc Tukey ($P < 0.05$) showed that each area was significantly different.

Based on the quality standards [ANZECC and ARMCANZ, 2000]. The concentration of heavy metal Pb in water has passed the quality standard (0.0044 mg/L) at the observation station, which is influenced by aquaculture and port activities (Figure 3A). While the areas affected by urban river activities, in general, did not detect Pb metal. Outliers from Pb indicate higher enrichment. Lead (Pb) is a metalloid that is often used as a poison (Usman et al., 2020; Silva-Gigante et al., 2023). As commonly used in ship transportation fuel and industrial waste [Chen et al., 2022]. Pb enrichment is directly related to anthropogenic activity. There are large-scale ports, aquaculture, and urban rivers or waste disposal on the Banyuasin Coast (Purwiyanto et al., 2020; Almaniar et al., 2021). Pb enrichment can cause a decrease in ecosystem health (Liu et al., 2022). On the other hand, the concentrations of Pb and Cu in sediments were higher than in water because they had accumulated for a long time. According to Yu et al., (2022) this could be due to the influence of dynamic water conditions.

The concentrations of heavy metals Pb and Cu in the sediments obtained did not exceed the quality standards (Table 1). This means that the sediment in the waters of the study location is still classified as a good habitat for the macrozoobenthos group. Observation stations 11–15 in areas affected by port activities have a higher concentration than aquaculture and urban river areas (Figure 3B). The port is a place for loading and unloading export-import goods, raising and lowering passengers, and inter-island trade so it becomes a land-sea coordinated area that is heavily influenced by human activities (Wang et al., 2019). These activities can release pollutants into the water and sediments (Lim et al., 2022). Generally, ports are semi-enclosed water areas with limited water circulation and slow renewal after being polluted. This causes this area to be vulnerable to a large accumulation of pollutants, especially in sediments, which are considered anthropogenic pollution hotspots [Gu and Gao, 2019]. Pollutants at observation stations 1–5 in areas affected by aquaculture activities are lower than those in port areas. This can be caused by sources of pollution, which can come from leftover feed and cultivated manure in the form of suspended and dissolved solids that are transported through the water flow, which is a source of organic matter in pond land. Other factors can come from the activities of fishing boats transporting pond products (Herbeck et al., 2013; Mustafa et al., 2022). Another factor can come from the activities of fishing boats carrying pond products (Prasetiawan et al., 2022; Lim et al., 2022). Whereas at observation stations 6–10, the areas affected by urban river activity had concentrations of Pb and Cu metals that were not significantly different ($P > 0.05$) from the cultivation areas. Pollution in the Musi River Estuary is caused by domestic and industrial activities [Tjahjono et al., 2022]. Domestic activity is said to have more impact than industry. Its condition can be seen in organic decay due to household waste [Abdel-Shafy and Mansour, 2018]. Not only that, Gaete et al., (2017) reported that metal-containing residue receptors from anthropogenic activities in river mouths have different basin levels.

The results in Figure 3C show fluctuations in the concentrations of Pb and Cu metals in the polychaeta collected from three different locations. These data also indicate that the polychaeta contains relatively low levels of lead and copper. This may be due to environmental conditions and the concentration of heavy metals in sediments, which is also relatively low. The concentrations of the heavy metals Pb and Cu in the polychaeta obtained did not exceed the established quality standards (Table 1). Each observation station, starting from areas affected by aquaculture activities, urban rivers, and ports, was not significantly different ($P > 0.050$) for Pb and Cu concentrations. The concentration of heavy metals can increase depending on the environmental conditions of the waters (Tchounwou et al., 2012; Briffa et al., 2020; Mitra et al., 2022). Heavy metals can move into the bodies of organisms through the food chain [Steinhausen et al., 2022]. Apart from going through the food chain, heavy metals can enter the body of the polychaeta through the habits and diet of the polychaeta. Macrozoobenthos has filter feeder properties that allow it to absorb several heavy metals in the waters (Rong et al., 2021; Windarto et al., 2023). There are variations in heavy metal uptake, which is an indication of the extent to which the species is taking up particulate matter from the surrounding water and sediments while feeding [Dange and Manoj, 2015]. Differences in heavy metal content in biota can be caused by species, the physiological capabilities of organisms, and environmental conditions (Rajeshkumar and Li, 2018; Zaynab et al., 2022). Wang et al., (2022) reported that macroinvertebrate community characteristics have a sensitive response to heavy metals in surface water and sediment of the Heihe River, which can be used to evaluate the status of heavy metal pollution in inland rivers. The content of heavy metals in polychaeta has been widely studied based on the source of pollution (Tabel 3). The presence of heavy metals in polychaeta originates from natural processes such as river abrasion and community activities such as disposal and household waste markets, ship repair, and painting, which are then carried by water and accumulated in various aquatic biota (Agoro et al., 2020; Zhang et al., 2023; Yozukmaz and Yabanlı, 2023). This indicates that the accumulation of heavy metals in polychaeta can be used as an instrument for monitoring environmental and ecological risks in marine waters.

Ecological risk assessments of heavy metals concentration

The results of the ecological risk assessment of heavy metal pollution in the aquaculture area are summarized in Table 4, the urban river area in Table 5, and the port area in Table 6. Overall, the results of polychaeta bioconcentration factor (BCF) from aquaculture areas, urban rivers, and harbors in carrying out soil metal bioaccumulation are an excluder for all Pb heavy metals (0.0276, 0.0026, 0.0113) and Cu (0.0250, 0.0125, 0.0155). The geo-accumulation index shows uncontaminated properties for Pb (-1.3458, -2.5823,

Tabel 3. Comparison of Pb and Cu concentrations associated with polychaetes from different locations in the world

Sub factor	Location	Species	Pb	Cu	Reference
Aquaculture	Banyuasin, South Sumatera, Indonesia	*Neoleanira tetragona*	0.0026 – 0.0044	0.0014 – 0.0022	This study
	Calimere Wildlife Sanctuary, Kodikkarai	Polychaeta	5.4 ± 2.21	0.8 ± 0.21	[Pandiyan et al., 2021]
	The Banyuasin estuary shrimp pond area	*N. violacea* *T. telescopium*	0.091 ± 0.143 0.026 ± 0.034	0.006 ± 0.003 0.021 ± 0.006	[Fitria et al., 2023]
Urban river	Banyuasin, South Sumatera, Indonesia	*Neoleanira tetragona*	0.0004 - 0.0020	0.0004 - 0.0021	This study
	Mar Grande of Taranto (Northern Ionian Sea)	*S. spallanzanii* *B. luctuosum* *B. bairdi*	0.383 ± 0.031 0.96 ± 0.012 -	13.9 ± 0.97 29 ± 0.132 14.5 ± 3.75	[Giangrande et al., 2017]
	Mar Piccolo of Taranto (Northern Ionian Sea)	*M. infundibulum* *M. lanigera*	0.409 ± 0.018 0.176 ± 0.096	7.79 ± 0.852 5.36 ± 0.613	[Giangrande et al., 2017]
	Aconcagua River estuary	*Perinereis gualpensis*	1.3 ± 0.2	112.4 ± 12	[Gaete et al., 2017]
	Maipo River estuary	*Perinereis gualpensis*	2.2 ± 0.2	29 ± 0.6	[Gaete et al., 2017]
	Catapilco River estuary	*Perinereis gualpensis*	0.3 ± 0.1	13.6 ± 0.8	[Gaete et al., 2017]
	Miami, Alexandria Coast, Egypt	*Pinctada radiata* *Brachidontes pharaonis* *Holothuria polii*	0.864 ± 0.608 3.742 ± 2.818 0.677 ± 0.451	0.623 ± 0.272 1.667 ± 0.703 0.940 ± 0.622	[Hamed et al., 2020]
Port	Banyuasin, South Sumatera, Indonesia	*Neoleanira tetragona*	0.0001 - 0.0037	0.0003 - 0.0022	This study
	Port of Aveiro, Portugal's northwest Atlantic coast	*Diopatra neapolitana*	1.07 ± 0.06 - 5.19 ± 0.00	0.55 ± 0.010 - 26.22 ± 8.99	[Pires et al., 2017]
	Termini Imerese Harbor (Sicily, Italy)	*S.spallanzanii* *M. galloprovincialis* *S. plicata*	0.05 – 2.21 0.123 ± 0.15 0.337 ± 0.163	0.1 – 2.94 0.252 ± 0.21 1.22 ± 0.92	[Bellante et al., 2016]

Table 4. The results of ecological risk assessment of heavy metal concentrations from areas affected by aquaculture

Station	BCF		Igeo		Cf		PLI
	Pb	Cu	Pb	Cu	Pb	Cu	
1	0.0225	0.0040	-1.1111	-4.9131	0.6767	0.0498	0.185935
2	0.0350	0.0049	-1.1484	-5.3383	-1.1484	0.0371	0.158393
3	0.0362	0.0046	-1.1028	-3.0985	-1.1028	0.0398	0.166727
4	0.0150	0.0075	-1.8853	-4.5766	-1.8853	0.0629	0.159766
5	0.0294	0.0040	-1.4811	-5.4178	-1.4811	0.0351	0.137311
Min	0.0150	0.0040	-1.8853	-5.4178	-1.8853	0.0351	0.137311
Max	0.0362	0.0075	-1.1028	-3.0985	0.6767	0.0629	0.185935
Average	0.0276	0.0250	-1.3458	-4.6688	-0.9882	0.0449	0.161626
Stdv	0.0089	0.0015	0.3400	0.9412	0.9821	0.0115	0.017479

-1.0097) and Cu (-4.6688, -5.6919, -2.5445). Contamination factor (CF) showed enrichment of various metals for Pb (-0.9882, 0.2724, and 0.7509) and Cu (0.0449, 0.0404, and 0.2634), indicating that heavy metal contamination did not occur high on the Banyuasin Coastal Shelf. The PLI ranges from 0.103796 to 0.4385, which indicates that the quality of pollution in these three areas is not polluted.

The bioconcentration factor, geoaccumulation index, contamination factor, and pollution load index (PLI) were calculated for the heavy metals Pb and Cu, which indicated that they did not experience a decrease in BCF < 1, Igeo < 0, CF <, and PLI < 1). Apart from industrial activities, many factors increase the pollution load in coastal areas, such as aquaculture, urban rivers, and ports. Several previous studies have reported similar findings. [Lyla et al., 2022] reported ecological risk assessment from the southwest Bay of Bengal, India, by heavy metals Mn, Zn, Ni, Cu, and Pb (CF = <1, Igeo = <0, Cp = <1, Eir = <40, and RI = <95) indicates the nature of waters that are not polluted by, while Hg is highly contaminated (CF = 1.538, Igeo = >0.04, Cp = <1.6, Eir = <80–>40, RI = 95> – <190–190> – <380). The source of mercury is traced to nearby industrial waste.

Water quality assessments often focus on a select number of contaminants based on regulatory standards, local concerns, or specific risks associated with particular pollutants in a given region. Other similar studies in different geographical locations was presented in Table 7. Pollution levels are being reported by Perumal et al., (2021) calculated EF, CF, Cd, mCd, Cp, RI, and Igeo Indices on Cu, Zn, Pb, and Cr in the Thondi coastal region of the southeastern coast of India induced by anthropogenic inputs. In contrast, the evaluation of the high metal pollution load index located in the Al-Salam Lagoon (Red Sea) indicates uncontrolled pollution due to anthropogenic impacts [Mannaa et al., 2021]. Likewise Iskenderun Bay, Turkey, with the risk of ecological contamination [Kutlu et al., 2021]. Dong et al. (2023) reported status of habitat quality (EcoQs) shows that although several locations in Laoshan Bay have

Tabel 5. The results of ecological risk assessment of heavy metal concentrations from areas affected by urban river

Station	BCF		Igeo		Cf		PLI
	Pb	Cu	Pb	Cu	Pb	Cu	
6	0.0043	0.0034	-2.1146	-4.6455	0.3464	0.0599	0.144074
7	0.0013	0.0009	-2.4119	-5.1296	0.2819	0.0428	0.109897
8	0.0019	0.0059	-2.2328	-4.8694	0.3191	0.0513	0.127966
9	0.0031	0.0020	-2.2574	-5.0728	0.3137	0.0446	0.118247
10	0.0026	0.0003	-3.8947	-8.7423	0.1008	0.0035	0.018794
Min	0.0013	0.0003	-3.8947	-8.7423	0.1008	0.0035	0.018794
Max	0.0043	0.0059	-2.1146	-4.6455	0.3464	0.0599	0.144074
Average	0.0026	0.0125	-2.5823	-5.6919	0.2724	0.0404	0.103796
Stdv	0.0011	0.0022	0.7413	1.7158	0.0986	0.0217	0.049188

Tabel 6. The results of ecological risk assessment of heavy metal concentrations from areas affected by port

Station	BCF		Igeo		Cf		PLI
	Pb	Cu	Pb	Cu	Pb	Cu	
11	0.0120	0.0040	-1.0097	-2.7093	0.7450	0.2294	0.4134
12	0.0014	0.0092	-0.7602	-2.9727	0.8856	0.1911	0.4114
13	0.0357	0.0281	-0.9574	-2.6719	0.7725	0.2354	0.4264
14	0.0000	0.0125	-1.3335	-2.0958	0.5952	0.3509	0.4570
15	0.0077	0.0238	-0.9878	-2.2729	0.7563	0.3104	0.4845
Min	0.0000	0.0040	-1.3335	-2.9727	0.5952	0.1911	0.4114
Max	0.0357	0.0281	-0.7602	-2.0958	0.8856	0.3509	0.4845
Average	0.0113	0.0155	-1.0097	-2.5445	0.7509	0.2634	0.4385
Stdv	0.0145	0.0101	0.2064	0.3542	0.1036	0.0653	0.0315

Table 7. Study of heavy metals Pb and Cu in some characteristics of aquatic environment

Location	Sources of Pb and Cu	Ecological risk implications	References
Winongo River, Indonesia	Urban, highway, fishery	The level of heavy metal pollution were classified as low, medium to high. However, the heavy metal content of water and sediment in the Winongo River must still be monitored because it was used for agriculture, household purposes, and fisheries.	[Fadlillah et al., 2023]
Houjing River, Taiwan	Industrial	Surface water and sediments showed signs of heavy metal contamination. This required treatment technology to improve water and sediment quality.	[Hoang et al., 2020]
Pearl Estuary, China	Industrial and urban	Ecological risks of metals to aquatic organisms decreased from the estuary to the sea. Cu had higher risk to ecosystem health than other metals	[Niu et al., 2021]
Yangtze Estuary, China	Urban anthropogenic	All sampling sites experienced mild to moderate pollution, respectively, and had a moderately high to high ecological risk of causing changes in microbial community composition	[Yi et al., 2021]
Tianjin Sea, North China	Marine transportation, ports, aquaculture, and metal fabrication	Adversely affect ecological systems and human health	[Han et al., 2021]
Abu Zenima Sea, Egypt	Gypsum and manganese industries, kaolin deposits, urban sewage, and coastal irrigation	Pose a high risk to marine mollusks and affects the food chain	[Nour and El-Sorogy, 2020]
Palk Bay, South India	Urban sewage, domestic sewage disposal, fishing port activities, industrial sewage, aquaculture	Impacted the entire food chain in the marine ecosystem.	[Perumal et al., 2021]
Laosan Bay, China	Natural and anthropogenic	Potential risks to the health of the Laosan Bay ecosystem	[Jin et al., 2023]
Honghu Lake, Liangzi Lake, Daye Lake and East Lake are located on the Jianghan Plain, China	Agriculture, transportation, and chemical industry	Disruption of heavy metal pollution control in lakes with high human activity loads	[Wang et al., 2023]

relatively high levels of heavy metal (Hg and Cd) pollution due to its semi-enclosed nature in the Yellow Sea facing various external pressures, including increased metal pollution weight in seawater and sediment and the expansion of land-based ponds, vessel (seaweed) and fish farming, and port operations. This ecological risk assessment of heavy metal pollution is very helpful in describing the environmental status. Moreover, by using this index, the trend of load pollution from time to time can be understood. Based on the pollution status, stakeholders can formulate appropriate control measures [Goher et al., 2017].

CONCLUSIONS

Total concentrations of Pb and Cu were evaluated statistically to have significant differences ($P < 0$) in water and sediment samples collected from areas affected by aquaculture, urban rivers, and Meanwhile, the polychaeta of each area did not differ significantly ($P > 0$). The concentration of Pb in the water at all stations exceeded the quality standard that had been set; Cu was not detected. Pb and Cu concentrations in sediments and polychaeta (*Neoleanira tetragona*) are still below the quality standards. The levels of Pb and Cu contamination in sediments and polychaeta were also evaluated by bioconcentration factor, geoaccumulation index, contamination factor, and ecological risk assessment. The observed heavy metals Pb and Cu did not accumulate in the polychaeta; the concentrations of Pb and Cu were found to be low in the sediment, resulting in no significant ecological risk.

Acknowledgements

The research of this article was funded by Ministry of Research, Technology, and Higher Education of the Republic of Indonesia (Grant Number: 059/E5/PG.02.00.PL/2023). The authors would like to Head of the Marine Bioecology Laboratory for supporting the facilities and helping the accomplishment of this work.

REFERENCES

1. Abdel-Shafy HI, Mansour MSM. 2018. Solid waste issue: Sources, composition, disposal, recycling, and valorization. Egyptian Journal of Petroleum, 27(4), 1275–1290.
2. Agasti N. 2021. Decontamination of heavy metal ions from water by composites prepared from waste. Current Research in Green and Sustainable Chemistry, 4, 100088.
3. Agoro MA, Adeniji AO, Adefisoye MA, Okoh OO. 2020. Heavy Metals in Wastewater and Sewage Sludge from Selected Municipal Treatment Plants in Eastern Cape Province, South Africa. Water, 12(10), 2746.
4. Ali H, Khan E, Ilahi I. 2019. Environmental chemistry and ecotoxicology of hazardous heavy metals: Environmental persistence, toxicity, and bioaccumulation. Journal of Chemistry, 2019.
5. Almahasheer H. 2019. High levels of heavy metals in Western Arabian Gulf mangrove soils. Molecular Biology Reports, 46(2), 1585–1592.
6. Almaniar S, Rozirwan, Herpandi. 2021. Abundance and diversity of macrobenthos at Tanjung Api-Api waters, South Sumatra, Indonesia. AACL Bioflux, 14, 1486–1497.
7. Antoniadis V, Golia EE, Liu YT, Wang SL, Shaheen SM, Rinklebe J. 2019. Soil and maize contamination by trace elements and associated health risk assessment in the industrial area of Volos, Greece. Environment International, 124, 79–88.
8. ANZECC, ARMCANZ. 2000. Australian and New Zealand Guidelines for Fresh and Marine Water Quality. National Water Quality Management Strategy.
9. Bellante A, Piazzese D, Cataldo S, Parisi MG, Cammarata M. 2016. Evaluation and comparison of trace metal accumulation in different tissues of potential bioindicator organisms: Macrobenthic filter feeders Styela plicata, Sabella spallanzanii, and Mytilus galloprovincialis. Environmental toxicology and chemistry, 35(12), 3062–3070.
10. Bendary RE, Goher ME, El-Shamy AS. 2023. Taxonomic and functional diversity of macroinvertebrates in sediment and macrophyte habitats: A case study, the Ibrahimia Canal, Nile River, Egypt. The Egyptian Journal of Aquatic Research, 49(2), 129–135.
11. Bonifazi A, Galli S, Gravina MF, Ventura D. 2023. Macrozoobenthos Structure and Dynamics in a Mediterranean Hypersaline Ecosystem with Implications for Wetland Conservation. Water (Switzerland), 15(7), 1411.
12. Bozorg-Haddad O, Delpasand M, Loáiciga HA. 2021. Water quality, hygiene, and health. Economical, Political, and Social Issues in Water Resources, 217–257.
13. Briffa J, Sinagra E, Blundell R. 2020. Heavy metal pollution in the environment and their toxicological effects on humans. Heliyon, 6(9), e04691.
14. Chen M, Carrasco G, Park E, Morgan K, Tay SHX, Tanzil J, Ooi SK, Zhou K, Boyle EA. 2022. Monsoonal variations of lead (Pb) in coastal waters around Singapore. Marine Pollution Bulletin, 179, 113654.
15. Chenot J, Gaget E, Moinardeau C, Jaunatre R, Buisson E, Dutoit T. 2017. Substrate Composition and Depth Affect Soil Moisture Behavior and Plant-Soil Relationship on Mediterranean Extensive Green Roofs. Water, 9(11), 817.
16. Dan SF, Udoh EC, Wang Q. 2022. Contamination and ecological risk assessment of heavy metals, and relationship with organic matter sources in surface sediments of the Cross River Estuary and nearshore areas. Journal of Hazardous Materials, 438, 129531.
17. Dange S, Manoj K. 2015. Polychaetes (Annelid)

Worms, Mud Skipper and Mud Crab at Purna River Estuary. Original Research Article Bioaccumulation of Heavy Metals in Sediment, 4(9), 571–575.

18. Delgado J de F, Amorim RM, Lima L da S, Gaylarde CC, Neto JAB, Pinto SC de S, Gonçalves BF dos S, Fonseca EM da. 2023. Negative Impacts of Trace Metal Contamination on the Macrobenthic Communities along the Santos Port Complex—Brazil. Eng, 4(2), 1210–1224.
19. Dolagaratz Carricavur A, Chiodi Boudet L, Romero MB, Polizzi P, Marcovecchio JE, Gerpe M. 2018. Toxicological responses of Laeonereis acuta (Polychaeta, Nereididae) after acute, subchronic and chronic exposure to cadmium. Ecotoxicology and Environmental Safety, 149(August 2017), 217–224.
20. Dong JY, Wang X, Zhang X, Bidegain G, Zhao LL. 2023. Integrating multiple indices based on heavy metals and macrobenthos to evaluate the benthic ecological quality status of Laoshan Bay, Shandong Peninsula, China. Ecological Indicators, 153, 110367.
21. Duque G, Gamboa-García DE, Molina A, Cogua P. 2022. Influence of water quality on the macroinvertebrate community in a tropical estuary (Buenaventura Bay). Integrated Environmental Assessment and Management, 18(3), 796.
22. Elfidasari D, Ismi LN, Sugoro I. 2020. Heavy metal concentration in water, sediment, and pterygoplichthys pardalis in the Ciliwung River, Indonesia. AACL Bioflux, 13(3), 1764–1778.
23. Eriksen TE, Brittain JE, Søli G, Jacobsen D, Goethals P, Friberg N. 2021. A global perspective on the application of riverine macroinvertebrates as biological indicators in Africa, South-Central America, Mexico and Southern Asia. Ecological Indicators, 126, 107609.
24. Fadlillah LN, Utami S, Rachmawati AA, Jayanto GD, Widyastuti M. 2023. Ecological risk and source identifications of heavy metals contamination in the water and surface sediments from anthropogenic impacts of urban river, Indonesia. Heliyon, 9(4), e15485.
25. FAO. 1983. Compilation of legal limits for hazardous substances in fish and fishery products. FAO Fisheries Circular (FAO) no 764,. https://doi.org/10.3/JQUERY-UI.JS.
26. Fitria Y, Rozirwan, Fitrani M, Nugroho RY, Fauziyah, Putri WAE. 2023. Gastropods as bioindicators of heavy metal pollution in the Banyuasin estuary shrimp pond area, South Sumatra, Indonesia. Acta Ecologica Sinica, in press.
27. Gaete H, Álvarez M, Lobos G, Soto E, Jara-Gutiérrez C. 2017. Assessment of oxidative stress and bioaccumulation of the metals Cu, Fe, Zn, Pb, Cd in the polychaete Perinereis gualpensis from estuaries of central Chile. Ecotoxicology and Environmental Safety, 145(April), 653–658.
28. Gao Y, Qiao Y, Xu Y, Zhu L, Feng J. 2021. Assessment of the transfer of heavy metals in seawater, sediment, biota samples and determination the baseline tissue concentrations of metals in marine organisms. Environmental science and pollution research international, 28(22), 28764–28776.
29. Ghosh S, Bakshi M, Mahanty S, Chaudhuri P. 2021. Understanding potentially toxic metal (PTM) induced biotic response in two riparian mangrove species Sonneratia caseolaris and Avicennia officinalis along river Hooghly, India: Implications for sustainable sediment quality management. Marine Environmental Research, 172, 105486.
30. Giangrande A, Licciano M, Pasqua M del, Fanizzi FP, Migoni D, Stabili L. 2017. Heavy metals in five Sabellidae species (Annelida, Polychaeta): ecological implications. Environmental Science and Pollution Research, 24(4), 3759–3768.
31. Goher ME, Abdo MH, Bayoumy WA, Mansour El-Ashkar TY. 2017. Some heavy metal contents in surface water and sediment as a pollution index of El-Manzala Lake, Egypt. Journal of Basic and Environmental Sciences, 4, 210–225.
32. Gu YG, Gao YP. 2019. An unconstrained ordination- and GIS-based approach for identifying anthropogenic sources of heavy metal pollution in marine sediments. Marine Pollution Bulletin, 146, 100–105.
33. Hama Aziz KH, Mustafa FS, Omer KM, Hama S, Hamarawf RF, Rahman KO. 2023. Heavy metal pollution in the aquatic environment: efficient and low-cost removal approaches to eliminate their toxicity: a review. RSC Advances, 13(26), 17595.
34. Hamed E sayed AE, Khaled A, Ahdy H, Omar Ahmed H, Aly Abdelrazek F. 2020. Health risk assessment of heavy metals in three invertebrate species collected along Alexandria Coast, Egypt. Egyptian Journal of Aquatic Research, 46(4), 389–395.
35. Han X, Wang J, Cai W, Xu X, Sun M. 2021. The Pollution Status of Heavy Metals in the Surface Seawater and Sediments of the Tianjin Coastal Area, North China. International Journal of Environmental Research and Public Health, 18(21), 11243.
36. Herbeck LS, Unger D, Wu Y, Jennerjahn TC. 2013. Effluent, nutrient and organic matter export from shrimp and fish ponds causing eutrophication in coastal and back-reef waters of NE Hainan, tropical China. Continental Shelf Research, 57, 92–104.
37. Hoang H-G, Lin C, Tran H-T, Chiang C-F, Bui X-T, Cheruiyot NK, Shern C-C, Lee C-W. 2020. Heavy metal contamination trends in surface water and sediments of a river in a highly-industrialized region. Environmental Technology & Innovation, 20, 101043.
38. Huang L, Gu M. 2019. Effects of Biochar on Container Substrate Properties and Growth of Plants—A Review. Horticulturae 2019, Vol 5, Page 14, 5(1), 14.
39. Jin Y, Du J, Sun Y, Wang E, Yan W. 2023. Source and pollution assessment of heavy metals in surface

sediments of Laoshan Bay, South Yellow Sea, China. Marine Pollution Bulletin, 197, 115691.

40. Jomova K, Makova M, Alomar SY, Alwasel SH, Nepovimova E, Kuca K, Rhodes CJ, Valko M. 2022. Essential metals in health and disease. Chemico-Biological Interactions, 367, 110173.
41. Kies F, Kerfouf A, Elegbede I, Matemilola S, Los P De, Escalante R, Khorchani A, Savari S. 2020. Assessment of the coastal and estuarine environment quality of western Algeria using the bioindicator Polychaeta; the genus Nereis. J Mater Environ Sci, 2020(9), 1472–1481.
42. Kohlenbach K, Knauber H, Brandt A, Saeedi H. 2023. Distribution and Species Richness of Benthic Polychaeta and Sipuncula in the Northwestern Pacific. Diversity, 15(4), 557.
43. Kusumaningtyas AR. 2023. Index of Seagrass Ecology at Prawean Beach, Jepara 12(2), 230–239.
44. Kutlu B, Özcan T, Özcan G. 2021. Analysis of heavy metal contamination in surface sediments of Iskenderun Bay, Turkey. Oceanological and Hydrobiological Studies, 50(4), 411–420.
45. Li Q, Yan X, Wang Z, Li Z, Cao S, Tong Q. 2022. Inversion of the Full-Depth Temperature Profile Based on Few Depth-Fixed Temperatures. Remote Sensing 2022, 14(23), 5984.
46. Lim Y-C;, Chen C-F;, Tsai M-L;, Wu C-H;, Lin Y-L;, Wang M-H;, Albarico FPJB;, Chen C-W;, Dong C-D, Southern T, Lim Y-C, Chen C-F, Tsai M-L, Wu C-H, Lin Y-L, Wang M-H, Paolo F, Albarico JB, Chen C-W, Dong C-D. 2022a. Impacts of Fishing Vessels on the Heavy Metal Contamination in Sediments: A Case Study of Qianzhen Fishing Port in Southern Taiwan. Water 2022, 14(7), 1174.
47. Lim YC, Chen CF, Tsai ML, Wu CH, Lin YL, Wang MH, Albarico FPJB, Chen CW, Dong C Di. 2022b. Impacts of Fishing Vessels on the Heavy Metal Contamination in Sediments: A Case Study of Qianzhen Fishing Port in Southern Taiwan. Water (Switzerland), 14(7).
48. Liu L, Li A, Zhu L, Xue S, Li J, Zhang C, Yu W, Ma Z, Zhuang H, Jiang Z, Mao Y. 2023. The Application of the Generalized Additive Model to Represent Macrobenthos near Xiaoqing Estuary, Laizhou Bay. Biology 2023, 12(8), 1146.
49. Liu Y, Kuang W, Xu J, Chen J, Sun X, Lin C, Lin H. 2022. Distribution, source and risk assessment of heavy metals in the seawater, sediments, and organisms of the Daya Bay, China. Marine pollution bulletin, 174.
50. Liu Y, Zhou Y, Lu J. 2020. Exploring the relationship between air pollution and meteorological conditions in China under environmental governance. Scientific Reports, 10(1), 14518.
51. Lyla PS, Manokaran S, Ajmalkhan S, Ansari KGMT, Raja S, Reshi O. 2022. Spatial analysis, ecological risk assessment, control factors, and sources of heavy metal pollution in the shelf surface sediments of the southwest Bay of Bengal, India. Regional Studies in Marine Science, 56, 102705.
52. Mangadze T, Dalu T, William Froneman P. 2019. Biological monitoring in southern Africa: A review of the current status, challenges and future prospects. Science of The Total Environment, 648, 1492–1499.
53. Mannaa AA, Khan AA, Haredy R, Al-Zubieri AG. 2021. Contamination evaluation of heavy metals in a sediment core from the al-salam lagoon, jeddah coast, Saudi Arabia. Journal of Marine Science and Engineering, 9(8), 899.
54. Melake BA, Endalew SM, Alamirew TS, Temesegen LM. 2023. Bioaccumulation and Biota-Sediment Accumulation Factor of Metals and Metalloids in Edible Fish: A Systematic Review in Ethiopian Surface Waters. Environmental Health Insights, 17.
55. Mitra S, Chakraborty AJ, Tareq AM, Emran T Bin, Nainu F, Khusro A, Idris AM, Khandaker MU, Osman H, Alhumaydhi FA, Simal-Gandara J. 2022. Impact of heavy metals on the environment and human health: Novel therapeutic insights to counter the toxicity. Journal of King Saud University - Science, 34(3), 101865.
56. Moltedo G, Martuccio G, Catalano B, Gastaldi L, Maggi C, Virno-Lamberti C, Cicero AM. 2019. Biological responses of the polychaete Hediste diversicolor (O.F.Müller, 1776) to inorganic mercury exposure: A multimarker approach. Chemosphere, 219, 989–996.
57. Mugoša B, Đuroviā D, Nedović-Vuković M, Barjaktarović-Labović S, Vrvić M. 2016. Assessment of Ecological Risk of Heavy Metal Contamination in Coastal Municipalities of Montenegro. International Journal of Environmental Research and Public Health, 13(4).
58. Muller G. 1979. Schwermetalle in den sedimenten des Rheins, VeranderungenSeit 1971 – ScienceOpen. Umschanvol,.
59. Mustafa A, Paena M, Athirah A, Ratnawati E, Asaf R, Suwoyo HS, Sahabuddin S, Hendrajat EA, Kamaruddin K, Septiningsih E, Sahrijanna A, Marzuki I, Nisaa K. 2022. Temporal and Spatial Analysis of Coastal Water Quality to Support Application of Whiteleg Shrimp Litopenaeus vannamei Intensive Pond Technology. Sustainability, 14(5), 2659.
60. Niu L, Cai H, Jia L, Luo X, Tao W, Dong Y, Yang Q. 2021. Metal pollution in the Pearl River Estuary and implications for estuary management: The influence of hydrological connectivity associated with estuarine mixing. Ecotoxicology and Environmental Safety, 225, 112747.
61. Nogueira M, Magalhães W, Mariano-Neto E, Neves E, Johnsson R. 2023. Taxonomical and functional

analyses of epifaunal polychaetes associated with Mussismilia spp.: the effects of coral growth morphology. PeerJ, 11.

62. Nour HE, El-Sorogy AS. 2020. Heavy metals contamination in seawater, sediments and seashells of the Gulf of Suez, Egypt. Environmental Earth Sciences, 79, 1–12.
63. Oluwagbemiga AP, Olatayo AA, Funso AI. 2019. Coastal Marine Sediment Heavy Metals Contamination of a Transgressive Marine Science : Research & Development. Journal Marine Science : Research and Development, 9(2).
64. Özşeker K, Erüz C, Terzi Y. 2022. Evaluation of toxic metals in different grain size fractions of sediments of the southeastern Black Sea. Marine Pollution Bulletin, 182, 113959.
65. Pandiyan J, Mahboob S, Govindarajan M, Al-Ghanim KA, Ahmed Z, Al-Mulhm N, Jagadheesan R, Krishnappa K. 2021. An assessment of level of heavy metals pollution in the water, sediment and aquatic organisms: A perspective of tackling environmental threats for food security. Saudi Journal of Biological Sciences, 28(2), 1218.
66. Perumal K, Antony J, Muthuramalingam S. 2021. Heavy metal pollutants and their spatial distribution in surface sediments from Thondi coast, Palk Bay, South India. Environmental Sciences Europe, 33(1), 1–20.
67. Pires A, Velez C, Figueira E, Soares AMVM, Freitas R. 2017. Effects of sediment contamination on physiological and biochemical responses of the polychaete Diopatra neapolitana, an exploited natural resource. Marine Pollution Bulletin, 119(1), 119–131.
68. Prasetiawan NR, Sudirman N, Salim HL, Ati RNA, Kepel TL, Daulat A, Kusumaningtyas MA, Permana SM, Setiawan A, Pranowo WS, Rustam A, Suryono DD, Jayawiguna MH, Sukoraharjo SS. 2022. Preliminary Study of Marine Debris Composition from Fisherman Activities : A Case Study on Cikidang Fishing Port, Pangandaran. IOP Conference Series: Earth and Environmental Science, 1118(1).
69. Purwiyanto AIS, Suteja Y, Ningrum PS, Putri WAE, Agustriani F, Cordova MR, Koropitan AF. 2020. Concentration and adsorption of Pb and Cu in microplastics: case study in aquatic environment. Marine pollution bulletin, 158, 111380.
70. Qu F, Nunnally CC, Lemanski JR, Wade TL, Amon RMW, Rowe GT. 2016. Polychaete annelid (segmented worms) abundance and species composition in the proximity (6–9 km) of the Deep Water Horizon (DWH) Oil Spill in the Deep Gulf of Mexico. Deep Sea Research Part II: Topical Studies in Oceanography, 129, 130–136.
71. Quirós-Rodríguez JA, Santafé-Patiño G, Dueñas-Ramírez P. 2023. Polychaetes (Polychaeta, Annelida) from Rhizophora mangle roots in Cispatá Bay, Colombian Caribbean. Regional Studies in Marine Science, 65, 103083.
72. Rajeshkumar S, Li X. 2018. Bioaccumulation of heavy metals in fish species from the Meiliang Bay, Taihu Lake, China. Toxicology Reports, 5, 288–295.
73. Rapi HS, Awatif Che Soh N, Azam NSM, Maulidiani M, Assaw S, Haron MN, Ali AM, Idris I, Ismail WIW. 2020. Effectiveness of Aqueous Extract of Marine Baitworm Marphysa moribidii Idris, Hutchings and Arshad, 2014 (Annelida, Polychaeta), on Acute Wound Healing Using Sprague Dawley Rats. Evidence-based Complementary and Alternative Medicine : eCAM, 2020.
74. Rebai N, Mosbahi N, Dauvin JC, Neifar L. 2022. Ecological Risk Assessment of Heavy Metals and Environmental Quality of Tunisian Harbours. Journal of Marine Science and Engineering 2022, Vol 10, Page 1625, 10(11), 1625.
75. Rizk R, Juzsakova T, Ali M Ben, Rawash MA, Domokos E, Hedfi A, Almalki M, Boufahja F, Shafik HM, Rédey Á. 2022. Comprehensive environmental assessment of heavy metal contamination of surface water, sediments and Nile Tilapia in Lake Nasser, Egypt. Journal of King Saud University - Science, 34(1), 101748.
76. Rizqydiani M, Ismet MS, Bengen DG. 2018. Diversity of meiofauna and its association to seagrass beds characteristics in Pramuka Island, Seribu Islands. IOP Conference Series: Earth and Environmental Science, 176(1).
77. Romano E, Magno MC, Bergamin L. 2017. Grain size data analysis of marine sediments, from sampling to measuring and classifying. A critical review. IMEKO TC19 Workshop on Metrology for the Sea, MetroSea 2017: Learning to Measure Sea Health Parameters, 2017-Octob, 173–178.
78. Romero-Estévez D, Yánez-Jácome GS, Navarrete H. 2023. Non-essential metal contamination in Ecuadorian agricultural production: A critical review. Journal of Food Composition and Analysis, 115, 104932.
79. Rong Y, Tang Y, Ren L, Taylor WD, Razlutskij V, Naselli-Flores L, Liu Z, Zhang X. 2021. Effects of the filter-feeding benthic bivalve corbicula fluminea on plankton community and water quality in aquatic ecosystems: A mesocosm study. Water (Switzerland), 13(13), 1–12.
80. Rozirwan, Fauziyah, Nugroho RY, Melki, Ulqodry TZ, Agustriani F, Ningsih EN, Putri WAE. 2022a. An ecological assessment of crab's diversity among habitats of migratory birds at berbak-sembilang national park indonesia. International Journal of Conservation Science, 13(3), 961–972.
81. Rozirwan, Hananda H, Nugroho RY, Apri R, Khotimah NN, Fauziyah F, Putri WAE, Aryawati R. 2023a. Antioxidant Activity, Total Phenolic, Phytochemical Content, and HPLC Profile of Selected

Mangrove Species from Tanjung Api-Api Port Area, South Sumatra, Indonesia. Tropical Journal of Natural Product Research Available, 7(7), 3482–3489.

82. Rozirwan, Melki, Apri R, Fauziyah, Agussalim A, Hartoni, Iskandar I. 2021a. Assessment the macrobenthic diversity and community structure in the Musi Estuary, South Sumatra, Indonesia. Acta Ecologica Sinica, 41(4), 346–350.
83. Rozirwan, Melki, Apri R, Nugroho RY, Fauziyah, Agussalim A, Iskandar I. 2021b. Assessment of phytoplankton community structure in Musi Estuary, South Sumatra, Indonesia. AACL Bioflux, 14, 1451–1463.
84. Rozirwan, Nugroho RY, Hendri M, Fauziyah, Putri WAE, Agussalim A. 2022b. Phytochemical profile and toxicity of extracts from the leaf of Avicennia marina (Forssk.) Vierh. collected in mangrove areas affected by port activities. South African Journal of Botany, 150, 903–919.
85. Rozirwan R, Muhtadi M, Ulqodry TZ, Nugroho RY, Khotimah NN, Fauziyah F, Putri WAE, Aryawati R, Mohamed CAR. 2023b. Insecticidal Activity and Phytochemical Profiles of Avicennia marina and Excoecaria agallocha Leaves Extracts. ILMU KELAUTAN: Indonesian Journal of Marine Sciences, 28(2), 148–160.
86. Rozirwan, Ramadani S, Ayu W, Putri E, Nur N, Nugroho RY. 2023c. Evaluation of Calcium and Phosphorus content in Scallop Shells (Placuna placenta) and Blood Cockle Shells (Anadara granosa) from Banyuasin Waters, South Sumatra. Egyptian Journal of Aquatic Biology & Fisheries Zoology Department, Faculty of Science, 27(3), 1053–1068.
87. Rugebregt MJ, Nurhati IS. 2020. Preliminary Study of Ocean Acidification: Relationship of pH, Temperature, and Salinity in Ohoililir, Southeast Maluku. IOP Conference Series: Earth and Environmental Science, 618(1).
88. Ryabchuk D, Orlova M, Kaskela A, Kotilainen A, Sergeev A, Sukhacheva L, Zhamoida V, Budanov L, Neevin I. 2020. The eastern Gulf of Finland—brackish water estuary under natural conditions and anthropogenic stress. Seafloor Geomorphology as Benthic Habitat: GeoHab Atlas of Seafloor Geomorphic Features and Benthic Habitats, 281–301.
89. Saputra A, Nugroho RY, Isnaini R, Rozirwan. 2021. A review: The potential of microalgae as a marine food alternative in Banyuasin Estuary, South Sumatra, Indonesia. Egyptian Journal of Aquatic Biology and Fisheries, 25(2), 1053–1065.
90. Schulze A. 2023. Worms, Annelida. Reference Module in Life Sciences,. https://doi.org/10.1016/B978-0-12-822562-2.00094-3.
91. Shaheen SM, Abdelrazek MAS, Elthoth M, Moghanm FS, Mohamed R, Hamza A, El-Habashi N, Wang J, Rinklebe J. 2019. Potentially toxic elements in saltmarsh sediments and common reed (Phragmites australis) of Burullus coastal lagoon at North Nile Delta, Egypt: A survey and risk assessment. Science of The Total Environment, 649, 1237–1249.
92. Shaheen SM, Shams MS, Khalifa MR, El-Dali MA, Rinklebe J. 2017. Various soil amendments and environmental wastes affect the (im)mobilization and phytoavailability of potentially toxic elements in a sewage effluent irrigated sandy soil. Ecotoxicology and Environmental Safety, 142, 375–387.
93. Shimod KP, Vineethkumar V, Prasad TK, Jayapal G. 2022. Effect of urbanization on heavy metal contamination: a study on major townships of Kannur District in Kerala, India. Bulletin of the National Research Centre, 46(1).
94. Silva-Gigante M, Hinojosa-Reyes L, Rosas-Castor JM, Quero-Jiménez PC, Pino-Sandoval DA, Guzmán-Mar JL. 2023. Heavy metals and metalloids accumulation in common beans (Phaseolus vulgaris L.): A review. Chemosphere, 335, 139010.
95. Singh JK, Kumar P, Kumar R. 2020. Ecological risk assessment of heavy metal contamination in mangrove forest sediment of Gulf of Khambhat region, West Coast of India. SN Applied Sciences, 2(12), 1–11.
96. Singh V, Singh N, Rai SN, Kumar A, Singh AK, Singh MP, Sahoo A, Shekhar S, Vamanu E, Mishra V. 2023. Heavy Metal Contamination in the Aquatic Ecosystem: Toxicity and Its Remediation Using Eco-Friendly Approaches. Toxics, 11(2).
97. Slobodian MR, Petahtegoose JD, Wallis AL, Levesque DC, Merritt TJS. 2021. The Effects of Essential and Non-Essential Metal Toxicity in the Drosophila melanogaster Insect Model: A Review. Toxics, 9(10).
98. Smeds J, Öquist M, Nilsson MB, Bishop K. 2022. A Simplified Drying Procedure for Analysing Hg Concentrations. Water, Air, and Soil Pollution, 233(6), 1–9.
99. Smethurst DGJ, Shcherbik N. 2021. Interchangeable utilization of metals: New perspectives on the impacts of metal ions employed in ancient and extant biomolecules. The Journal of Biological Chemistry, 297(6), 1.
100. Steinhausen SL, Agyeman N, Turrero P, Ardura A, Garcia-Vazquez E. 2022. Heavy metals in fish nearby electronic waste may threaten consumer's health. Examples from Accra, Ghana. Marine pollution bulletin, 175, 113162.
101. Su J, Huang G, Zhang Z. 2022. Migration and diffusion characteristics of air pollutants and meteorological influences in Northwest China: a case study of four mining areas. Environmental Science and Pollution Research, 29(36), 55003–55025.
102. Sui Q, Duan L, Zhang Y, Zhang X, Liu Q, Zhang H. 2022. Seasonal Water Quality Changes and the Eutrophication of Lake Yilong in Southwest China. Water, 3385, 14(21), 3385.

103. Susilowati DI, Affandi R, Sulistiono. 2022. Analysis of heavy metals content Hg, Cd, Pb, and Cu of green mussel Perna viridis (Linnaeus, 1758) in Bojonegara Coastal Waters of Banten Bay, Indonesia. IOP Conference Series: Earth and Environmental Science, 1083(1).
104. Taslima K, Al-Emran M, Rahman MS, Hasan J, Ferdous Z, Rohani MF, Shahjahan M. 2022. Impacts of heavy metals on early development, growth and reproduction of fish - A review. Toxicology reports, 9, 858–868.
105. Tchounwou PB, Yedjou CG, Patlolla AK, Sutton DJ. 2012. Heavy Metals Toxicity and the Environment. EXS, 101, 133.
106. Tjahjono A, Sugiharto R, Wahyuni O. 2022. Study of water and sediment surface quality on defilement of heavy metals Pb & Cd at a downstream section of Musi River, South Sumatera, Indonesia. Revista Ambiente e Agua, 17(1), 1–20.
107. Usman K, Abu-Dieyeh MH, Zouari N, Al-Ghouti MA. 2020. Lead (Pb) bioaccumulation and antioxidative responses in Tetraena qataranse. Scientific Reports, 10(1), 17070.
108. Wang C, Chen J, Li Z, Abouel Nasr ES, El-Tamimi AM. 2019. An indicator system for evaluating the development of land-sea coordination systems: A case study of Lianyungang port. Ecological Indicators, 98, 112–120.
109. Wang C, Wang K, Zhou W, Li Y, Zou G, Wang Z. 2023. Occurrence, Risk, and Source of Heavy Metals in Lake Water Columns and Sediment Cores in Jianghan Plain, Central China. International Journal of Environmental Research and Public Health, 20(4), 3676.
110. Wang R, Zhang L, Chen Y, Zhang S, Zhuang T, Wang L, Xu M, Zhang N, Liu S. 2020. Elevated non-essential metals and the disordered metabolism of essential metals are associated to abnormal pregnancy with spontaneous abortion. Environment International, 144, 106061.
111. Wang Y, long Li B, Zhu J le, Feng Q, Liu W, hua He Y, Wang X. 2022. Assessment of heavy metals in surface water, sediment and macrozoobenthos in inland rivers: a case study of the Heihe River, Northwest China. Environmental science and pollution research international, 29(23), 35253–35268.
112. Windarto AB, Rampengan RM, Pratasik SB. 2023. Morphometric study of macrozoobenthos community in Manado Beach, North Sulawesi. AACL Bioflux, 16(3), 1682–1690.
113. Xie Z, Zhu G, Xu M, Zhang H, Yi W, Jiang Y, Liang M, Wang Z. 2022. Risk assessment of heavy metals in a typical mangrove ecosystem - A case study of Shankou Mangrove National Natural Reserve, southern China. Marine Pollution Bulletin, 178, 113642.
114. Yi J, Lo LSH, Liu H, Qian P-Y, Cheng J. 2021. Study of heavy metals and microbial communities in contaminated sediments along an urban estuary. Frontiers in Marine Science, 8, 741912.
115. Yozukmaz A, Yabanlı M. 2023. Heavy Metal Contamination and Potential Ecological Risk Assessment in Sediments of Lake Bafa (Turkey). Sustainability, 15(13), 9969.
116. Yu Z, Wang Q, Xu Y, Lu M, Lin Z, Gao B. 2022. Dynamic impacts of changes in river structure and connectivity on water quality under urbanization in the Yangtze River Delta plain. Ecological Indicators, 135, 108582.
117. Yuan Y, Sun T, Wang H, Liu Y, Pan Y, Xie Y, Huang H, Fan Z. 2020. Bioaccumulation and health risk assessment of heavy metals to bivalve species in Daya Bay (South China Sea): Consumption advisory. Marine pollution bulletin, 150.
118. Zaynab M, Al-Yahyai R, Ameen A, Sharif Y, Ali L, Fatima M, Khan KA, Li S. 2022. Health and environmental effects of heavy metals. Journal of King Saud University - Science, 34(1), 101653.
119. Zhang Q, Ren F, Xiong X, Gao H, Wang Y, Sun W, Leng P, Li Z, Bai Y. 2021. Spatial distribution and contamination assessment of heavy metal pollution of sediments in coastal reclamation areas: a case study in Shenzhen Bay, China. Environmental Sciences Europe, 33(1), 1–11.
120. Zhang S, Fu K, Gao S, Liang B, Lu J, Fu G. 2023. Bioaccumulation of Heavy Metals in the Water, Sediment, and Organisms from The Sea Ranching Areas of Haizhou Bay in China. Water, 15(12), 2218.
121. Zhong WS, Ren T, Zhao LJ. 2016. Determination of Pb (Lead), Cd (Cadmium), Cr (Chromium), Cu (Copper), and Ni (Nickel) in Chinese tea with high-resolution continuum source graphite furnace atomic absorption spectrometry. Journal of Food and Drug Analysis, 24(1), 46–55.