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RESEARCH ARTICLE

Patterns of Physico-Chemical Interactions of Heavy Metal Lead (Pb) in the Jagir River Estuary System, Surabaya

Viv Djanat Prasita[1]*, Supriyatno Widagdo[2], Mahmiah[2]

[1]Department of Marine Engineering, Faculty of Engineering and Marine Science, Universitas Hang Tuah, Surabaya, East Java, Indonesia,
[2]Department of Oceanography, Faculty of Engineering and Marine Science, Universitas Hang Tuah, Surabaya, East Java, Indonesia

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Correspondent email :
viv.djanat@hangtuah.ac.id

Abstract. The Jagir River estuary system constitutes a significant ecosystem in Surabaya that sustains the livelihoods of the surrounding communities. Despite its importance, the river is subjected to substantial pollution originating from domestic and industrial waste. Therefore, this study aims to investigate the patterns of physicochemical interactions between lead (Pb) in the Jagir River estuary system. Water and sediment samples were collected at 5 strategic points, and the concentration of Pb was analyzed using Inductively Coupled Plasma optical emission spectrometry (ICP-OES). The correlation between Pb and various environmental parameters (temperature, salinity, DO, pH & TDS) was analyzed using Principal Component Analysis (PCA). The results showed that the concentrations of Pb in the water column and sediment were 0.1637 – 1.8905 ppm and 0.0735 – 0.2349 ppm, respectively, exceeding the established quality standards for water. Pb content in the waterbody exhibited an increasing trend from upstream to the sea. These results show the salinity and tidal parameters as characteristic features of the Jagir River estuary system, which influence Pb content in water and sediment. The distinct characteristics of this estuary system vary for each region or location, showing that the results can contribute to the development of environmental policies and monitoring of water quality.

1. Introduction

Heavy metal pollution in aquatic environments, specifically lead (Pb), has become a global concern due to its significant impact on ecosystems and human health. Estuary is a zone of convergence between freshwater and seawater, which has become more vulnerable to the accumulation of pollutants, including heavy metals. These zones function as natural filters, removing metals and other pollutants from river water before reaching the ocean, thereby providing essential micronutrients for aquatic life (Karbassi et al., 2016). The export of organic matter from the mouth of estuary to nearby coastal areas supports secondary production and influences the biodiversity and functional characteristics of macrobenthic coastal communities. Long-term ecological studies, such as those conducted in Patos Laguna, provide valuable data on species occurrence and abundance, which is crucial for understanding and predicting the dynamics of estuary and its broader ecological impacts (Lemos et al., 2022). The synergistic relationship between estuary and coastal habitats shows the need for an integrated management approach that preserves this association and improves the provision of ecosystem services. Therefore, the ecological significance of estuary in coastal areas is multifaceted, comprising pollution control, nutrient cycles, support for biodiversity, and maintenance of important ecosystem services for both natural and human communities.

According to previous studies, river mouth system has complex hydro-oceanographic characteristics affected by various factors, such as temperature, salinity, wind, and tidal currents. The temperature at river mouth has significant spatial and temporal variability, often influenced by changes in climate and seasonality. In the Texas coastal system, salinity is characterized by events of a certain magnitude and duration, exhibiting significant spatial ecological patterns (Johns & Heger, 2018). In addition, wind plays a significant role in influencing the dynamics of river mouth by affecting surface currents and mixing processes. Several studies have shown that the circulation pattern of the Sado River Estuary is influenced by the tidal regime, with water moving through the main navigation channel (Biguino et al., 2021). The impacts of climate change, such as sea-level rise and changes in precipitation, exacerbate the hydrological cycle, affecting salinity and water quality. This situation was observed in the Florida estuary, where a decrease in river flow and an increase in maximum river flow characteristics contribute to a decrease in salinity (Croteau et al., 2023).

Physicochemical parameters, such as pH, salinity, dissolved oxygen (DO), temperature, and organic carbon have been reported to significantly influence the behavior and bioavailability of heavy metals, including lead (Pb), in river estuary systems. These parameters affect the speciation and partitioning of metals, determining their toxicity and potential for bioaccumulation. For example, in the Gironde River mouth, dynamic fractions of Pb were influenced by salinity gradients and photoreduction processes, which dissolve Pb into more bioavailable forms (Abdou et al., 2022). Similarly, in the Mundau-Manguaba estuary-lagoon system, significant interactions between organic matter in suspended particulate matter (SPM) and Pb^{2+} ions show that organic matter can enhance its mobility and bioavailability (Da Silva et al., 2021). pH and salinity also play important roles, but, at the Porong River mouth, it was observed that these parameters did not significantly affect the biological concentration factor (BCF) in the biota. This showed that other factors are more influential in environment (Sari, 2017). Anthropogenic activities, such as urban and industrial waste disposal and dredging operations, can also exacerbate pollution levels and disrupt physicochemical equilibrium. The pollution can lead to increased turbidity and suspended solids, which in turn affect the DO content and overall water quality (Izougarhane et al., 2016). The disruption often leads to higher bioavailability of heavy metals, posing risks to aquatic life and human health (Rodrigues et al., 2018). Seasonal dynamics and spatial distribution play a significant role, as observed in Muara Yongjiang, where Pb concentrations peaked during the winter season. In numerous estuarine environments, interaction between lead and SPM or benthic sediments is identified as a primary mechanism for the deposition or mobilization of metal within the aquatic ecosystem.

The Jagir River estuary system, constituting the mangrove conservation area on the eastern coast of Surabaya, has experienced alterations in its environmental conditions. This region is often subjected to the expansion of adjacent residential areas (Prasita et al., 2019), which possess the potential to increase concentrations of heavy metals, such as Pb. Therefore, several questions addressed in this study include 1) what are the physicochemical parameters that influence the distribution and concentration of heavy metal Pb in the Jagir River estuary system? 2) what is the relationship between pH, temperature, salinity, and organic content with the mobility and bioavailability of Pb in the Jagir River estuary?, 3) what are interaction patterns between heavy metal Pb and physicochemical parameters in the Jagir River estuary?

At present, there is a lack of comprehensive study on the distribution of lead (Pb) from upstream areas with diverse land uses to downstream regions, particularly in the Jagir River estuary system, which serves as the ultimate destination for contaminants. The patterns of physicochemical interactions, including lead within estuarine system, remain inadequately elucidated. There is also a dearth of information regarding the physicochemical characteristics of water along the Jagir River estuary, which discharges into the Pamurbaya mangrove conservation area.

To address this gap, a comprehensive investigation of the physicochemical interaction patterns of Pb in the Jagir River estuary is essential. The assessment of metal is important due to its potentially severe detrimental impact on the Jagir River estuary system within the Pamurbaya mangrove conservation area. The management of coastal environments necessitates a particular focus on estuary-system approach characterized by tidal fluctuations and salinity gradients. Therefore, this study aims to investigate the patterns of physicochemical interactions of lead (Pb) in the Jagir River estuary system.

2. Methods

This study was conducted from December 2023 to August 2024, focusing on the Jagir River estuary system area, specifically at coordinates 7°17' South Latitude and 112°44' East Longitude, as well as 7°19' South Latitude and 112°52' East Longitude, as showed in Figure 1. Field data was collected on May 23, 2024, in the area of Surabaya. This estuary system extended from the Jagir River in the west to the waters surrounding the Pamurbaya coastal area. System was divided into 3 zones, namely (1) the rural-industrial zone on the west side, characterized by high urban activity with its associated ecological residues, including various types of pollution that ultimately discharged into estuary, (2) the transition zone that functioned as an area of change between the rural-industrial zone and the relatively natural zone, featuring mangrove habitats with multiple ecological benefits and services, and (3) Zone 3 comprised river mouth and surrounding seawater.

The instrumentation in this study comprised 2 components, namely physical and chemical oceanography

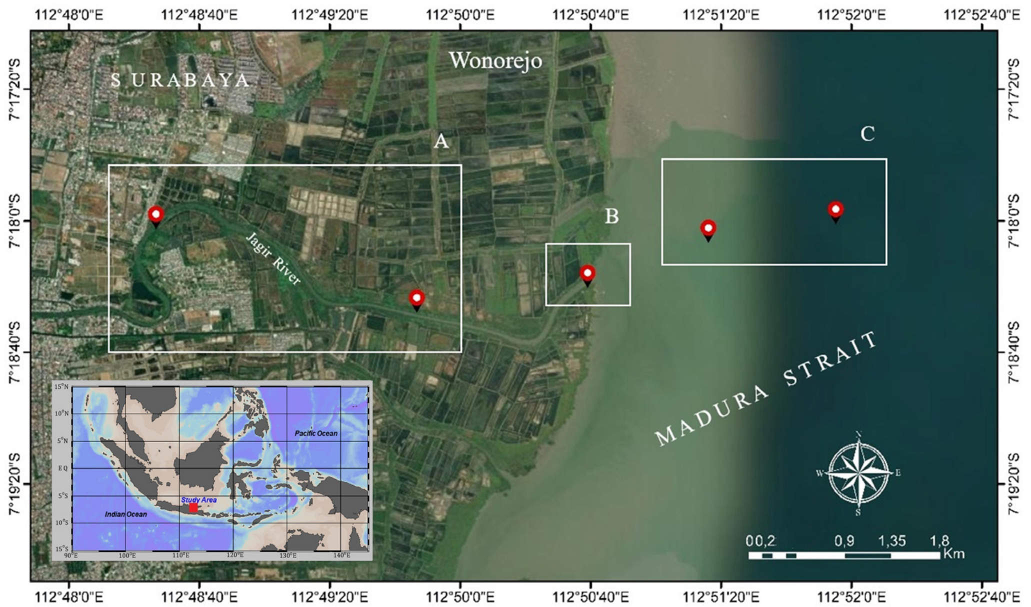

Figure 1. The study location for the Jagir River estuary system was categorized into 3 areas: upstream, estuarine, and oceanic.

Table 1. The study types of equipment and their functions

No	Equipment	Functions
A.	Physical Oseanography Parameters	
1	Niskin bottle	Taking water samples at a certain depth
2	Sediment grab	Sampling bottom sediments
3	Thermometer	Measuring temperature
4.	Hand Refractometer	Measuring salinity
B.	Chemical Oseanography Parameters	
1	ICP-OES (Inductively Coupled Plasma – Optical Emission Spectrometry)	Measuring heavy metal : Pb
2	DO Meter	Measuring Dissolved Oxygen (DO)
3	pH Meter	Meauring pH.
4	TDS Meter	Measuring Total Dissolved Solid (TDS)

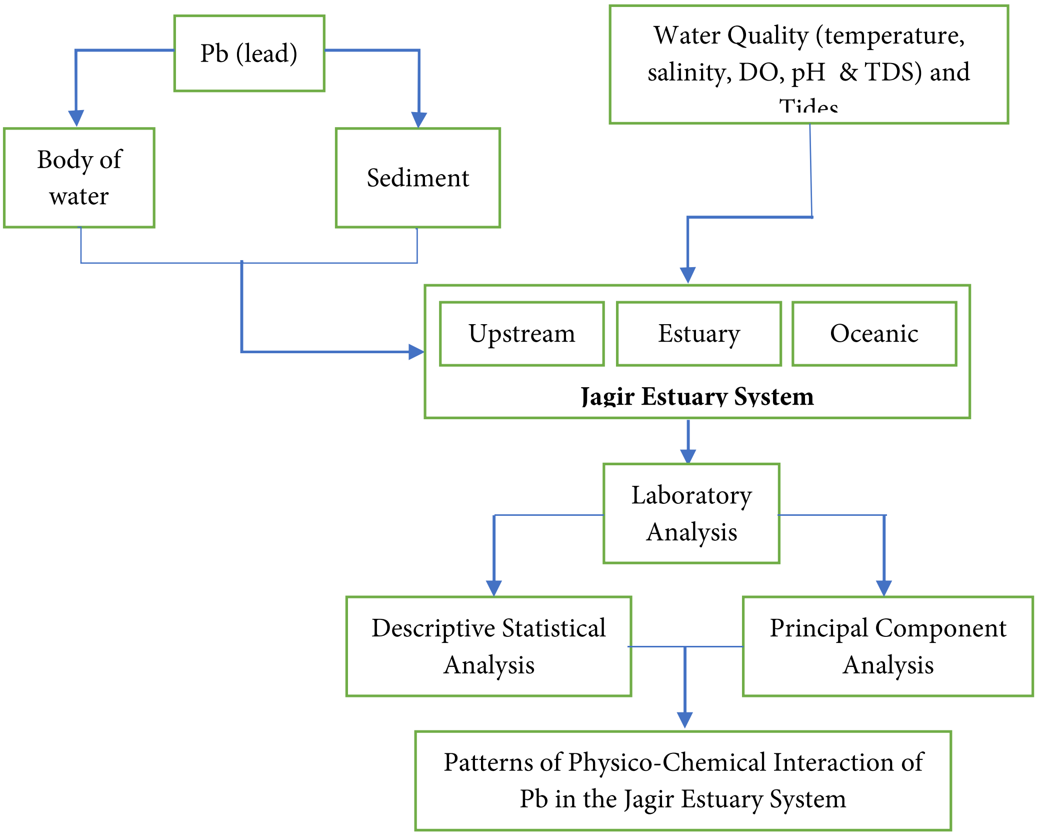

Figure 2. Flowchart showing the correlation between lead (Pb) and physico-chemical properties of the study area using estuary system approach.

instruments. Furthermore, the measured physical parameters included pH, DO, temperature, salinity, and total dissolved solids (TDS). The specific instruments and their applications were presented in Table 1. A schematic representation of the study methodology was shown in Figure 2.

Data Processing and Analysing

Data processing and analysis comprised tidal and water quality data. Tidal data were obtained from tidal prediction data published by Pushidrosal in May 2024, coinciding with the field data collected on May 2, 2024. These tidal data were used to analyze the salinity content in the Jagir River estuary system, which influenced the concentrations of heavy metal Pb.

The data for temperature, salinity, and Pb were analyzed using Principal Component Analysis (PCA) on XL-Stat to obtain statistical descriptions. Visualization of the data was conducted at 5 study stations to determine the magnitude of each parameter and elucidate its distribution. The primary steps in PCA were (1) Normalization of Data, wherein the initial step required standardizing the data to ensure that each variable had a mean of 0 and a variance of 1. This was crucial because PCA was sensitive to the scale of the variables. (2) Formation of Covariance Matrices, wherein after normalizing the data, the subsequent step was to calculate the covariance matrices, which described the correlation between variables in the data. (3) Eigen Decomposition, wherein eigenvalues and eigenvectors were calculated from the covariance matrices.

Eigenvalues showed the amount of variance captured by each principal component, while eigenvectors showed the direction of the principal component. (4) Formation of Principal Components, wherein principal components were linear combinations of the original variables that maximized the variance of the data. The first principal component (PC1) captured the maximum variance, while the second principal component (PC2) captured the subsequent maximum variance. (5) Data Projection, the original data were projected onto a lower-dimensional space formed by a selected number of principal components. The quantity of principal components selected depended on the quantity of variance in the data that must be retained. Therefore, PCA was a robust tool for data analysis and understanding multivariate data structures, facilitating dimensionality reduction and the detection of patterns that were not apparent in the original dimensions.

Heavy metal concentrations in the water and sediment samples were quantified using an ICP-OES instrument according to the SNI 8910:2021 method. Subsequent analysis focused on heavy metal Pb as the dependent variable, with pH, DO, TDS, temperature, and salinity functioning as independent variables. Furthermore, the distribution of heavy metals in the coastal-oceanic region was consistent with patterns of flow and wave dynamics.

The calculation of heavy metal pollution index (Pi) in seawater was determined using the formula (Luo et al., 2022):

$$Pi = \frac{Ci}{Cb}$$

Ci represented the concentration of heavy metals in the water, and Cb denoted the concentration of heavy metals based on the standard set by the Government Regulation of the Republic of Indonesia Number 22 in 2022. Concerning the Implementation of Environmental Protection and Management, the pollution index Pi was categorized into 4 classes, including low (Pi < 1, Class I), moderate (1 < Pi < 3, Class II), considerable (3 < Pi < 6, Class III), and very high contamination (Pi > 6, Class IV).

3. Result and Discussion

Physico-chemical Parameters and Level of Heavy Metal Lead (Pb) in Jagir River

The results of physicochemical quality parameters of Jagir River waters were presented in Table 2, with the pH values in the study area ranging from 7.1 to 8.09, showing neutral to alkaline conditions. Furthermore, the water temperatures were within normal range, varying from 30.3°C to 31.9°C. The DO levels exhibited an increase from zero salinity at the upstream river station to 27.3 ‰ at the sea station, while TDS values ranged from 37.9 mg/L to 99.5 mg/L.

The results of heavy metal analysis for Pb in water and sediment samples from multiple stations obtained using the ICP-OES method were presented in Table 3. These concentrations were significantly increased and exceeded the standard quality guidelines (Peraturan Pemerintah Republik Indonesia, 2021), particularly at Stations 4 and 5. The measurements showed that lead content in the water exhibited an increasing trend from the upstream to the downstream regions of estuary system, while those in the sediment remained relatively constant. Furthermore, the calculated pollution index (Pi) values at all stations for heavy metal content (Luo et al., 2022) showed Pi values > 6, which signified a class IV category (heavily polluted) for both water and sediment.

Based on the results from the observations presented in Table 3, the concentration of Pb in the sediment exceeded the concentration of Pb in the column water at Stations 1 and 2, which were situated in rivers with zero salinity. However, the

Table 2. Result of Physico-chemical Parameters in Waters

Location	Physico-chemical Parameter in waters				
	pH	Temperature (^{0}C)	DO (mg/L)	Salinity (‰)	TDS (mg/L)
Station 1	7.43	31.9	6.9	0.00	37.9
Station 2	7.38	31.1	9.4	0.00	99.5
Station 3	7.10	30.3	9.8	5.00	95.2
Station 4	7.31	30.4	9.9	26.67	95.5
Station 5	8.09	31.1	12.6	27.30	96.4
Guidelines value (*)	6,5-8,5	28-32	>5.0	Max. 34.00	80.0

(*) Government Regulation of the Republic of Indonesia Number 22 in 2021 Concerning the Implementation of Environmental Protection and Management.

Table 3. Heavy metal testing results for Pb in water and sediment samples.

Location	Heavy metal Pb contents (ppm)	
	in water sample	in sediment sample
Station 1	0.1637	0.2108
Station 2	0.1200	0.2349
Station 3	0.2929	0.2253
Station 4	1.4135	0.0735
Station 5	1.8905	0.0736
Guidelines value (*)	0.005	0,0080

(*) Government Regulation of the Republic of Indonesia Number 22 in 2021 Concerning the Implementation of Environmental Protection and Management.

concentration was higher compared to Pb in the sediment at Stations 3, 4, and 5, which were located at river mouth. The elevated concentration, in comparison to that in the sediment, was influenced by the presence of NO_3^- and NO_2.

The concentration of lead (Pb) in water was influenced by several factors, including the presence of NO_3^- and NO_2^-. Environmental lead contamination primarily originated from industrial waste, which often contained a mixture of heavy metals and other pollutants, such as nitrate and nitrite (Muhammad et al., 2020). The dynamics of Pb adsorption in sediment were influenced by physicochemical properties of the sediment, including pH and particle size, which could affect the sediment's binding capacity for heavy metals (Anyinkeng et al., 2022). In a study of sediment from Buea, Southwest Cameroon, it was observed that the presence of heavy metals in water and sediment was significantly affected by anthropogenic activities, including the disposal of nitrate and nitrite from agricultural runoff and industrial processes (Anyinkeng et al., 2022). Furthermore, the equilibrium and kinetics of Pb adsorption to sediment showed that the process was spontaneous and exothermic, showing the presence of other ions, such as NO_3^-, as well as NO_2. This could influence the efficiency of adsorption and sediment capacity for Pb (Ayuba et al., 2020). The accumulation in plants and aquatic organisms, such as common carp, further elucidated the complex interactions between various pollutants in the water. Nitrate and nitrite played a significant role in altering the availability and mobility of Pb (Valkova et al., 2016). Various plant species exhibited distinct abilities and potentials for accumulating heavy metals (Kapungwe, 2012). Studies in Bulgaria had shown that the concentration of Pb in sediment and aquatic organisms could serve as an ecological indicator for pollution assessment, showing the relationship between several pollutants in the aquatic environment (Valkova et al., 2022). Furthermore, the differential accumulation of Pb in aquatic plant leaves in Kayeli Bay showed that the presence of other ions, including nitrate and nitrite, could affect the distribution and concentration in various components of the ecosystem (Natsir & Rijal, 2020). The concentrations of NO_3^- and NO_2^- in the water influenced the concentration of Pb in the water compared to sediment, thereby affecting the overall pollution dynamics of heavy metals in the aquatic environment.

Effect of Tides on Salinity in Jagir River Estuary System

The results of the tidal analysis, as shown in Figure 3, showed that the tidal type at the study location exhibited a mixed trend. According to the classification, tides at the study location predominantly occurred twice daily with 2 high tides and 2 low tides, although occasionally there was a high tide and a low tide per day. The mean sea level in May 2024 was calculated at 1.50 m with a mean high water spring of 2.71

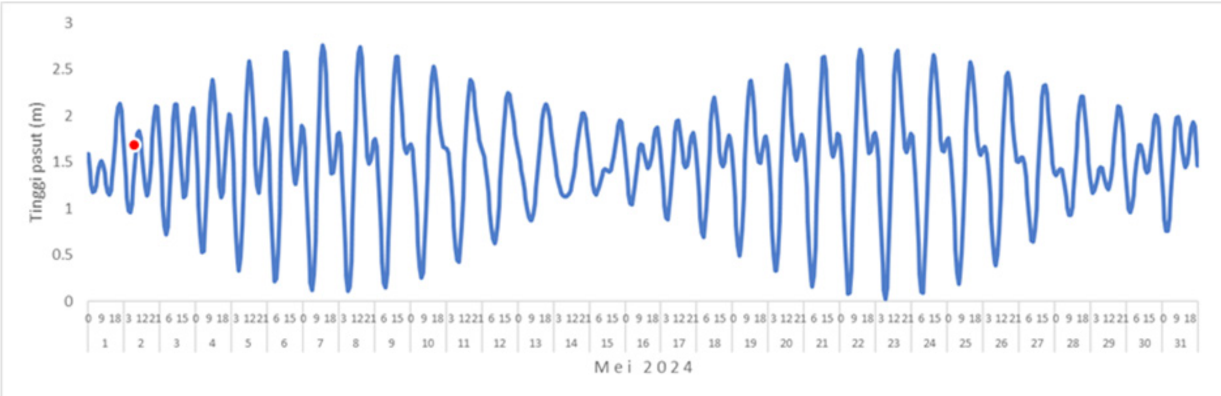

Figure 3. Tidal fluctuations during May 2024, showed that mixed tidal types tended to double. The red dot was showed when Pb data were collected from 10.00 to 11.00 when the water conditions were high tide.

Figure 4. The concentration of lead (Pb) in water and sediment in the Jagir Estuary System.

m and a mean water neap of 1.58 m. With the average tidal height during the full moon and neap tide, the mass of saline seawater was propelled towards river at high tide, thereby increasing the salinity of estuarine waters to the nearest river bodies. However, when river water receded, the salinity value in the affected oceanic water bodies decreased. This condition influenced the Pb content in water resulting from tidal flushing. Data collected at high tide had the potential to show the effect of high Pb content in the water due to the higher salinity compared to those in river water bodies (Figure 4). The sea served as a source of tidal water as well as saltwater. Consequently, salinity tended to be higher when the tides (water depth) were high and lower when the tides were low (Atekwana et al., 2022). The high level of Pb in oceanic water bodies remained relatively constant, with a decrease in concentration values, considering that seawater had a higher salinity than rivers.

Effect of Jagir Estuary system on heavy metal (Pb) contamination level

The ecological characteristics of Pb in the Jagir River mouth system were influenced by natural zones, such as rivers, mangroves, and the sea, each playing a different role in Pb dynamics. In river environments, Pb was primarily found in a truly dissolved phase, and transported in freshwater rivers (Ren et al., 2023). As river water transitioned to mangroves, the mangrove ecosystem served as a natural bioaccumulator, with species such as Avicennia alba and Avicennia lanata showing a significant ability to accumulate and translocate Pb from sediment to their roots, stems, and leaves (Lufthansa et al., 2021). This bioaccumulation was crucial because mangrove forests could absorb and immobilize Pb, reducing its mobility and potential ecological risk. In river mouth zone, the salinity gradient played a significant role in its behavior, such as increasing the salinity caused by dissolved Pb to deposit into the sediment, while Pb colloids remained more mobile and less affected by the changes (Ren et al., 2023). Sediment in the mangrove area showed higher concentrations of Pb compared to the water, showing that it acted as a sink (Sofiana et al., 2024). Furthermore, its speciation, often in the form of residues, posed ecological risks that required preventive measures (Chen et al., 2022). The transport and transformation of Pb from rivers to the sea were also influenced by human activities such as industrial and agricultural runoff, which contributed to coastal pollution (Chen et al., 2022). Overall, the natural zones of the Jagir River mouth system, from river to mangrove to sea, collectively determined the ecological characteristics of Pb, with each zone playing a crucial role in its transport, transformation, and accumulation, thereby affecting the overall ecological risk posed by this heavy metal.

Interactions of Physico-chemical Parameters with Lead (Pb) in the Jagir Estuary System

The content provided was a description of the presence of lead (Pb) in the wetland area, its concentration exhibited an increasing gradient from the upstream to the coastal area, both in water and sediment. An exception was observed in the sediment at station 1 (upstream), where the area was characterized by relatively dense domestic industrial activities that served as sources of pollution, including Pb. The Pb contained in the sediment showed relatively static behavior compared to that in the water body. Consequently, its concentration was more likely to accumulate in the sediment. The concentrations in both sediment and water were also influenced by the physicochemical parameters of the water (Figure 4).

The influence of salinity on lead (Pb) was explained in this study. In freshwater with a salinity of zero (0), a reaction occurred between heavy metal Pb and halide ions (Cl-) to form $PbCl_2$, which precipitated in the sediment. An increase in salinity in the aqueous environment potentially influenced the solubility of $PbCl_2$ in the sediment, resulting in the formation of a complex ion such as $[PbCl_4]^{2-}$, as showed in the reaction equation (Svehla, 2008).

$$Pb^{2+} + 2Cl^- \longrightarrow PbCl_2\downarrow$$

$$PbCl_2 + 2Cl^- \longrightarrow [PbCl4]^{2-}$$

In this study, the influence of pH on lead (Pb) was elucidated as follows. The pH of water influenced the solubility of Pb in both water and sediment. This phenomenon occurred due to the reaction between Pb and OH- to form $Pb(OH)_2$, which precipitated in the sediment. An increase in pH levels in the water could affect the solubility of $Pb(OH)_2$ in sediment, resulting in the formation of a complex ion such as $[Pb(OH)_4]^{2-}$, as showed by the reaction equation (Svehla, 2008).

$$Pb^{2+} + 2OH^- \longrightarrow Pb(OH)2\downarrow$$

$$Pb(OH)2 + 2OH^- \longrightarrow [Pb(OH)4]^{2-}$$

Based on Tables 4 and 5, an increase in Pb concentrations was observed in the water column, while a decrease was noted in the sediment samples at each location with increasing salinity and pH levels from station 1 to station 5. Furthermore, a direct relationship was observed between increasing DO values at each observation station and Pb concentrations in the water column, while an inverse relationship was observed between DO values and Pb concentrations in sediment samples. The presence of DO in the water affected the solubility due to the redox reactions from ammonia to nitrite (NO_2^-) and nitrate (NO_3^-), which increased the solubility in the water and decreased the concentrations in the sediment. In this study, the reduction in Pb levels in the sediment was influenced by the presence of mangroves around locations 3 to 5. Mangroves functioned as sediment traps (Prasita et al., 2023) as well as bioaccumulators of heavy metals, thereby reducing heavy metal pollution in water (Mahmiah et al., 2023). The regulation of water temperature affected other water parameters, such as salinity, which in turn influenced Pb levels in water and sediment.

PCA was used to analyze interaction of physicochemical parameters with Pb in the Jagir River estuary system. Eigenvalues and Eigenvectors in PCA were presented in Tables 4 and 5, while factor loadings were shown in Table 6. In PCA, eigenvalues quantified the magnitude of the variance captured by each principal component. Each principal component had 1 eigenvalue corresponding to it. Consequently, eigenvalues in PCA were a significant measure of the quality of information (variation) explained by each principal component. By selecting components with the largest eigenvalues, the

Table 4. Eigenvalues in PCA

	F1	F2	F3	F4
Eigenvalue	3.696	2.607	0.632	0.065
Variability (%)	52.801	37.249	9.027	0.922
Cumulative %	52.801	90.051	99.078	100.000

Table 5. Eigenvectors in PCA

	F1	F2	F3	F4
Pb_Water (ppm)	0.491	0.168	-0.233	-0.164
Pb_Sediment (ppm)	0.093	0.588	-0.319	0.218
pH	0.330	0.401	0.529	0.043
Temperatur (^{0}C)	-0.234	0.508	0.419	-0.486
DO (mg/L)	0.488	-0.091	0.353	0.563
Salinitas (‰)	0.481	0.090	-0.424	-0.366
TDS (mg/L)	0.342	-0.437	0.291	-0.487

Table 6. Factor loadings, which show the correlation between variables and the primary factor.

	F1	F2	F3	F4
Pb_Water (ppm)	0.944	0.271	-0.185	-0.042
Pb_Sediment (ppm)	0.179	0.949	-0.254	0.055
pH	0.635	0.648	0.420	0.011
Temperatur (^{0}C)	-0.450	0.820	0.333	-0.123
DO (mg/L)	0.938	-0.148	0.280	0.143
Salinitas (‰)	0.925	0.146	-0.337	-0.093
TDS (mg/L)	0.658	-0.706	0.232	-0.124

dimensions of the data were reduced while preserving the original variance, facilitating data analysis and visualization. In this study, a cumulative variance of 90.8051 % was used to describe the correlation of the data and to create a biplot using the F1 and F2 principal components.

The correlation between variables against observation stations in Principal Components F1 and F2 was showed in Figure 5 (A). At Stations 1 and 2 (representing the upper estuary zone, which comprised river water up to the mouth), water temperature was characterized by significant parameter variation. At Station 1, this parameter was temperature, while at Station 2, there was considerable variation in Pb in the sediment, which was also a characteristic of Station 3, a zone of exchange between river water and seawater during tidal fluctuations. The significant parameters were DO and TDS at Station 4, while at Station 5, the significant physicochemical parameters were salinity, pH, and concentration in water. Stations 4 and 5 represented the oceanic zone of estuary extending to the open sea in this study. Furthermore, the varying environmental conditions resulted in differences in Pb content in the water and sediment.

The levels of heavy metals presented at each station could influence their concentration. Ionic halides (Cl^-, I^-, and Br^-) reacted with Pb in seawater, resulting in soluble Pb salts that dissolved in water and settled with sediment. This concentration in seawater was also influenced by DO, with higher DO levels reducing solubility in water. At stations 1 to 5, the neutral pH tended towards being basic, which also led to lower solubility. The formation of complex compounds caused by other ions, such as nitrate (NO_3^-), nitrite (NO_2^-), and phosphate (PO_4^{3-}), led to higher levels of heavy metals in both water and sediment.

The correlation between the variables in the main components F1 and F2 was showed in Figure 5 (B). A positive correlation existed between the DO and Pb concentrations in the column water, showing that as the DO and salinity levels increased, the Pb concentrations also increased. DO played a significant role in influencing the concentration of lead (Pb) in water, primarily through its impact on chemical speciation and solubility of lead. The presence of DO led to the oxidation of lead compounds, which affected their solubility and mobility in aquatic environments. This study showed that higher levels of DO could promote the formation of lead oxides, which were generally less soluble than other lead compounds. Furthermore, this process resulted in the precipitation of lead from the water column, thereby reducing its concentration in the dissolved phase (Wang, 2012). This was corroborated by previous studies showing that in oxygen-rich environments, Pb tended to form stable complexes with oxygen, resulting in its removal from water through sedimentation (Wei et al., 2020) because the lack of oxygen prevented the oxidation of lead, maintaining it in a more soluble and mobile state (Mohammadzadeh et al., 2015). Moreover, interactions among DO and other environmental factors, such as pH and the presence of organic matter, could influence lead solubility. For instance, in environments where organic matter was abundant,

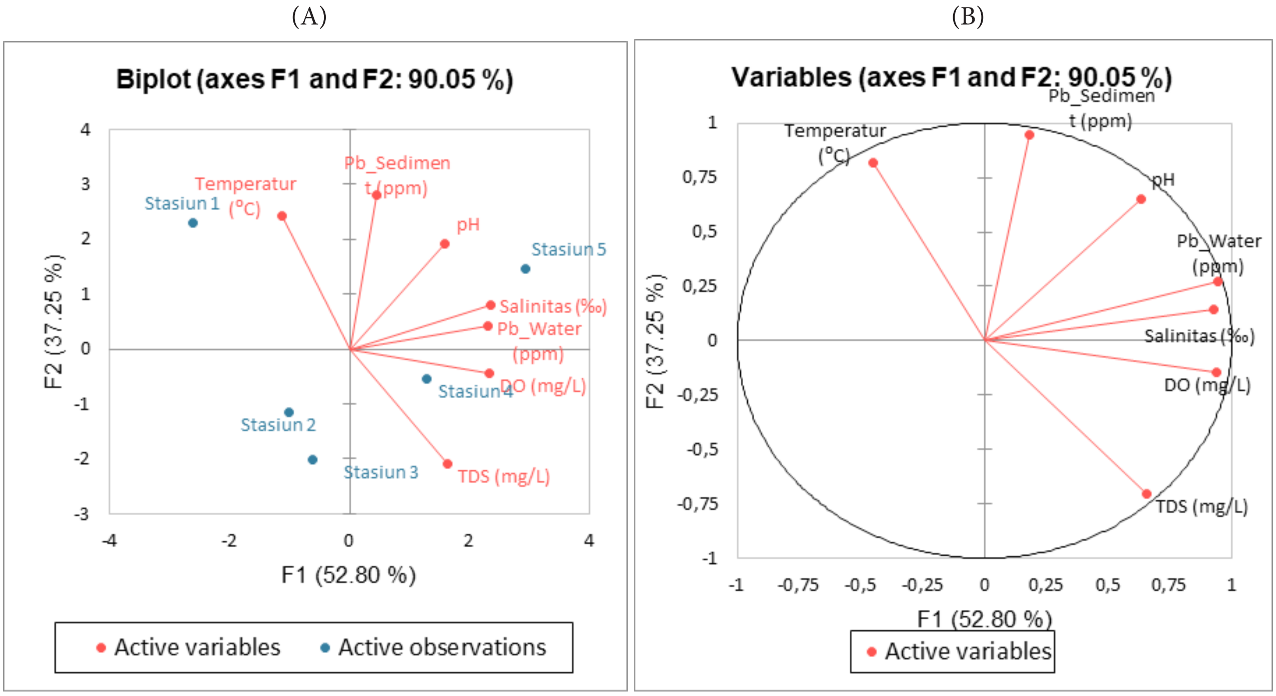

Figure 5. (A) Correlation between variables against observation stations in Principal Components F1 and F2, (B) Correlation between variables in Principal Components F1 and F2.

the complexation of lead with organic ligands could be enhanced under low oxygen conditions, potentially increasing its concentration in the dissolved phase. The concentration of lead in water was inversely related to the levels of DO, with higher DO levels generally leading to lower dissolved lead concentrations due to the formation of less soluble lead compounds. However, this relationship could be modulated by other environmental factors, highlighting the complexity of Pb chemistry in aquatic systems. Understanding these interactions was crucial for managing lead contamination in water bodies, particularly in areas prone to oxygen depletion.

The influence of DO levels on the concentration of lead (Pb) in sediment was a critical factor in elucidating the mobility and bioavailability of Pb in aquatic ecosystems. Increased DO levels generally facilitated lead oxidation, resulting in the transformation of metal to less soluble forms, thereby reducing its concentration in sediment. This phenomenon was corroborated by several studies, such as Macías et al. (2022), which showed that Pb predominantly formed associations with fractions of Fe/Mn oxides in sediment, exhibiting greater stability and reduced bioavailability under oxic conditions. Similarly, Zhang et al. (2023) observed that Pb (II) adsorption by river sediment was significantly influenced by pH and redox conditions, with higher DO levels promoting the formation of stable Pb complexes and diminishing their mobility. According to Rzetala et al (2023), sediment concentrations were influenced by several environmental parameters, including DO levels, which subsequently affected the geoaccumulation index and contamination. A study on sediment speciation showed that environmental factors such as DO, temperature, and pH significantly impacted the release and transformation of heavy metals, such as Pb, from the sediment (Zhao et al., 2024). These investigations collectively showed that elevated DO levels contributed to the stabilization of Pb in less soluble forms, thereby reducing its concentration and potential environmental risks in sedimentary environments.

The relationship between DO, salinity, and lead (Pb) concentrations in sediment was highly complex and influenced by multiple environmental factors. Increased salinity generally reduced Pb adsorption onto sediment due to competitive effects, as observed in the Qiantang River study, where elevated salinity resulted in a decrease in adsorption onto sediment particles (Zhang et al., 2023). This suggested that higher salinity could reduce Pb concentrations in sediment by facilitating its release into the water column. Furthermore, in the Yellow River Delta, it was found that increased salinity improved the risk of Pb migration, showing that Pb was more likely to remain in the water than in the sediment under high salinity conditions (Li et al., 2020). A study on the behavior of Pb transformation and transport in the colloidal phase from river to the sea in the Yellow River Delta showed a substantial increase in salinity-induced sedimentation. However, this effect diminished as salinity approached seawater levels, particularly in areas with extensive anthropogenic activity (Ren et al., 2023). This suggested that while an initial increase in salinity could enhance sedimentation, very high salinity, specifically in industrial and aquacultural areas, could inhibit this process. Therefore, while higher salinity promoted Pb release from the sediment, very high salinity and anthropogenic activities could counteract this effect. Although the role of DO concentration was not directly addressed in the provided context, it affected the redox conditions of the sediment, which influenced speciation and mobility. Higher salinity reduced Pb concentrations in sediment by promoting its release into the water column, but, this effect was modulated by the magnitude of salinity increase and anthropogenic activities in the area (Ren et al., 2023).

4. Conclusion

In conclusion, this study presented an integrated analysis of heavy metal content, specifically Pb, in the sediment and water of the Jagir River estuary system. The results showed that heavy metals exhibited higher concentrations in sediments compared to water. Furthermore, the concentrations of Pb at this location exceeded the established quality standards, showing potential significant risks to ecosystems and human health. The characteristics of Pb contamination were influenced by the natural zones of the Jagir River estuary system, including River-Fresh, Estuary Mangrove-Natural Bioaccumulator, and sea salt. Pb contamination increased from river waters to Marine Waters, except in estuary zone. The mangrove habitat could potentially serve as a bioaccumulator to mitigate the contamination flowing to the sea.

A significant result of this investigation was the observed correlation between lead (Pb) concentrations as well as salinity and DO, which emphasized the importance of managing heavy metal contamination in estuarine systems. In estuarine systems, salinity levels were strongly influenced by tidal currents. The Pb concentrations in both the aqueous and sediment phases were influenced by salinity and DO levels. A strong positive correlation was observed between the concentration in the water column and both salinity and DO, while the concentration in the sediment exhibited a negative correlation with these parameters. The study emphasized the necessity for a comprehensive approach to environmental management, comprising the monitoring and regulation of physicochemical parameters, as well as the reduction of pollution sources. These results provided a robust scientific foundation for mitigation strategies and water quality management initiatives at the Jagir River Mouth, aimed at preserving marine ecosystems and safeguarding the health of local communities.

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References

Abdou, M., Tercier-Waeber, M. L., Dutruch, L., Bossy, C., Pougnet, F., Coynel, A., Bakker, E., Blanc, G., & Schäfer, J. (2022). Estuarine dissolved speciation and partitioning of trace metals: a novel approach to study biogeochemical processes. *Environmental Research*, *208*(October 2021). https://doi.org/10.1016/j.envres.2021.112596

Anyinkeng, N., Neba, G. A., & Tening, A. S. (2022). Physico-Chemical Properties of Sediments from Some Water Sources in Buea, Southwest Cameroon: Ecotoxicological Implications. *Journal of Environment and Earth Science*, *12*(4), 44–53. https://doi.org/10.7176/jees/12-4-05

Atekwana, E. A., Ramatlapeng, G. J., Ali, H. N., Njilah, I. K., & Ndondo, G. R. N. (2022). Tide-salinity patterns reveal seawater-freshwater mixing behavior at a river mouth and tidal creeks in a tropical mangrove estuary. *Journal of African Earth Sciences*, *196*(January). https://doi.org/10.1016/j.jafrearsci.2022.104684

Ayuba, A. M., Ladan, M., & Muhammad, A. S. (2020). Thermodynamic and Kinetic Study of Pb (II) Amputation by River Sediment. *Applied Journal of Environmental Engineering Science*, *3*, 213–226.

Biguino, B., Sousa, F., & Brito, A. C. (2021). Variability of currents and water column structure in a temperate estuarine system (Sado estuary, Portugal). *Water (Switzerland)*, *13*(2), 1–13. https://doi.org/10.3390/w13020187

Chen, B., He, R., Cai, P., Huang, G., & Wang, F. (2022). Geochemical Speciation, Risk Assessment, and Sources Identification of Heavy Metals in Mangrove Surface Sediments from the Nanliu River Estuary of the Beibu Gulf, China. *Sustainability (Switzerland)*, *14*(15). https://doi.org/10.3390/su14159112

Croteau, A. C., Gancel, H. N., Gebremicael, T. G., Caffrey, J. M., & Deitch, M. J. (2023). Implications of changing trends in hydroclimatic and water quality parameters on estuarine habitats in the Gulf Coastal Plain. *Frontiers in Ecology and Evolution*, *11*(June), 1–15. https://doi.org/10.3389/fevo.2023.1167767

Da Silva, E. A., Da Silva, A. M. B., Santos, J. S., Del Colle, V., Mendonça, A. G. R., Fernandes, A. P., De Oliveira, L. C., & Botero, W. G. (2021). Interaction of suspended particulate material with Cd2+and Pb2+in a Brazilian lagoon estuarine system. *Journal of the Brazilian Chemical Society*, *32*(1), 137–144. https://doi.org/10.21577/0103-5053.20200163

Izougarhane, M., Mansouri, D., El Ibaoui1, H., Chakiri, S., & Fadli, M. (2016). Physico-Chimie Et Teneurs Metalliques Des Eaux De L'estuaire De L'oued Sebou Durant Des Annees De Dragage Du Sable/ 2007, 2014, 2015, 2016. *European Scientific Journal, ESJ*, *12*(30), 127. https://doi.org/10.19044/esj.2016.v12n30p127

Johns, N. D., & Heger, N. A. (2018). Characterizing estuarine salinity patterns with event duration and frequency of reoccurrence approaches. *Limnology and Oceanography: Methods*, *16*(3), 180–198. https://doi.org/10.1002/lom3.10236

Kapungwe, E. M. (2012). Traditional Farming Practices and Wastewater Irrigation Farming in Periurban, Zambia. *Indonesian Journal of Geography*, *44*(2), 103–119.

Karbassi, A. R., Tajziehchi, S., & Farhang Adib, N. (2016). Role of estuarine natural processes in removal of trace metals under emergency situations. *Global Journal of Environmental Science and Management*, *2*(1), 31–38. https://doi.org/10.7508/gjesm.2016.01.004

Lemos, V. M., Lanari, M., Copertino, M., Secchi, E. R., De Abreu, P. C. O. V., Muelbert, J. H., Garcia, A. M., Dumont, F. C., Muxagata, E., Vieira, J. P., Colling, A., & Odebrecht, C. (2022). Patos Lagoon estuary and adjacent marine coastal biodiversity long-term data. *Earth System Science Data*, *14*(3), 1015–1041. https://doi.org/10.5194/essd-14-1015-2022

Li, X., Wang, X., Yu, J., Yang, J., Yu, Y., Zhou, D., & Li, Y. (2020). Effect of Water Level and Salinity on Metal Fractionation in Sediments of the Yellow River Delta. *Wetlands*, *40*(6), 2765–2774. https://doi.org/10.1007/s13157-020-01337-x

Lufthansa, U. M., Titah, H. S., & Pratikno, H. (2021). The Ability of Mangrove Plant on Lead Phytoremediation at Wonorejo Estuary, Surabaya, Indonesia. *Journal of Ecological Engineering*, *22*(6), 253–268. https://doi.org/10.12911/22998993/137675

Luo, M., Zhang, Y., Li, H., Hu, W., Xiao, K., Yu, S., Zheng, C., Wang, X., Atekwana, E. A., Ramatlapeng, G. J., Ali, H. N., Njilah, I. K., Ndondo, G. R. N., Zhang, L., Guo, Y., Xiao, K., Pan, F., Li, H., Li, Z., … Hu, J. (2022). Hydrochemistry and trace metals in water and sediments in forest coastal wetlands influenced by tidal regime in the middle Río de la Plata estuary, Argentina. *Marine Pollution Bulletin*, *807*(January). https://doi.org/10.1016/j.jafrearsci.2022.104684

Macías, R., Ramos, M. S., Guerrero, A. L., Farfán, M. G., Mitchell, K., & Avelar, F. J. (2022). Contamination Assessment and Chemical Speciation of Lead in Soils and Sediments: A Case Study in Aguascalientes, México. *Applied Sciences (Switzerland)*, *12*(17). https://doi.org/10.3390/app12178592

Mahmiah, M., Sa'adah, N., Kisnarti, E. A., & Millenia, F. V. (2023). Akumulasi Logam Berat Cu Dan Hg pada Mangrove Rhizopora mucronata di Pantai Timur Surabaya (Pamurbaya). *Jurnal Kelautan Nasional*, *18*(1), 59. https://doi.org/10.15578/jkn.v18i1.11740

Mohammadzadeh, M., Basu, O. D., & Herrera, J. E. (2015). Impact of Water Chemistry on Lead Carbonate Dissolution in Drinking Water Distribution Systems. *Journal of Water Resource and Protection*, *07*(05), 389–397. https://doi.org/10.4236/jwarp.2015.75031

Natsir, N. A., & Rijal, M. (2020). The quality of kayeli bay waters: Pb and Hg accumulation in water, sediments, and seagrass (enhalus acoroides) of buru island in Maluku. *International Journal of Scientific and Technology Research*, *9*(3), 114–120.

Prasita, V. D., Bintoro, R. S., Nurmalia, I., Widagdo, S., Rosana, N., & Sugianto, E. (2023). The Coastline Change Pattern of Gresik Beach around the Madura Strait, Indonesia. *Indonesian Journal of Geography*, *55*(3), 527–537. https://doi.org/10.22146/ijg.80934

Prasita, V. D., Nuhman, Subianto, A., & Soegianto, A. (2019). Assessment of the mangrove protected area in the eastern coast of surabaya. *Ecology, Environment and Conservation*, *25*, S55–S65.

PERATURAN PEMERINTAH REPUBLIK INDONESIA, (2021).

Ren, P., Schmidt, B. V., Liu, Q., Wang, S., Liu, X., Liu, K., & Shi, D. (2023). Fractionation of toxic metal Pb from truly dissolved and colloidal phases of seaward rivers in a coastal delta. *Frontiers in Marine Science*, *9*(February), 1–20. https://doi.org/10.3389/fmars.2022.1085142

Rodrigues, P. A., Ferrari, R. G., & Conte-Junior, C. A. (2018). Application of molecular tools to elucidate the microbiota of seafood. *Journal of Applied Microbiology*, *124*(6), 1347–1365. https://doi.org/10.1111/jam.13701

Rzetala, M. A., Machowski, R., Solarski, M., Bakota, D., Płomiński, A., & Rzetala, M. (2023). Toxic Metals, Non-Metals and Metalloids in Bottom Sediments as a Geoecological Indicator of a Water Body's Suitability for Recreational Use. *International Journal of Environmental Research and Public Health*, *20*(5). https://doi.org/10.3390/ijerph20054334

Sari, Y. (2017). *Penentuan Faktor Bioakumulasi Logam Berat Pb, Cd Dan Zn Pada Bentos Di Wilayah Reklamasi Lumpur Sidoarjo Di Muara Sungai Porong*. *4*(1), 1–10. http://repository.ub.ac.id/id/eprint/157651/

Sofiana, M. S. J., Safitri, I., & Nurhidayanti. (2024). Occurrence of Lead (Pb) Metal in Water, Sediment, and Bioaccumulation in Giant Mudskipper (Boleopthalmus : Gobiidae) from the Pemangkat Mangrove Area West Kalimantan. *Jurnal Ilmiah PLATAX*, *12*(1), 345–357. https://doi.org/10.35800/jip.v12i1.55131

Valkova, E., Atanasov, V., Tzanova, M., Atanassova, S., Sirakov, I., Velichkova, K., Marinova, M. H., & Yakimov, K. (2022). Content of Pb and Zn in Sediments and Hydrobionts as Ecological Markers for Pollution Assessment of Freshwater Objects in Bulgaria—A Review. *International Journal of Environmental Research and Public Health*, *19*(15). https://doi.org/10.3390/ijerph19159600

Valkova, E., Atanasov, V., Velichkova, K., Kostadinova, G., & Mihaylova, G. (2016). Content of PB in water, sediment, aquatic plants and musculature of Common carp (Cyprinus carpio L.) from different water bodies in Stara Zagora Region, Bulgaria. *Bulgarian Journal of Agricultural Science*, *22*(4), 566–572.

Wang, Y. (2012). *Redox Reactions Influencing Lead Concentrations in Drinking Water: Formation and Dissolution of Lead(IV) Oxide and Impact of Galvanic Corrosion*. *Iv*. http://dx.doi.org/10.7936/K70G3H63

Wei, W., Chen, N., Zuo, M., & Liu, Z. W. (2020). Disturbance rejection control for the dissolved oxygen in a wastewater treatment process. *Measurement and Control (United Kingdom)*, *53*(5–6), 899–907. https://doi.org/10.1177/0020294020909953

Zhang, W., Shi, X., & Lu, J. (2023). Adsorption characteristics of Zn(II) and Pb(II) by river sediments under hydrodynamic conditions. *Water Supply*, *23*(5), 2175–2187. https://doi.org/10.2166/ws.2023.104

Zhao, Y., Zhao, S., Shi, X., Lu, J., Cui, Z., Yu, H., Ye, B., & Li, X. (2024). Influence of environmental factors on changes in the speciation of Pb and Cr in sediments of Wuliangsuhai Lake, during the ice-covered period. *Environmental Geochemistry and Health*, *46*(4). https://doi.org/10.1007/s10653-023-01842-y