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ASSESSING THE HEALTH OF SOUTH KALIMANTAN COASTAL SWAMP WETLANDS USING MEASUREMENTS OF HEAVY METALS IN COMMERCIAL FISH SPECIES

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Abstract

Heavy metals pollution damages coastal swamp ecosystems. This study's primary purpose was to determine the amounts of heavy metals in coastal swamp waters and the tissues of three fish species (Mugil cephalus, Arius sagor and Plotosus lineatus). This study determined that the water in the coastal swamps of South Kalimantan was contaminated with heavy metals in the following order: Fe > Cu > Zn > Cr > Pb > Cd > Hg. The heavy metal concentrations found in the three commercial fish species are as follows: Fe > Zn > Cu > Cr > Pb > Cd > Hg. The bioaccumulation of heavy metals was highest in Mugil cephalus, followed by Arius sagor and Plotosus lineatus. The Fe, Cu and Cr concentrations in Mugil cephalus, Arius sagor and Plotosus lineatus exceeded the international and national MPLs. The liver tissue has the highest capacity to bioaccumulate heavy metals. Regular monitoring of these metals in fish and water sources is recommended to ensure the safety and conservation of coastal swamp wetlands.

***Keywords**: Fish metal accumulation; Bioindicators; Biodiversity threats; Coastal swamp conservation*

Introduction

The coastal swamp wetland is a tidal swamp part of the estuary ecosystem. Wetland habitats are well recognized as highly productive ecosystems, providing favorable conditions for various fish species to flourish. Numerous fish species find refuge, nourishment and reproduction opportunities in coastal swamp wetland environments [1]. Nevertheless, wetland ecosystems also exhibit high sensitivity and ecological vulnerability [2]. Several wetland ecosystems, including coastal swamps, face severe threats from heavy metal contamination. It is essential to promptly address this issue [3]. Due to the ease with which these contaminants enter the food chain, coastal swamp ecosystems are susceptible to the negative impacts of heavy metal contamination. Heavy metals harm coastal swamp ecosystems due to their inherent toxicity, permanence, nonbiodegradability and tendency to bioaccumulate in organisms, a phenomenon known as biomagnification [4]. Heavy metals in coastal wetland habitats are caused by two primary sources of contamination: naturally occurring deposits and human activities, such as waste produced by households, industries and agricultural practices [5, 6]. The coastal swamp ecosystems of Kuala Lupak and Kuala Tambangan are prone to heavy metal contamination due to unregulated waste disposal. Unfortunately, monitoring water quality in

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these places has been neglected, necessitating the deployment of assessments to collect vital information regarding the health of these coastal swamp ecosystems. The presence of heavy metal contamination in wetland ecosystems not only accelerates the decline in water quality but also disrupts delicate biological equilibrium and affects biodiversity. Organisms inhabiting wetland ecosystems, mainly fish, can accumulate heavy metals over long periods, exposing them to the potential for both lethal and sublethal effects linked with these metals [2]. The absence of routine monitoring of heavy metal contamination results in the increasing accumulation of heavy metals in fish, making their recovery a challenging problem. The presence of high levels of heavy metal contamination in fish has substantial long-term effects, including the development of diseases. This poses a significant threat to organisms' health, biological systems' viability and coastal ecosystems' correct functioning [7].

Due to their outstanding capability to accumulate heavy metals, fish have been utilised to evaluate the ecological health of aquatic systems. This characteristic is essential because it is directly related to their trophic location, frequently at the top of the food chain. The presence of heavy metals in fish has histological and lethal significance [2]. Compared to other aquatic animals, fish are more sensitive to the toxicity of heavy metals, making them an ideal indicator of the ecological health of wetland ecosystems [8]. In contrast to organic pollutants, heavy metals are more resistant to decomposition by natural processes. The deposition of heavy metals in sediments is followed by their mobilization up the food chain, which results in biomagnification at higher trophic levels. This problem threatens the health and biodiversity of fish and human populations [3, 9]. Using fish as a biomonitoring instrument for assessing heavy metal concentrations and their subsequent bioaccumulation in aquatic environments is an appropriate and relevant method for determining the bioavailability of heavy metals [10]. Fish are valuable bioindicators in ecological research. They can reveal chronic and acute exposure patterns, provide the prognosis of pollution threats within ecosystems and thoroughly understand trophic and ecosystem health [11]. This assessment is vital to the mitigation procedure for effectively managing coastal swamp ecosystems. The study by Santoso *et al.* [12] concentrated on the mitigation measures utilized to mitigate the negative impacts of heavy metal pollution on giant mudskipper fish in the estuary of the Barito River. However, there has been no exploration of the presence of heavy metal contaminants in commercially consumed fish species, such as mullets (*Mugil cephalus*), eel-tailed catfish (*Plotosus lineatus*) and sea catfish (*Arius sagor*), that coastal residents of South Kalimantan frequently consume. The evaluation of heavy metal deposition in commercial fish is essential for assessing the health of coastal wetland ecosystems and monitoring food safety in the community.

Mullets, or belanak (the local name), are a species of fish that inhabit maritime environments and estuaries and have substantial economic importance. Mullets have a remarkable tolerance for salinity and temperature fluctuations, allowing them to adapt to various dietary sources within their biological niche. Therefore, they commonly inhabit tropical and subtropical coastal and estuarine habitats. Most of a mullet's diet comprises zooplankton, decaying plants, algae and detritus. When the digestive tract is dissected, sometimes it is found that the stomach contents consist of bits of sand and dirt [13]. This species has a gray coloration and the typical length is between 10-47cm, accompanied by an average body mass ranging from 5-176g [14]. Eel-tailed catfish, known as Sembilang locally, is an economically valuable fish resource in estuarine ecosystems. The general public usually consumes this specific fish as a smoked fish, which is immensely popular due to its excellent flavor and nutritious benefits [15]. The average length of the carnivorous eel-tailed catfish is 25-60cm. Its distribution range encompasses maritime regions, river estuaries and freshwater habitats. This aquatic species demonstrates predatory behavior, preying primarily on juvenile fish and benthic creatures, such as gastropods, mollusks and crustaceans. The position of this fish's second dorsal fin along the vertical axis between its anal and pelvic fins is one of its distinguishing characteristics. In addition, its upper lip can grow upward or forwards. The barbels can reach the back of the eye and are predominantly dark brown [16]. In estuarine and marine habitats of tropical and subtropical regions, sea catfish, sometimes known as otek in the local dialect, are frequently observed. This fish species demonstrates a dual habitat strategy, first inhabiting freshwater habitats, then migrating to estuary waters for breeding and finally relocating to the open sea. This particular kind of fish belongs to the group of large demersal fish. This type of fish is typically captured between 250-700mm in length, with the potential to reach a maximum size of 1,500mm. Sea catfish have a predominantly carnivorous and predatory diet, devouring mollusks, gastropods and crustaceans. In Indonesia, sea catfish can be spotted in various coastal settings, particularly where river estuaries meet the ocean. This species is typically found between 20 and 100 meters below the surface. It is distinguished by the presence of adipose fins on its dorsal fin and a stiff plate, such as a butterfly or sagor on its head structure [17].

In South Kalimantan, the coastal swamp wetland ecosystems of Kuala Lupak and Kuala Tambangan are characterized by considerable anthropogenic activities. High levels of maritime transportation activities are present in both ecosystems, including the shipping and unloading of coal and the collection of waste from coal mining operations. The discharge of coal mining waste and the occurrence of coal avalanches during loading and unloading/transportation procedures can lead to the introduction of pollutants into water bodies. The accumulation of these contaminants over a lengthy period has the potential to contaminate estuaries. These procedures generate waste containing iron (Fe), manganese (Mn), mercury (Hg), cadmium (Cd), chromium (Cr), lead (Pb) and copper (Cu) [18]. In addition, this aquatic ecosystem is exposed to waste discharge from both industrial and residential sectors. The Kuala Lupak coastal wetland is distinguished by converting mangrove land into ponds, which serve as a hub for ship traffic and residential communities. Along the riverbanks are several industries, including wood/plywood processing facilities, rubber production, fisheries and oil palm plantations. Therefore, the discharge of waste from these sectors creates a substantial threat of contaminating estuarine waters [19, 20]. Our hypothesis contends that insufficient treatment and subsequent discharge of this waste into water bodies may substantially threaten aquatic ecosystems and human health. Consequently, it is essential to undertake biomonitoring activities to effectively address and mitigate the adverse effects of heavy metal contamination. Accordingly, this study aims to evaluate the levels of heavy metals in aquatic environments and commercially consumed fish species to understand the ecological health of coastal swamp wetland ecosystems. This study intends to shed light on the bioavailability and biomagnification of heavy metals in commercial fish populations. In addition, the results of this study were compared to maximum permissible limits (MPL). This study has been carried out in the coastal swamp of Kuala Lupak and Kuala Tambangan river estuaries, South Kalimantan Province in July 2023.

Materials and Methods

Materials

The study was conducted in the coastal swamp waters of Kuala Lupak river estuaries in the Barito Kuala district and Kuala Tambangan river estuaries in the Tanah Laut district of South Kalimantan Province. The study locations are separated by approximately 60km along the coastline of South Kalimantan, which converges with the southern coast of the Java Sea. Table 1 provides a complete summary of each location and study station, encompassing relevant details. Additionally, Figure 1 graphically represents the sample locations.

Table 1. Study station description

Location	Station	Description
Kuala Lupak	Coastal swamp waters	Kuala Lupak is a wildlife conservation area distinguished by the presence of a mangrove swamp forest environment. The Kuala Lupak River traverses this region and residential areas can be found near its mouth. The waters of the river Kuala Lupak flow into the Java Sea. Samples were collected from the coastal swamp located at coordinates 3°27'28.223"S 114°22'04.780" E.
	Coastal waters	The coastal waters of Kuala Lupak are located approximately 8.0km west of the Barito River's mouth, the largest river in South Kalimantan. A high level of human activities characterizes this river. The coastal region of Kuala Lupak is physically connected to the Java Sea, with a coastline spanning approximately 30km. Mangrove swamp forests dominate the shoreline of Kuala Lupak. The study collected samples from the coastal waters where the Kuala Lupak River discharges at 3°28'02.383"S 114°21'31.282"E.
Kuala Tambangan	Coastal swamp waters	There are fishing settlements and mangrove woods in the vicinity of the Kuala Tambangan estuary, which empties into the Java Sea. In the coastal swamp area of this estuary, numerous fishing vessels operate and anchor. Samples were collected from coastal swamp waters of the river estuary located at coordinates 3.968195" S 114.632223" E.
	Coastal waters	Kuala Tambangan's coastal waters are near the Java Sea, with a coastline of approximately 20km. A large number of fishing vessels and coal ships use the coastal waterways. The samples were collected from the coastal waters located at coordinates 3.968005" S 114.629447" E, in the vicinity of the Kuala Tambangan River discharges.

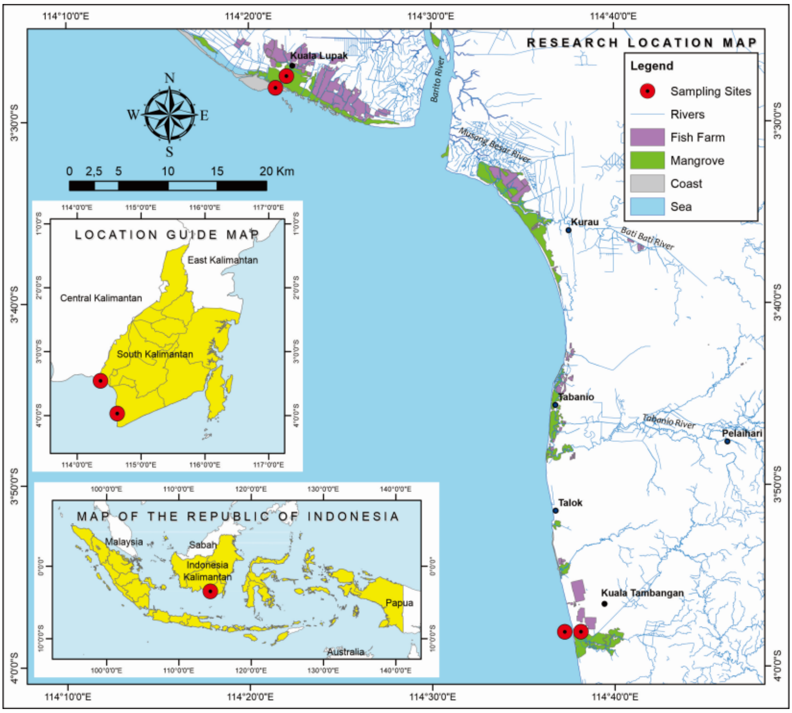

Fig. 1. Study area map and sampling locations in the Kuala Lupak estuary and Kuala Tambangan South Kalimantan, Indonesia

Methods

Water and fish samples were collected in July 2023. The study employed the purposive sampling technique, which involves selecting samples based on predetermined criteria, such as identifying probable contamination sources. Various actions that cause contamination have been considered to pinpoint these sources precisely. Figure 1 shows the collection of fish and water samples at the research location.

Surface water samples were obtained from two stations around the study locations using the Aqua trap water sampler. To facilitate subsequent analysis, a volume of approximately 2mL of concentrated nitric acid (HNO_3) was introduced to each 1.0L after a filtration process. The concentration level of dissolved heavy metals was determined using the liquid–liquid extraction method, as described by Jayaprakash *et al.* [21]. A 100mL unfiltered sample was added to a separating funnel and combined with 2mL of a 2% solution of ammonium pyrrolidine dithiocarbonate (APDC). After vigorous stirring, 10ml of isobutyl methyl ketone (IBMK) was used for the extraction process. The resulting aqueous phase was then treated for further extraction using strong HNO_3 and high-purity water. Atomic absorption spectrometry (AAS Thermo Scientific ICE 3500 series Germany) was used to examine the final solution after any traces of organic solvents in the solutes were evaporated on a low-temperature hot plate. The AAS was used to quantify lead (Pb), mercury (Hg), cadmium (Cd), zinc (Zn), iron (Fe), copper (Cu) and chromium (Cr) concentrations in both water and fish samples. The concentration of water was quantified in micrograms per liter (μgL^{-1}). Finally, the samples for metal analysis were properly prepared following established procedures Jayaprakash *et al.* [21].

The fish samples included *Plotosus lineatus*, *Arius sagor* and *Mugil cephalus*. Local fishermen obtained these specimens from coastal swamp wetland waters (Fig. 2).

Fig. 2. Fish species used in the Study A: *Mugil cephalus*; B: *Arius sagor*; C: *Plotosus lineatus*

To ensure representativeness, a sample size of 15 fish per species was taken from each station (coastal swamp and coastal) and sampling location (Kuala Lupak and Kuala Tambangan). The identification of the fish samples was also used cross-referencing with the information from Kottelat *et al.* [22]. This was done to ensure that the classification of the species as either commercial or noncommercial and the determination of its name, family, diet, habitat and type were accurate. To preserve and keep the samples in the best possible condition for further analysis, they were carefully transported to the lab in an insulated container filled with ice. In addition, fish dissection entails using ice cubes to protect the animals and surgical tools made of stainless steel to help remove the liver, muscles and skin tissues. A digestion tube preloaded with 5mL of HNO_3 and sulfuric acid (H_2SO_4) was used for each organ sample to activate the reaction. A hot block digestion equipment kept at 60°C for 30 minutes was used to process the samples. After the samples were cooled, 10mL of HNO_3 was added and the mixture was then heated at temperatures between 120 and 150°C until the solution developed a distinctly dark color. One milliliter of hydrogen peroxide (H_2O_2) was added to the mix to produce a clear solution, which aided the filtration procedure. These filtered samples were then subjected to an AAS analysis to determine the number of heavy metals in the fish tissues, expressed in $mg \cdot kg^{-1}$. The limits of detection used for analysis of Pb, Cd, Zn, Fe, Cr, Cu and Hg were 0.001, 0.001, 0.001, 0.006, 0.002, 0.007 and 0.00004$mgkg^{-1}$, respectively.

Statistical analysis

The collected data about heavy metal concentrations in water bodies and fish tissues met the assumptions required to analyze variance (ANOVA), specifically normality and homogeneity. Therefore, factorial ANOVA can be used to diagnose the data correctly. Then, a post hoc test, precisely Tukey's honestly significant difference (Tukey's HSD) test, with a 95% confidence level was used to identify the difference in treatment ($P < 0.05$). The information is presented in tabular form, showing the means±SDs. To determine the relationship between heavy metal concentration variables in water and fish tissues, Pearson correlation analysis was used at a 95% confidence level. The statistical analysis was performed using version 9.4 of the Statistical Analysis System (SAS) software (SAS institute North Carolina State University).

Results and discussion

Heavy metal concentrations in the water column

The water samples collected at the research location exhibited a range of heavy metal concentrations, spanning from 0.075 to 620μgL^{-1}. At the Kuala Lupak location, the water shows varying concentrations of heavy metals. The Fe concentration is the highest at 620μgL^{-1}, while the Hg concentration is the lowest at 0.075μgL^{-1}. In the Kuala Tambangan location, the highest concentration is Fe at 370μgL^{-1} while the lowest is Cd at 0.19μgL^{-1}, as indicated in Table 2. Heavy metal concentrations in water were significantly different at the locations of Kuala Lupak and Kuala Tambangan ($P < 0.05$). Cd, Cr, Cu, Fe, Pb and Zn concentrations in the water at the Kuala Lupak location are higher than those at the Kuala Tambangan location. Except for Cr, the results of comparing the concentrations of seven different heavy metals in water at two designated stations suggest no statistically significant changes. The concentration of Cr in the coastal swamp is more significant than that of the coast, as seen in Table 2.

Table 2. The concentration of heavy metals in water bodies at the study location

Station	Consentration (μgL^{-1})						
	Cd	Cr	Cu	Fe	Hg	Pb	Zn
Coastal swamp	0.20±0.00^a	15±0.00^a	43±0.024^a	495±0.137^a	0.198±0.135^a	0.97±0.00002^a	21±0.016^a
Coastal	0.20±0.00^a	14±0.001^b	43±0.025^a	494±0.133^a	0.186±0.122^a	0.95±0.00004^a	20±0.015^a
Location							
Kuala Lupak	0.21±0^a	15±0^a	65±0.001^a	620±0.00^a	0.075±0.001^b	0.98±0.00001^a	35±0.001^a
Kuala Tambangan	0.19±0^b	14±0^b	21±0.001^b	370±0.00^b	0.309±0.013^a	0.93±0.00002^b	6±0.00^b

Values are the mean and SD. According to the Honestly Significant Difference test with a 95% confidence level, values followed by various letters on the same type of metal reveal a significant difference

This indicates that the coastal swamp and coastal stations do not significantly impact the amounts of heavy metals in the water ($P > 0.05$). In this study, the general order of heavy metal concentrations in water was Fe > Cu > Zn > Cr > Pb > Cd > Hg. Table 3 demonstrates that Fe has the highest concentration in water bodies based on the findings of this study and prior research conducted at estuaries or coastal stations in various parts of the world. Even though the concentrations of just three heavy metals (Fe, Cu and Zn) were found to be excessive in comparison to earlier studies conducted in estuaries of other countries, the total results of this study, except for Fe, remained below the limits set by the World Health Organization (WHO) and the United States Environmental Protection Agency (USEPA). The provisions of Indonesia Government Regulation No. 22 of 2021 on the Implementation of Environmental Protection and Management, specifically regarding the seawater quality criteria for marine biota, determined that the concentrations of Fe, Cu and Cr are above the MPL listed in Table 3.

It is necessary to assess heavy metal pollution in coastal wetland ecosystems to comprehend the status of contamination, emission sources and environmental behavior, given the importance of wetland ecosystems in maintaining environmental stability and providing essential ecological services, particularly for protecting rich biodiversity and conservation. In addition, knowledge regarding the amounts of heavy metals in water and commercial fish is vital to ensuring the safety of human food consumption [23].

Table 3. Heavy metal concentrations (μgL^{-1}) in coastal swamps of Kuala Lupak and Kuala Tambangan and other parts of the world

Study site	Cd	Cr	Cu	Fe	Hg	Pb	Zn	References
Kuala Lupak estuary, Indonesia	0.21	15	65	620	0.075	0.98	35	Present study
Kuala Tambangan estuary, Indonesia	0.19	14	21	370	0.309	0.93	6	Present study
Southeast coast of India	1.34	2.16	3.04	67.16	-	3.65	31.72	Adani *et al*. [7]
Karachi coasts of Pakistan	5.64	6.83	8.12	24.21	-	21.21	-	Mehar *et al*. [24]
Great Vedarnyam Swamp, India	0.1	2.9	0.1	-	1.5	1.4	0.3	Pandiyan *et al*.[1]
Yangtze River Estuary, China	0.0413	0.279	1.47	-	0.0363	0.829	8.91	Fan *et al*. [25]
San Carlo, Southern Atlantic coast of Spain	0.1	0.5	1.6	8	< 0.1	0.5	12	Usero *et al*. [26]
USEPA	5	100	1300	300	-	15	5000	USEPA (2018)
WHO	3	50	2000	300	-	10	3000	WHO (2008)
Indonesia Gov. Reg. No. 22 of 2021	1	5	8	300	1	8	50	Indonesia Gov. Reg. No. 22 of 2021

International and National Guidelines values: WHO-World Health Organization; USEPA-United States Environmental Protection Agency; Indonesia Government Regulation No. 22 of 2021 on the Implementation of Environmental Protection and Management specifically regarding the seawater quality criteria for marine biota

According to the findings, it has been observed that the coastal swamp waters of South Kalimantan exhibit the highest concentration of Fe (370 and 620μgL^{-1}). This observation is consistent with the earlier findings of researchers from three other countries, implying that increased Fe levels are the primary characteristic of estuary water pollution. Nonetheless, the concentration of Fe in this study exceeds the Fe values found on the southeastern coast of India (67.16μgL^{-1}) [7], Karachi coast of Pakistan (24.21μgL^{-1}) [24] and San Carlos coast of Spain (8μgL^{-1}) [26] (Table 3). Increased Fe concentrations in estuarine and coastal waters may result from natural events such as terrestrial geological processes (weathering and decomposition of rocks and ore materials) and volcanic eruptions, which are released into water bodies through runoff, erosion and flooding. In addition, Fe is produced by human activities such as coal transportation loading and unloading and mining operations [27]. Other anthropogenic activities on land, such as domestic waste, industrial waste and corrosion of water pipelines delivered by rivers to estuaries, also increase Fe concentrations. Iron (Fe^{2+}) is released by the oxidation of iron pyrite (FeS_2) in coal seams to sulfuric acid and sulfur [28]. Toxic heavy metals also come from agricultural waste disposal, agricultural runoff, mine surface drainage, irrigation return flow, urban rainwater discharge and leachate water [2], the removal of mangrove vegetation and coastal development (ports, industrial districts and civil engineering works) [3]. Near the study location, shipping transportation activities, loading and unloading of coal on barges, coal transportation, industrial areas and activities on riverbank land, residential areas, agricultural activities and the conversion of mangrove land into fishing/farming land were observed.

Heavy metal concentrations in various tissues of different fish species

Table 4 shows that the highest Cd concentration in the liver of *Arius sagor* was found in the Kuala Tambangan estuary (0.072$mgkg^{-1}$), which was substantially different from the coast ($P < 0.05$). The lowest Cd concentration (0.001$mgkg^{-1}$) was found in the muscle and skin tissue of the examined fish species. The liver of *Mugil cephalus* in the Kuala Tambangan estuary had the highest Cr concentration (6.70$mgkg^{-1}$). The skin of *Plotosus lineatus* in the estuary (0.49$mgkg^{-1}$) and the coast of Kuala Tambangan (0.46$mgkg^{-1}$) exhibited the lowest Cr concentration. The liver of *Plotosus lineatus* from the Kuala Lupak estuary had the most Cu (14.48$mgkg^{-1}$). In comparison, the skin and muscle of *P. lineatus* from the Kuala Tambangan estuary and coast contained the least (0.01$mgkg^{-1}$). The liver of *M. cephalus* in the estuary (800.97$mgkg^{-1}$) and coast (800.91$mgkg^{-1}$) of Kuala Tambangan contained the highest quantity of Fe ($P > 0.05$). In contrast, the skin of *P. lineatus* in the estuary and coast of Kuala

Tambangan had the lowest Fe concentrations (17.73 and 17.72mgkg^{-1}, respectively). The same Hg concentration (0.00004mgkg^{-1}) was identified in three tissues from three test species at two locations and two stations (Table 5). The highest Pb concentration was found in the liver of *M. cephalus* from the Kuala Lupak coast (0.701mgkg^{-1}). Nevertheless, the skin and muscles of the three test species collected Pb at the same concentration between the estuary and coastal stations, precisely 0.001mgkg^{-1} (Table 6). Table 6 depicts the estuary (64.41mgkg^{-1}) and coast (64.39mgkg^{-1}) of Kuala Lupak as having the highest Zn concentration in the liver of *A. sagor* ($P > 0.05$). The muscle of *P. lineatus* from the estuary and coast of Kuala Lupak had the lowest Zn concentration (0.72 and 0.70mgkg^{-1}; $P > 0.05$). The findings of this study indicate that liver tissue exhibited the highest bioaccumulation of heavy metals, with skin and muscle following suit in terms of their respective levels of bioaccumulation. The amounts of Fe, Cu, Cr, Zn and Pb in the liver tissue of *M. cephalus* were significantly higher than those detected in the liver tissue of *A. sagor* and *P. lineatus*. Based on the geographical positioning, it may be inferred that the coastal swamps of Kuala Lupak are more heavily contaminated with heavy metals than those of Kuala Tambangan. Based on a combination of different locations, stations, species and fish tissues, the order of heavy metal concentrations in this finding is Fe > Zn > Cu > Cr > Pb > Cd > Hg. Iron is the predominant heavy metal polluting the coastal swamp waters of South Kalimantan's Kuala Lupak and Kuala Tambangan.

Table 4. Concentrations of Cd, Cr and Cu in various tissues of different fish species

Species	Loc	Sta.	Concentration (mgkg^{-1})								
			Cd			Cr			Cu		
			Muscles	Liver	Skin	Muscles	Liver	Skin	Muscles	Liver	Skin
Mugil cephalus	KL	E	0.001±0.0e	0.048±0.001c	0.001±0.0e	1.68±0.00	1.63±0.01	1.53±0.00	6.87±0.00	1.92±0.00	1.86±0.00
		C	0.001±0.0e	0.041±0.001d	0.001±0.0e	1.68±0.01	1.6±0.03	1.51±0.00	6.85±0.01	1.91±0.02	1.83±0.01
	KT	E	0.001±0.0e	0.001±0.0e	0.001±0.0e	1.48±0.00	6.70±0.00a	0.96±0.01	1.22±0.01	10.98±0.01c	0.45±0.00
		C	0.001±0.0e	0.001±0.0e	0.001±0.0e	1.47±0.01	6.67±0.01a	0.91±0.01	1.16±0.03	10.87±0.01d	0.44±0.01
Arius sagor	KL	E	0.001±0.0e	0.001±0.0e	0.001±0.0e	1.81±0.00	1.25±0.03	0.88±0.01	2.63±0.01	10.11±0.01	1.51±0.00
		C	0.001±0.0e	0.001±0.0e	0.001±0.0e	1.79±0.02	1.23±0.00	0.81±0.01	2.62±0.01	10.09±0.03	1.49±0.00
	KT	E	0.001±0.0e	0.072±0a	0.001±0.0e	2.58±0.00b	2.12±0.00d	2.03±0.01	0.77±0.01	4.03±0.00	1.1±0.00
		C	0.001±0.0e	0.062±0b	0.001±0.0e	2.52±0.01c	2.11±0.01d	2.01±0.01	0.57±0.01	4.01±0.00	1.09±0.01
Plotosus lineatus	KL	E	0.001±0.0e	0.001±0.0e	0.001±0.0e	0.74±0.00	1.54±0.01	1.47±0.00	2.18±0.01	14.48±0.01a	2.93±0.01
		C	0.001±0.0e	0.001±0.0e	0.001±0.0e	0.72±0.01	1.44±0.03	1.45±0.01	2.15±0.01	14.43±0.02b	2.87±0.01
	KT	E	0.001±0.0e	0.001±0.0e	0.001±0.0e	1.2±0.00	1.63±0.00	0.49±0.01u	0.01±0.00w	9.39±0.00	0.01±0.00w
		C	0.001±0.0e	0.001±0.0e	0.001±0.0e	1.19±0.01	1.61±0.01	0.46±0.01u	0.01±0.00w	9.36±0.00	0.01±0.00w
Permissible limits in fishes			0.50 (FAO)			0.15 (WHO) 1 (US FDA) 2.5 (BPOM RI)			3 (WHO) 30 (FAO)		

Loc.: location; KL: Kuala Lupak; KT: Kuala Tambangan; Sta.: station; E: estuarine/coastal swamp; C: coastal. Values are the mean and SD. Mean±std.dev followed by different letters for the same type of metal shows a significant difference based on Tukey's HSD post hoc test with a 95% confidence level;
FAO (Food and Agriculture Organization of the United Nations, 1983); WHO (World Health Organization) Expert Committee on Food Additives (1989); US FDA (United States Food and Drug Administration); BPOM RI (Food and Drug Supervisory Agency of the Republic of Indonesia, 2018)

Table 5. Concentrations of Fe and Hg in various tissues of different fish species

Species	Loc.	Sta.	Concentration (mgkg^{-1})					
			Fe			Hg		
			Muscles	Liver	Skin	Muscles	Liver	Skin
Mugil cephalus	KL	E	21.83±0.00	515.55±0.01b	31.12±0.00	0.00004±0	0.00004±0	0.00004±0
		C	21.82±0.01	515.47±0.02b	31.09±0.00	0.00004±0	0.00004±0	0.00004±0
	KT	E	26.96±0.01	800.97±0.00a	47.31±0.01	0.00004±0	0.00004±0	0.00004±0
		C	26.92±0.01	800.91±0.01a	47.29±0.01	0.00004±0	0.00004±0	0.00004±0
Arius sagor	KL	E	22.24±0.01	300.28±0.06c	22.87±0.00	0.00004±0	0.00004±0	0.00004±0
		C	22.21±0.01	300.34±0.03c	22.83±0.01	0.00004±0	0.00004±0	0.00004±0
	KT	E	25.28±0.00	25.61±0.00	26.45±0.01	0.00004±0	0.00004±0	0.00004±0
		C	25.23±0.01	25.55±0.01	26.43±0.01	0.00004±0	0.00004±0	0.00004±0
Plotosus lineatus	KL	E	24.91±0.00	266.33±0.01	20.18±0.00u	0.00004±0	0.00004±0	0.00004±0
		C	24.2±0.07	265.92±0.52	20.15±0.01u	0.00004±0	0.00004±0	0.00004±0
	KT	E	21.48±0.01	147.12±0.00	17.73±0.01v	0.00004±0	0.00004±0	0.00004±0
		C	21.41±0.01	145.12±0.01	17.72±0.01v	0.00004±0	0.00004±0	0.00004±0
Permissible limits in fishes				100 (WHO) 1 (SNI 7387:2009)			0.0005 (US FDA)	

Loc.: location; KL: Kuala Lupak; KT: Kuala Tambangan; Sta.: station; E: estuarine/coastal swamp; C: coastal. Values are the mean and SD. Mean±std.dev followed by different letters for the same type of metal shows a significant difference based on Tukey's HSD post hoc test with a 95% confidence level;
WHO (World Health Organization) Expert Committee on Food Additives (1989); SNI 7387:2009 (Indonesian National Standard: Maximum limits for heavy metal contamination in food); US FDA (United States Food and Drug Administration)

Table 6. Concentrations of Pb and Zn in various tissues of different fish species

Species	Loc.	Sta.	Concentration ($mgkg^{-1}$)					
			Pb			Zn		
			Muscles	Liver	Skin	Muscles	Liver	Skin
Mugil cephalus	KL	E	0.001±0c	0.698±0b	0.001±0c	17.98±0.01	17.95±0.04	26.01±0.01
		C	0.001±0c	0.701±0a	0.001±0c	17.92±0.01	17.93±0.02	25.89±0.02
	KT	E	0.001±0c	0.001±0c	0.001±0c	9.61±0.01	20.69±0.01	6.22±0.01
		C	0.001±0c	0.001±0c	0.001±0c	9.46±0.01	20.51±0.02	6.21±0.01
Arius sagor	KL	E	0.001±0c	0.001±0c	0.001±0c	7.91±0.00	64.41±0.01a	17.41±0.00
		C	0.001±0c	0.001±0c	0.001±0c	7.84±0.03	64.39±0.02a	17.24±0.01
	KT	E	0.001±0c	0.001±0c	0.001±0c	12.85±0.01	14.97±0.00	23.67±0.01
		C	0.001±0c	0.001±0c	0.001±0c	12.65±0.01	14.93±0.00	23.45±0.02
Plotosus lineatus	KL	E	0.001±0c	0.001±0c	0.001±0c	0.72±0.00z	34.62±0.01b	8.41±0.00
		C	0.001±0c	0.001±0c	0.001±0c	0.70±0.02z	34.59±0.03b	8.35±0.01
	KT	E	0.001±0c	0.001±0c	0.001±0c	4.61±0.01	31.08±0.00	4.43±0.00z
		C	0.001±0c	0.001±0c	0.001±0c	4.59±0.01	32.08±0.01c	4.42±0.01z
Permissible limits in fishes			0.5 (FAO) 2 (WHO) 0.3 (SNI 7387:2009)			30 (FAO) 100 (WHO) 100 (BPOM RI)		

Loc.: location; KL: Kuala Lupak; KT: Kuala Tambangan; Sta.: station; E: estuarine/coastal swamp; C: coastal. Values are the mean and SD. Mean±std.dev followed by different letters for the same type of metal shows a significant difference based on Tukey's HSD post hoc test with a 95% confidence level
FAO (Food and Agriculture Organization of the United Nations, 1983)
WHO (World Health Organization) Expert Committee on Food Additives (1989)
BPOM RI (Food and Drug Supervisory Agency of the Republic of Indonesia, 2018)
SNI 7387:2009 (Indonesian National Standard: Maximum limits for heavy metal contamination in food)

According to the Pearson correlation analysis presented in Table 7, a significant and positive association is observed between heavy metal concentrations in water bodies and the tissues of *M. cephalus*, specifically the liver (r = 0.782), muscles (r = 0.665) and skin (r = 0.683). These findings indicate that as the concentration of heavy metals in the water increases, there is a corresponding increase in the concentration of heavy metals in the tissues above. A significant and positive correlation also exists between the concentration of heavy metals in water and the corresponding concentration found in the liver (r = 0.780), muscles (r = 0.732) and skin (r = 0.560) of *Arius sagor*. A significant and positive correlation between the concentrations of heavy metals found in water bodies and the corresponding concentrations was also observed in the tissues of *Plotosus lineatus*, specifically the liver (r = 0.885), muscles (r = 0.864) and skin (r = 0.812). In general, the liver tissue of the three test fish species exhibited the most significant and positive correlation with concentrations of heavy metals in aquatic environments.

Table 7. Correlation of heavy metal concentrations in water and heavy metal concentrations in different tissues in different fish species

Mugil cephalus	Liver	Muscles	Skin	Water
Liver	1			
Muscles	.842**	1		
Skin	.901**	.972**	1	
Water	.782**	.665**	.683**	1
Arius sagor				
Liver	1			
Muscles	.647**	1		
Skin	.565**	.942**	1	
Water	.780**	.732**	.560**	1
Plotosus lineatus				
Liver	1			
Muscles	.964**	1		
Skin	.948**	.953**	1	
Water	.885**	.864**	.812**	1

The numbers displayed are correlation coefficient values; coefficients followed by
* indicate a relationship between two variables at the 95% confidence level. Correlation at level $P < 0.05$;
** Correlation at level $P < 0.001$

Estuaries are known as "sinks," dilution sites and storage grounds for heavy metal-containing waste from land and rivers [29]. Due to dredging activities, massive transportation, waves and storms, silt is remobilized and particles containing heavy metals are mixed back up from sediment polluted with heavy metals, increasing the concentration of dissolved heavy metals in water bodies [29]. Therefore, aquatic biota, including fish, readily absorb and accumulate heavy metals through their food, skin and gills from contaminated water bodies and sediments. Concentrations of heavy metals in fish mainly refer to heavy metal concentrations in water bodies and sediments that fish typically inhabit [30]. This is consistent with the finding that there is a significant and positive correlation between the concentration of heavy metals in the water and the concentration of heavy metals in the tissues of the test fish (Table 7). Yogeshwaran *et al.* [31] and Soltani *et al.* [32] revealed that the bioaccumulation of heavy metals in estuarine aquatic biota is closely correlated with water contamination. Heavy metals are present in marine biota due to their abundance in water bodies, sediments and fish diets. Deposits include diverse forms of heavy metals, including dissolved, bonded to suspended particles and accumulated, which increases their assimilation into biological processes. The accumulation of heavy metals in fish at concentrations surpassing the threshold value (MPL) can harm human health [5, 33]. It has been reported that the accumulation of metals in fish tissues beyond permissible limits has severe implications that negatively affect fish populations and humans [34]. To reduce the potential health risks connected with fish consumption, it is essential to detect and quantify the levels of heavy metals in commonly consumed commercial fish species.

These data suggest that the liver of *M. cephalus* contains the highest concentration of heavy metals, while the skin of *P. lineatus* contains the lowest. Despite living in identical ecological settings, the three test fish species exhibited differences in metal accumulation that might be attributed to differences in eating preferences, trophic levels, living behavior and heavy metal contamination gradients [21]. Due to its diet of zooplankton, dead plants and sedimentary material, *Mugil cephalus* accumulates the heaviest metals. Upon dissection, the digestive tract of *M. cephalus* carries sand or dirt [13]. The study by Santoso *et al*. [12] revealed that Fe (13.704.410mgkg^{-1}), Zn (81.863mgkg^{-1}), Cu (37.635mgkg^{-1}), Pb (23.772mgkg^{-1}) and Cd (1.142mgkg^{-1}) were found in high concentrations in sediments in the coastal swamp waters of South Kalimantan, indicating that fish that consume sediment detritus and live in a polluted environment will accumulate more heavy metals than other fish species. Fish may easily bioaccumulate several types of heavy metals from water, sediments and aquatic foods [24].

The Fe concentrations in the test fish tissues ranged between 17.72 and 800.94mgkg^{-1}, above the MPL set by the WHO (100mgkg^{-1}) and SNI 7387:2009 (1mg/kg). The liver of *Mugil cephalus* contained the highest concentration of Fe (800.97mgkg^{-1}), whereas the skin of *Plotosus lineatus* contained the lowest concentration (17.72mgkg^{-1}). The Fe concentration in the liver of *M. cephalus* in this study (800.97mg/kg) was more significant than that in previous similar studies conducted by Fazio *et al.* [35] in the Black Sea of Bulgaria (502.300mgkg^{-1}), Karadede *et al.* [36] in Turkey (200.86mgkg^{-1}), Usero *et al.* [26] in the southern Atlantic coast of Spain (199mgkg^{-1}), El-hak *et al.* [37] in Lake Manzala in Egypt (85.08mgkg^{-1}) and Fazio *et al.* [35] in the Ionian Sea of Italy (33.150mgkg^{-1}). These studies indicated that Fe is the primary pollutant and that the liver is the organ that bioaccumulates heavy metals. The liver of *M. cephalus* accumulated the most Fe, Cu, Cr, Zn and Pb in this study, followed by the livers of *A. sagor* and *P. lineatus*. According to Zaoui *et al.* [30], the liver accumulates the highest amount of heavy metals as fish absorb them from their environment. The accumulation of heavy metals in the liver may be related to its metabolic function. High amounts of heavy metals in liver tissues are often associated with a natural binding protein, such as metallothionein, which serve as a necessary metal store (i.e., Zn and Cu) to meet enzymatic and other metabolic requirements. Fe also tends to accumulate in liver tissues due to the physiological role of the liver in the formation of red blood cells and hemoglobin [6]. In addition, the elevated metal concentrations identified in the liver may result from its metabolic activity, allowing it to accumulate high metal concentrations. High metal concentrations in the liver may indicate that this organ stores sequestered products. When assessing metal contamination in aquatic environments, the liver is often recommended as a target tissue [38]. The liver is the primary organ responsible for metal accumulation among fish organs. The liver is involved in the natural binding of metallothionein (MT) proteins and plays an essential role in trace metal metabolism in fish. Due to its more significant metabolic activity and function of storing and transporting metals throughout the body, the liver accumulates more than the muscle. In addition, the liver is essential for detoxification [39]. Lower metal accumulation in skin and muscle results from a decreased susceptibility for fat to absorb or combine with heavy metals and a reduced metabolic rate [40].

The highest concentration of Fe in the muscles was found in *M. cephalus* (26.96mgkg^{-1}), while *P. lineatus* had the lowest (21.02mgkg^{-1}). This result is higher than previous findings *on M. cephalus* muscles by El-hak *et al*. [37] in Lake Manzala in Egypt (13.29mgkg^{-1}), Fazio *et al.* [35] in the Black Sea of Bulgaria (11.06 mgkg^{-1} and in the Ionian Sea of Italy (5.92mgkg^{-1}), Karadede *et al.* [36] in Ataturk Dam Lake in Turkey (6.88mgkg^{-1}), Usero *et al.* [26] in the San Carlos estuary of Spain (4.11mgkg^{-1}) and Albuquerque *et al.* [3] in the Maranhao estuary of Brazil (0.72mgkg^{-1}). Muscles were examined for metal contamination since it is the final site of metal contamination and the portion of fish most frequently consumed by humans [2]. The concentration of Fe in the skin of *M. cephalus* was the highest (47.31mgkg^{-1}), while that of *P. lineatus* was the lowest (17.73mgkg^{-1}). Lakra *et al.* [34] discovered lower Fe concentrations in catfish skin (36.18mgkg^{-1}) from India's coal mine waste. Possibly due to the continual release of mucus and shedding of dead cells, the buildup of heavy metals in the skin was not as significant as that reported in the liver. The skin possesses mucogenic activity and vigorous mucus exfoliation to remove clinging toxins; as a result, its concentration is lower than that of the liver [41].

In this study, Zn concentrations were detected in all fish tissue samples. The Zn concentration ranges from 0.70 to 64.41mgkg^{-1}, above the FAO MPL of 30mgkg^{-1} but still below the BPOM RI MPL of 100mgkg^{-1}. The highest Zn content was found in the liver of *A. sagor* (64.41mgkg^{-1}), while the lowest concentration was found in the muscle of *P. linealtus* (0.70mgkg^{-1}). This finding is higher than previous findings in *M. cephalus* liver by Usero *et al.* [26] in San Carlos estuary of Spain (38.40mgkg^{-1}), Fazio *et al.* [35] in the Ionian Sea of Italy (30.00mgkg^{-1}) and Black sea of Bulgaria (18.48mgkg^{-1}), Al-Kazaghly *et al.* [42] off the Zliten coast of Libya (25.27mgkg^{-1}), but these findings are relatively similar to previous results by Hauser-Davis *et al.* [43] in the liver of *M. cephalus* in Itaipu beach of Brazil (64.61mgkg^{-1}). In this study, the Zn concentration in muscles was highest in *A. sagor* (17.98mgkg^{-1}), higher than previous findings in *A. sagor* muscles by Pandion *et al.* [44] in Kalpakkam coast of India (0.90mgkg^{-1}), Usero *et al.* [26] in San Carlos estuary of Spain (3.87 mgkg^{-1}), Albuquerque *et al.* [3] in Maranhao estuary of Brazil (0.09mgkg^{-1}), Fazio *et al.* [35] in the Black Sea of Bulgaria (4.53mgkg^{-1}), Al-Kazaghly *et al.* [42] off the Zliten coast of Libya (5.90mgkg^{-1}), Karadede *et al.* [36] in Atatu¨rk Dam Lake in Turkey (7.74mgkg^{-1}). However, this finding is lower than previous findings by Fazio *et al.* [35] on *M. cephalus* muscles in the Ionian Sea Italy (19.30mgkg^{-1}) and Darvish *et al.* [45] in the Persian Gulf (18.75mgkg^{-1}). *M. cephalus* has the highest levels of Zn in its skin (26.01mgkg^{-1}). The majority of fish species receive Zn through their diet. Zn is crucial for metabolic activities and the proper functioning of many enzymes; hence, fish consume vast amounts of Zn, resulting in increased levels of Zn in fish tissues [46]. Zn is a necessary element for metabolic activities and a cofactor for several enzymes involved in these processes. Despite this, Zn poisoning is marked by nausea, diarrhea, fever, lethargy and fatigue. Zinc metalloenzymes and Zn^{2+}-protonated enzymes can also cause Zn accumulation by generating five- or six-membered stable ring chelates [47]. The primary sources of zinc in estuarine waterways include wastewater from the textile industry, detergent waste, waste from crude oil production, refineries, brass manufacture, metal plating and immersion of painted idols [47-48].

Cu concentrations in the fish tissues ranged from 0.01 to 14.48mgkg^{-1}, above the WHO MPL (3mgkg^{-1}). The highest Cu content was identified in the liver of *P. lineatus* (14.48mgkg^{-1}), while the lowest concentration was found in the skin and muscle of *P. lineatus* (0.01mgkg^{-1}). This finding is lower than previous findings in *M. cephalus* liver by Usero *et al.* [26] in the San Carlos estuary of Spain (17.00mgkg^{-1}), El-hak *et al.* [37] in Lake Manzala in Egypt (19.79mgkg^{-1}), Fazio *et al.* [35] in the Black Sea of Bulgaria (68.62mgkg^{-1}) and Karadede *et al.* [36] in Atatu¨rk Dam Lake in Turkey (267.86mgkg^{-1}). In this study, the muscles of *M. cephalus* had the highest Cu concentration (6.87mgkg^{-1}), while *P. lineatus* skin tissue had the highest Cu concentration (2.88mgkg^{-1}). Cu is a known essential element in fish, plays a vital role in enzymatic activities and is required to synthesize hemoglobin. However, excessive intake will have negative health consequences [49]. Cu is an essential metal that facilitates iron release during hemoglobin synthesis. Cu can cause liver, kidney and brain damage and even death at high doses and with prolonged exposure [50]. Through mercapto and disulfide, Cu deposited in the liver forms tetrahedral metallothionein and metalloenzyme complex species [47]. Increased water transportation by boats and ships, repeated application of antifouling paint, oil discharge/leakage from ship engines, mining, electroplating, pesticides and commercial fishing operations are all associated with the rise in Cu concentrations in water [48, 51].

In this study, the Cr concentration in fish tissues ranged from 0.46 to 6.70mgkg^{-1}, above the WHO MPL (0.15mgkg^{-1}), US FDA (1mgkg^{-1}) and BPOM RI (2.5mgkg^{-1}). The highest Cr concentration was discovered in the liver of *M. cephalus* (6.70mgkg^{-1}), while the lowest was in the skin of *P. lineatus* (0.46mgkg^{-1}). The results of this study were higher than previous findings in *M. cephalus* liver by Usero *et al.* [26] in the San Carlos estuary of Spain (0.029mg/kg) and Fazio *et al.* [35] in the Ionian Sea of Italy (0.1506mgkg^{-1}) and in the Black Sea of Bulgaria (0.1303mg/kg). *Arius sagor* had the highest Cr concentration in its muscles (2.58mgkg^{-1}), whereas *P. lineatus* had the lowest (0.50mgkg^{-1}). This result is higher than previous findings in *M. cephalus* muscles by Albuquerque *et al.* [3] in the Maranhao estuary of Brazil (0.11mgkg^{-1}) and Fazio *et al.* [35] in the Ionian Sea of Italy (0.0213mgkg^{-1}) and in the Black Sea of Bulgaria (0.1809 mgkg^{-1}). *Arius sagor* has the highest concentration of Cr in its skin (2.03mgkg^{-1}). As a microelement with a critical role in glucose metabolism, Cr is considered a particularly hazardous pollutant. Although Cr is needed for glucose, lipid and protein metabolism, high concentrations of Cr are toxic to the liver, kidney and endocrine system [3]. Due to its higher availability, Cr is more readily absorbed by fish in estuaries, either directly from the water or indirectly through the food ingested. The rise in Cr concentration in waterways indicates that Cr is present in various oxidation states and is increasingly utilized in industrial applications [51]. Cr is produced by the mining, electroplating, textile and tannery industries [48]. For coastal communities that rely on local catches for sustenance, high concentrations of Cr in estuaries from anthropogenic causes are of great concern [3].

This study found that Pb concentrations in fish tissue ranged from 0.001 to 0.701mgkg^{-1}. The Pb concentration in the liver of *M. cephalus* was above the FAO MPL (0.5mgkg^{-1}) and SNI 7387:2009 (0.3mgkg^{-1}), but the values in *A. sagor* and *P. lineatus* were within the MPL. The highest Pb concentration was found in the liver of *Mugil cephalus* (0.701mgkg^{-1}), while the lowest value was found in the muscle and skin of all fish species (0.001mgkg^{-1}). The liver is presumably the target organ for Pb accumulation, resulting in low Pb concentrations in the muscles and skin. These data show lower Pb concentrations in the liver of *A. sagor* than in prior studies by Abdel-Warith *et al.* [52] in Saudi Arabia (5.54mgkg^{-1}), in *M. cephalus* liver by El-hak *et al.* [37] in Lake Manzala in Egypt (6.83mgkg^{-1}), but higher when compared to *M. cephalus* liver by Al Kazaghly *et al.* [42] off the Zliten coast of Libya (0.64mgkg^{-1}). This study found that the Pb concentrations in the muscles of *A. sagor* were lower than those in prior studies by Abdel-Warith *et al.* [52] in Saudi Arabia (1.27mgkg^{-1}), Pandion *et al.* [44] on the Kalpakkam coast of India (0.30mgkg^{-1}), El-hak *et al.* [37] in *M. cephalus* muscles (7.04mgkg^{-1}) in Lake Manzala in Egypt and Usero *et al.* [26] in the San Carlos estuary of Spain (0.04mgkg^{-1}). This study revealed lower Pb concentrations in the skin compared to an earlier study on *A. sagor* in Saudi Arabia (0.32mgkg^{-1}) [52]. Pb is the most common and widespread hazardous metal and it can be found in the civil construction industry, metal alloys, rainfall-runoff, refineries, marinas, fish processing industries, paint, pesticides, batteries, car emissions, mining and coal combustion [48]. Pb is highly toxic and harmful to human health. Toxicity in marine and estuarine organisms is proportional to the chemical form that is available and absorbed, with organic form absorption posing the most significant threat [23].

The Cd concentration in test fish tissues ranged between 0.001 and 0.072mgkg^{-1}, below the FAO MPL (0.50mgkg^{-1}). The Cd concentration in the muscles and skin of all fish samples was the same (0.001mgkg^{-1}); however, it differed in the livers of *Mugil cephalus* (0.041 and 0.048mgkg^{-1} and *Arius sagor* (0.062 and 0.072mgkg^{-1}). Presumably, Cd is momentarily kept in the liver, where its concentration rises, before accumulating in the muscles and skin. According to Jakimska *et al.* [46], Cd is briefly stored in the liver; however, if the exposure is prolonged, it is transferred to the kidneys, where it is absorbed and bioaccumulated. This occurs because Cd forms a mixture with metallothionein. The results of this study were lower than previous findings in *M. cephalus* livers in the San Carlos estuary of Spain by Usero *et al.* [26] (0.14mgkg^{-1}), Al-Kazaghly *et al.* [42] off the Zliten coast of Libya (0.44mgkg^{-1}), Fazio *et al.* [35] in the Black Sea of Bulgaria (0.239mgkg^{-1}) and Hauser-Davis *et al.* [43] in the Itaipu beach of Brazil (0.13mgkg^{-1}) but higher than the findings of Fazio *et al.* [26] in the liver of *M. cephalus* in the Ionian Sea of Italy (0.0351mgkg^{-1}). The Cd concentration in muscle in this study was lower than previous findings by Fazio *et al.* [26] in *M. cephalus* muscle in the Black Sea estuary of Bulgaria (0.0391mgkg^{-1}) and Al-Kazaghly *et al.* [42] (0.06mgkg^{-1}) but higher than previous findings by Fazio *et al.* [35] in *M. cephalus* muscle in the Ionian Sea of Italy (0.0008mgkg^{-1}). Cd is a highly hazardous element that is mainly transported by airborne particles. Because they are at the top of the marine food chain, fish, seabirds and marine mammals tend to collect large amounts of heavy metals in their livers. Cd poses a significant threat to the survival of estuarine and marine creatures since it can disrupt the reproductive system or even cause mortality. Its bioaccumulation in the human body can negatively affect the lungs, liver, bones, reproduction, kidneys and cancer [50]. The burning of fossil fuels (such as power plants, incineration and waste disposal sites, phosphate fertilizer factories and nonferrous metal smelting operations such as Cu, Pb and Zn), battery production, pigments, plastic stabilizers, welding, electroplating, pesticides, fertilizer and nuclear fission plants are associated with elevated concentrations of cadmium in water [33,48].

In this study, the Hg concentration in all tested tissues and fish species was 0.00004mgkg^{-1}, below the US FDA MPL (0.0005mgkg^{-1}). This suggests that Hg does not pollute coastal swamp waters and the concentration is very small in the fish tissues at the study location, because gold mining that uses Hg is few in number in South Kalimantan. Gold mining is more common in Central Kalimantan. In this study, Hg concentrations in the liver were lower than previous findings by Looi *et al.* [53] in the liver of *A. sagor* in the Strait of Malacca (0.48mgkg^{-1}), Usero *et al.* [26] in the liver of *M. cephalus* in San Carlos estuary of Spain (0.035mgkg^{-1}) and Al-Kazaghly *et al.* [42] in the liver of *M. cephalus* off the Zliten coast of Libya (0.31mgkg^{-1}). Meanwhile, the Hg concentration in muscles in this study was lower than previous findings by Morcillo *et al.* [54] in the muscles of *A. sagor* in Murcia of Spain (0.049mgkg^{-1}), in the Strait of Malacca (0.34mgkg^{-1}) by Looi *et al.* [53], in *M. cephalus* muscles in San Carlos estuary of Spain (0.010mgkg^{-1}) by Usero et al. [26], in Maranhao estuary of Brazil (0.17mgkg^{-1}) by Albuquerque *et al.* [3], off the Zliten coast of Libya (0.07mgkg^{-1}) by Al-Kazaghly *et al.* [42] and in Murcia of Spain (0.05mgkg^{-1}) by Morcillo *et al.* [54]. Even at low concentrations, Hg is highly toxic to numerous organisms. As the organ responsible for detoxifying, the liver typically has the most significant Hg concentrations [46]. The higher Hg concentrations in these species are presumably due to biomagnification along the food chain. Exposure to Hg can have unwanted effects, such as decreased movement coordination, vision loss, speech, hearing, walking impairments, memory loss and muscle weakness [50]. Waste from the hydroelectric, mining, pulp and paper, pesticide and battery industries increases Hg concentrations in estuaries [48]. In addition to emissions from coal-fired power plants, municipal and medical waste combustion contributes to high mercury concentrations [50]. Given the significance of coastal swamp habitats to biodiversity conservation, long-term monitoring and evaluation of Hg must remain a top priority.

In the study area, Fe, Cu and Cr concentrations that exceed the MPL suggested by national and international recommendations can be attributed to uncontrolled human activities. There is a need for additional research to identify point sources and assess their detrimental effects on fish. Depending on the species and organ, the concentration of heavy metals in fish can vary and excessive amounts can accumulate to dangerous levels. Two factors, known as abiotic and biotic factors, influence the bioaccumulation of heavy metals in fish bodies. The properties of heavy metals are influenced by abiotic variables, such as the nature of chemical elements, their concentration, speciation and the presence or absence of their biological function in the body. Although biotic factors pertain to species-specific vulnerability, life history, sex, age and diet, they are species-specific (including diet composition and metabolism). Active and passive processes eventually absorb metal contaminants. These factors influence the affinity or distribution, localization and bioaccumulation of metal contaminants in various tissues or organs, including the liver, kidneys, gills and to a lesser extent, muscles [6]. Physiochemical and biological factors, including pH, temperature, hardness, exposure duration, species feeding habits and habitat complexity, further influence the accumulation of heavy metals in fish organs. In addition to size, sex, reproductive cycle, feeding preferences, swimming patterns and environment, other characteristics affect heavy metal bioaccumulation [6]. Cunningham *et al.* [33] added that species differences (intrinsic) and environmental factors (extrinsic) influence the accumulation of metals in fish. Intrinsic species-dependent characteristics, such as trophic state and feeding tactics, are associated with fundamental food choice patterns (e.g., algae, phytoplankton, invertebrates, fish). In addition, intrinsic characteristics include the fish's age and the sexes and phases of sexual reproduction, which vary depending on the season in which the fish were captured. Extrinsic factors that influence metal bioaccumulation include the chemical form of the metal, the degree of contamination and the presence of other pollutants in the aquatic environment. Extrinsic factors include water quality features such as salinity, temperature, dissolved oxygen content, pH, total suspended particles and bottom sediment quality, which can serve as reservoirs for metal adsorption and resuspension [50].

Conclusions

South Kalimantan's Kuala Lupak and Kuala Tambangan coastal swamp waters are contaminated with heavy metals in the following order: Fe > Cu > Zn > Cr > Pb > Cd > Hg. The Fe concentration surpasses the international and national MPLs, whereas the Cu and Cr amounts only exceed the national MPL. Heavy metal concentration examinations were also conducted on commercial fish typically consumed by coastal communities, such as *Mugil cephalus*, *Arius sagus* and *Plotosus lineatus*, with the following findings: Fe > Zn > Cu > Cr > Pb > Cd > Hg. Based on these data, *Mugil cephalus* has the largest bioaccumulation of heavy metals, followed by *Arius sagor* and *Plotosus lineatus*. In the bodies of *Mugil cephalus*, *Arius sagor* and *Plotosus lineatus*, the Fe, Cu and Cr concentrations surpassed the international and national MPLs. The patterns of heavy metal concentrations in the liver, muscle and skin tissues of the three test fish species were also analyzed. According to these findings, liver tissue is the most bio-accumulative of heavy metals, followed by skin and muscle, particularly in the liver tissue of *M. cephalus*, which collects the highest concentrations of Fe, Cu, Cr, Zn and Pb. In the coastal swamp waters of Kuala Lupak and Kuala Tambangan, South Kalimantan, Indonesia, the predominant heavy metal is Fe, which pollutes the water and commercial fish species.

Long-term ingestion of fish with a high concentration of heavy metals can result in neurological, carcinogenic, nephrological and immunological issues, among others. Therefore, the concentrations of heavy metals, particularly Fe, Cu and Cr, should be monitored continually in the potentially polluted coastal swamps of South Kalimantan, as they tend to concentrate on the liver, skin and muscles. Furthermore, waste disposal from industrial activity and other sources must be regulated. In addition, routine evaluations of heavy metal concentrations in commercial fish species are required to better comprehend the pollution conditions of estuaries and coastlines and the accompanying human health hazards. To protect public health, it is necessary to prohibit fish consumption from water bodies contaminated with mining effluent. The severity of heavy metal bioaccumulation in fish tissues necessitates immediate, sustained and targeted actions by both government authorities and the local scientific community of research and development of mining agencies to assist in preventing and mitigating the situation and ensuring the physical well-being of the local population. Consideration must also be given to enforcing laws requiring the detoxification of effluents before their release into natural water bodies to protect aquatic ecosystems. To prevent the impacts of hazardous trace elements on human health, there is an immediate need for strong government regulation and continuous monitoring of trace metals in fish from mining areas.

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