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Assessment of water quality and mercury contamination in Tabukan Selatan Tengah District: Impacts on marine life and human health

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ABSTRACT

Illegal mining and mercury contamination in Indonesia pose significant challenges to communities and ecosystems, particularly impacting the region's rich natural resources like gold. The research aims to measure mercury levels in water, sediment, and fish to understand the health risks for the local community. The methodology measured three stations' water temperature, pH levels, and mercury concentrations. Gold mining activities are the primary source of mercury contamination in the coastal waters and fish of the Tabukan Selatan Tengah District. Mercury levels vary in water samples (0.005 to 0.138 mg/L), sediment samples (0.003 to 0.242 mg/kg), and fish samples (2 to 357 µg/g). All samples surpass the water quality standard of 0.001 mg/L, except for sediment samples at points 2 and 3. Mercury concentrations in fish exceed the quality standard of 0.5 µg/g. The distance between sampling sites and gold mining waste disposal areas influences mercury accumulation. In the Tabukan Selatan Tengah District, people consume fish at an average rate of 0.00071918 kg daily. The RQ value in the district is categorized as unsafe for health at points 1 and 2 and safe at points 3 and 4. The study underscores the significant health risks of mercury exposure, especially for communities that consume contaminated fish.

Keywords: amalgamation, gold, intake, mine, coastal.

INTRODUCTION

Indonesia has considerable potential in natural resources, particularly in metals and minerals, with an emphasis on precious metals. Estimates from the Ministry of Mines and Energy indicate that Indonesia has up to 2 billion tons of gold, with an annual production rate of 9.98 tons. Regulation 25 of 2023 has been enacted to govern mining business license areas (IUP). As of 2023, the government has granted 5.474 mining business licenses, encompassing a total mining area of 9,112.732 hectares. Mineral mining activities can enhance the economic sector of a country by generating tax revenue and fostering community welfare through employment opportunities in the mining sector, particularly in gold extraction. Furthermore, certain groups participate in PETI (illegal gold mining), which can produce a significant quantity of gold. Mining operations, such as gold extraction, may adversely affect the environment (Wahyono et al., 2024).

Community-based illegal gold mining typically employs amalgamation with mercury to extract gold metal. The amalgamation process is simpler than alternative methods, enabling the community to extract gold using basic equipment. The Tabukan Selatan Tengah District, situated in the Sangihe Islands Regency of North Sulawesi Province, is recognized for its significant potential in gold resources. The availability of gold resources promotes illegal mining activities, resulting in gold extraction in adjacent regions and the improper disposal of mining waste into nearby water bodies, thereby contributing to environmental degradation. The coastal regions of

Indonesia, especially the Tabukan Selatan Tengah District in the Sangihe Islands Regency, host a variety of ecologically and economically significant marine biodiversity. The rise in human activities, notably gold mining employing mercury, has adversely affected environmental quality, particularly in aquatic ecosystems. Mercury is a toxic heavy metal that poses significant risks to aquatic ecosystems and human health. The accumulation of mercury in marine organisms, especially in fish consumed by coastal communities, can result in various adverse health effects. Individuals in communities consuming fish from mercury-contaminated waters may experience adverse health effects (Canham et al., 2020).

Recent studies conducted by the North Maluku Environmental Agency reveal that the coastal waters of the Tabukan Selatan Tengah District in North Maluku, an area affected by illegal gold mining, exhibit elevated levels of mercury contamination. *Katsuwonus pelamis* (skipjack tuna) harvested from those waters exhibit mercury contamination. The impact of mercury pollution on the environment and the surrounding community necessitates closer examination. Recent studies have elucidated the distribution and concentration of mercury across diverse aquatic ecosystems. A study conducted in the Pearl River Estuary in Southern China indicated that humic acid significantly influences the behavior of mercury compounds, including inorganic mercury and methylmercury (Liu et al., 2020). In marine aquaculture sediments characterized by elevated humic acid levels, mercury absorption is enhanced, which facilitates its methylation and subsequent accumulation.

The spatial variations in the production, bioaccumulation, and biomagnification of methylmercury within marine food webs represent significant areas of research. Understanding the movement of mercury through various trophic levels, including fish, is crucial for addressing the risks it poses to both humans and wildlife. Methylmercury, an organic mercury compound, is a highly effective neurotoxin that presents a considerable risk to the health of both humans and wildlife. The primary source of increased methylmercury exposure in humans is the consumption of estuarine and marine fish, with developing fetuses being especially susceptible to its effects. A substantial body of research has investigated the impacts of methylmercury on wildlife. These studies demonstrate that while organisms possess the ability to demethylate and eliminate methylmercury from their environment, the compound's high toxicity and the physiological constraints of animals may result in significant accumulation within their bodies, posing serious health risks.

Mercury contamination in the coastal region of the Tabukan Selatan Tengah District primarily originates from artisanal gold mining operations. Mercury is employed in the separation of gold from its ore, resulting in significant environmental contamination. The mercury utilized in this process is frequently released into aquatic environments, either directly through liquid waste disposal or via rainwater runoff that transports mercury to river mouths and the ocean. Mercury released into aquatic environments can accumulate in sediments and subsequently enter the food chain via bioaccumulation. Fish dwelling in mercury-contaminated environments can absorb mercury and other heavy metals, leading to bioaccumulation in their tissues. The predominant form of mercury present in freshwater, brackish, and marine organisms is methylmercury, a highly toxic compound that is easily absorbed via the digestive system, thereby presenting considerable health risks to humans (Abera and Adimas, 2024).

The exposure assessment is usually used to examine mercury pollution from traditional gold mining. This method involves discovering how much pollution is in the environment, like in water and sediment, and how it affects marine life within specific time and space frames. This study assesses the impact of pollutants on communities directly or indirectly exposed to them by evaluating the potential risks of consuming contaminated marine biota. This study uses a health risk analysis approach to evaluate the impact of illegal mining activities by measuring mercury concentration in environmental matrices, including water, sediment, fish biota, fish consumption patterns, and health risk assessment through fish consumption.

Addressing these challenges requires a comprehensive understanding and effective management to maintain the balance of the coastal environment and protect the welfare of the local population. A comprehensive study of mercury levels in water and various fish species is essential for understanding the extent of contamination in this region. The data will be crucial for evaluating potential health risks to the local population and guiding effective mitigation strategies. This study aims to identify and analyze mercury concentrations in aquatic environments and biota, particularly fish, within the coastal region of the Tabukan

Selatan Tengah District, Sangihe Islands Regency. The investigation attempts to assess the potential health risks for the local community, which primarily relies on fish as its main protein source.

MATERIALS AND METHODS

Study area

The sampling locations in the Tabukan Selatan Tengah District were established at three stations, namely stations 1, 2, and 3 (Figure 1). At each station, water, sediment, and fish samples were collected. Sample preparation was conducted at the Politeknik Negeri Nusa Utara Laboratory, Sangihe Islands Regency, and sample analysis was carried out at the Integrated Research and Testing Laboratory, Gadjah Mada University, Yogyakarta. Water samples at each station were taken in 500 mL with three repetitions and then stored in plastic bottles; according to Nakazawa et al. (2015), the proper method for storing seawater samples to ensure their protection is using plastic bottles. Mud sediment at each station was taken using a PVC pipe of 250 g with three repetitions, and each sample was stored in plastic bags; the sample quantity was determined based on the study by Hidayati et al. (2022), which specified that approximately 250 g of sediment should be collected. Sediment samples were taken at a depth of 1 m below sea level because, according to Rachmansyah et al. (2017), samples should ideally be collected at depths of 1–5 m below sea level for Hg analysis in sediment. However, this study collected sediment samples 1 m below sea level due to equipment limitations.

Gold mining efforts by companies and communities in the research location generally dispose of liquid waste containing mercury in the surrounding area. The disposal of gold mining waste without treatment releases mercury and other toxic substances, causing an increase in mercury concentrations in public waters. River currents carry liquid waste from gold mining until

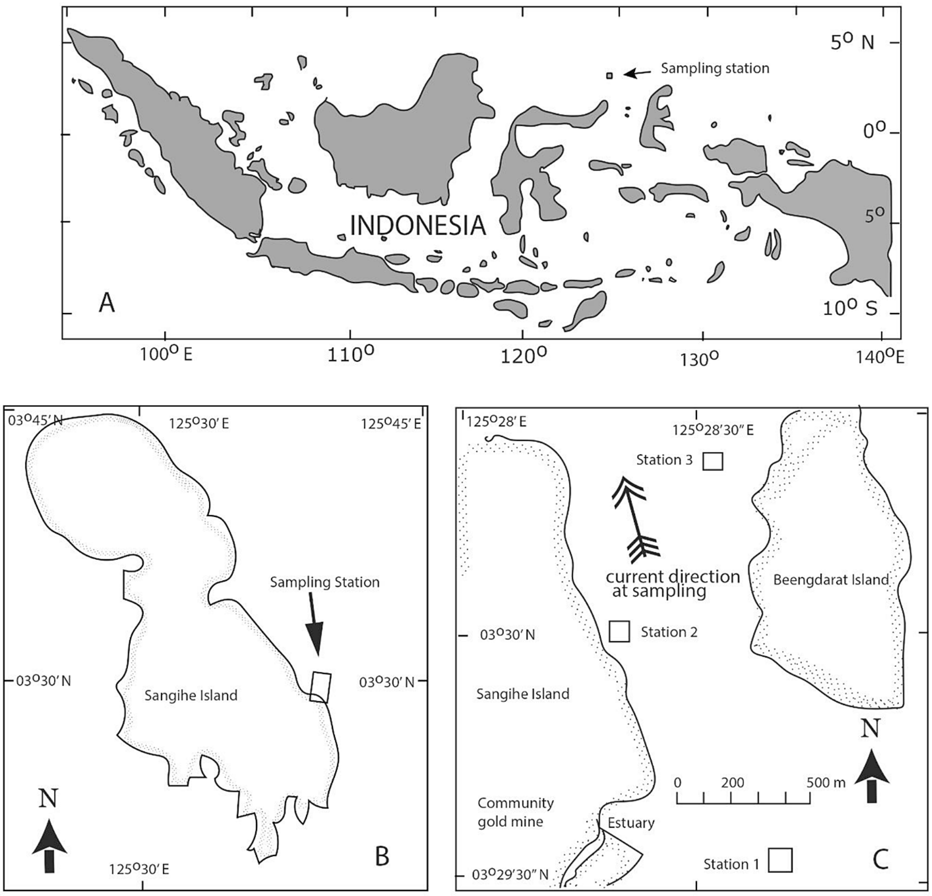

Figure 1. Map showing the research locations in Sangihe Islands Regency (A), including sampling locations in Tabukan Selatan Tengah District (B) and the locations of water, sediment, and fishes sampling at each station (C). Station 1 is closest to the gold mining wastewater disposal site, whereas station 3 is the furthest

it reaches the river mouth. The ecosystem in the river mouth and coast is a mangrove forest that grows with a thickness of about 500–1000 m.

Procedures

Mercury concentration measurement in water samples was carried out in the following manner. The water sample was stirred until homogeneous, then 100 mL was taken and filtered using 0.45 µm filter paper. Furthermore, 50 mL was taken and transferred into a 125 mL Erlenmeyer flask, and then 10 mL of HNO_3 and $HClO_4$ solution (1:1) was added. The sample was heated on a hotplate until white smoke appeared and became clear, then filtered, and 50 mL was taken using a measuring flask. The mercury content in the sample was measured using a mercury analyzer (AMA 300). The calibration curve was prepared using 0.1 mL of a 1000 ppm Hg stock solution, which was transferred into a 100 mL volumetric flask and diluted to the mark with distilled water. Then, 0.1 mL of the 1000 ppb Hg stock solution was placed into a 10 mL volumetric flask and diluted to the mark with distilled water. Standard concentrations in the range of (ppb): 0.05, 0.1, 0.2, 0.4, 0.8, 1.6, and 3.2 were prepared by taking 0.05, 0.1, 0.2, 0.4, 0.8, 1.6, and 3.2 mL of the prepared solution, respectively, into 10 mL volumetric flasks, diluting them to 10 mL with distilled water, and transferring them into vials. These solutions were then ready to be measured using a mercury analyzer.The results of measuring the mercury content in the sample were compared with a standard mercury solution that had been made sometime earlier.

Marine biota samples were obtained from fishermen's catches in Tabukan Selatan Tengah District waters, representing carnivorous, omnivorous, herbivorous and benthic organisms. Marine biota samples include *Rastreligger* sp., *Scarus* sp., *Neoniphon aurolineatus*, *Decapterus macarellus, Upeneus sulphureus, Ctenochaetus striatus, Loligo* sp, *Litopenaues vannamei*.

Fish sample preparation involved cleaning the fish, extracting the flesh, and drying it in an oven at 105 °C (Makahenggang et al., 2022). Similarly, sediment sample preparation involved drying the sediment in an oven at 105 °C and grinding it until it became homogeneous (Wahidah et al., 2019). Based on this process, sediment and fish biota samples were dried in an oven at 105 °C for 24 hours until the water content was < 10%. Furthermore, sediment and fish samples were ground using a mortar until they became powder. Sediment and fish powder samples were sampled as much as 10–20 mg and then analyzed for mercury content using a Mercury Analyzer (MA 3000) with minimum detection of 0.05 µg at the Integrated Research and Testing Laboratory of Gadjah Mada University.

Data analysis

Based on the results of mercury concentration measurements in water, sediment and aquatic organisms, the bioconcentration factor (BCF) and bioaccumulation factor (BAF) values were then calculated. BCF is the ratio between the concentration of chemicals in aquatic organisms and the concentration of chemicals in water. The bioconcentration value of mercury is calculated using the following formula, based on EPA 2003:

$$BCF = (\textit{Mercury concentration in the body of the organism})/(\textit{Mercury concentration in water}) \quad (1)$$

where: Ct is the concentration of mercury in the flesh of the organism and Cw is the concentration of mercury in water. BAF is the ratio of metal concentration in an organism to the concentration of metal in aquatic sediment, which measures chemicals that accumulate in organisms from the food chain and ecosystem. Bioaccumulation Factor is calculated using the formula:

$$BAF = (\textit{Mercury concentration in Organisms})/(\textit{Mercury concentration in sediment}) \quad (2)$$

Measurement of physical parameters, including temperature, pH, TSS, and TDS measurements, was done in three repetitions. The collection of respondents' data on fish consumption patterns was conducted in three villages in the South Central Tabukan District, with 20 respondents in each town, so the total number of respondents was 60. The respondent data was then used to calculate the health risk analysis where the results of the study of mercury content in marine biota were also used in calculating the intake of respondents using the formula from the Ministry of Health (2012):

$$Intake = (C \times R \times fE \times Dt)/(Wb \times tAVG) \quad (3)$$

where: C is the concentration of the risk agent of mercury; R is the rate of intake or consumption; fE is the frequency of exposure; Dt is the duration of exposure; and Wb is body weight. Based on the intake valve, the risk level (RQ) is then calculated with the RfD value for mercury of 1 x 10^(-4) mg/kg/day using the RQ formula (Ministry of Health, 2012):

$$RQ = (Intake)/(RfD) \quad (4)$$

The risk level is safe if the RQ value is ≤ 1 and can be declared unsafe if the RQ value is > 1. Water sample parameter data is analysed descriptively by comparing the results of sample tests with quality standards in accordance with those stipulated by Ministerial Decree Number 51 of 2004 concerning Sea Water Quality Standards. Analysis of mercury content data in fish is carried out statistically descriptively using data depiction from the analysis results in the form of graphs or tables.

RESULTS AND DISCUSSION

Result

Water quality

The results of water quality and mercury content measurements are presented in Table 1. The temperature at all locations did not exceed the quality standards based on the Decree of the Minister of State for the Environment number 51 of 2004 for marine biota in the mangrove area with a temperature range of 28–32 °C and seagrass areas 28–30 °C. The highest temperature was at station 2, with an average of 32.6 °C, and the lowest was at station 3, with an average of 30.0 °C. The pH value was found at all research locations to be 7, where, according to the reference quality standards of the Decree of the Minister of State for the Environment number 51 of 2004 for marine biota, the pH at all research locations was still within the range of the quality standards of 7.0–8.5.

Total dissolved solid (TDS) measures of dissolved substances (organic & inorganic substances) in a solution. The average TDS value at each location, respectively, station 1 was 87.3 mg/L, station 2 was 84.166 mg/L and station 3 was 88.6 mg/L so that it was still within the safe limits of the quality standards set based on the Decree of the Minister of State for the Environment number 51 of 2004 for a TDS value of 2.000 mg/L. Station 3 has the highest average TDS value and the highest average mercury concentration in water samples. Station 2 has the lowest average TDS value with the lowest mercury concentration in water samples. It shows a correlation between heavy metals in water and TDS concentration because an increase in TDS in water can cause the concentration of heavy metals to increase.

Total suspended solid (TSS) is a solid suspended in water from inorganic and organic materials. The TSS value at all locations exceeded the quality standards set by the Decree of the Minister of Environment Number 51 of 2004, namely for the mangrove area of 80 mg/L and the seagrass area of 20 mg/L with an average TSS of station 1, station 2 and station 3 of 413.33 mg/L, 460 mg/L and 620 mg/L, respectively. This high TSS value can affect mercury concentration in sediment and water. The concentration of TSS can affect the concentration of heavy metals because TSS affects the adsorption process of dissolved

Table 1. Characteristics of coastal water quality in South Central Tabukan District

Parameter	Sample	Station 1		Station 2		Station 3		Standard range
		Range	Average	Range	Average	Range	Average	
Temperature (°C)	Water	30.5–31.5	30.9	32.0–33.1	32.6	29.8–30.3	30.0	28–32* 28–30**
pH	Water	7	7	7	7	7	7	7–8.5
TDS (mg/L)	Water	86.1–87.9	87.3	84.1–84.2	84.16	88.0–88.9	88.6	2.000
TSS (mg/L)	Water	330–510	413.3	310–530	460	450–910	620	80* 20**
Mercury (mg/L) (mg/kg)	Water	0.018–0.024	0.0206	0.005–0.034	0.019	0.062–0.138	0.092	0.001***
	Sediment	0.073–0.420	0.242	0.015–0.079	0.039	0–0.006	0.003	0.15****

Note: (*) Quality standards based on the Decree of the Minister of State for the Environment number 51 of 2004 for marine biota in the mangrove area, (**) Quality standards based on the Decree of the Minister of State for the Environment number 51 of 2004 for marine biota in the seagrass area, (***) Seawater quality standards: Decree of the Minister of the Environment No. 51 of 2004, (****) Sediment quality standards: ANZECC/ARMCANZ 2000-Low.

heavy metals. Heavy metals that suspended particles have adsorbed will be at the bottom of the water so that the metal content in the water is low, and the higher the TSS can cause the concentration of heavy metals in the water to decrease. It is inconsistent with the findings at station 3, which has the highest average concentration of mercury in water and the lowest in sediment. At the same time, station 3 has the highest TSS value. The findings at station 2 are different, where station 2 has a higher TSS value than station 1 and has a lower average mercury concentration in water and a higher mercury concentration in sediment compared to station 1, so there is still a relationship between the TSS value and the concentration of mercury in water and sediment.

The water sample with the highest mercury concentration was at station 3, with a value of 0.138 mg/L, while the lowest mercury concentration was at station 2 at 0.005 mg/L. Data from the mercury content measurement in water and sediment shows that Tabukan Selatan Tengah District waters have been contaminated with mercury with a range of 0.018–0.138 with an average of 0.0923 mg/L. The range of mercury in sediment is 0.0–0.42045 mg/kg with an average of 0.095 mg/kg. The mercury concentration in water samples at the three research stations has exceeded the limit of mercury concentration in coastal waters as stipulated in the Decree of the Minister of Environment Number 51 of 2004 of 0.001 mg/L. Sediment samples at station one, which is closest to the source of liquid waste, have mercury concentration values that exceed the sediment quality standard limits based on the ANZECC/ARMCANZ 2000-Low provisions with mercury concentrations exceeding 0.15 mg/kg. The concentration of mercury in each sample at each station is presented in Table 2 or detailed information. The water sample at station 3 was higher than the mercury concentration in the water samples at station 1 and station 2. The mercury concentration in the sediment sample at Station 1 was higher than at Station 2 and Station 3. The one-way ANOVA test found that the mercury concentration in the water and sediment samples at each location did not have a significant difference with a significance value of 0.059, so the value > 0.05.

The sediment sample with the highest average mercury concentration was found at station 1, indicating the most significant contamination level in the study area, with a value of 0.242 mg/kg. In comparison, the lowest mercury concentration was found at station 3, with an average of 0.003. However, at station 3, there was one sediment sample whose mercury concentration was not detected because the minimum limit for mercury detection using a mercury analyzer is 0.05 mg/kg. Based on the one-way ANOVA test, it was found that the mercury concentration in water samples at each location had a significant difference with a Sig. < 0.05 value, namely a significance of 0.019, but in the follow-up post hoc test, it was found that the mercury content of each location did not have a significant difference with a Sig. > 0.05 value.

Mercury accumulation in fish

Based on the results of observations and interviews, it is known that eight types of fish are usually caught and consumed by the community in Tabukan Selatan Tengah District (Table 3). The types of fish that are often seen in fishing gear are *Ctenochaetus striatus*, *Decapterus macarellus, Neoniphon aurolineatus*, *Rastreligger* sp., *Scarus* sp., *Upeneus sulphureus*, *Loligo* sp., and *Litopenaeus*

Table 2. Mercury concentration in water and sediment at each sampling station

Sample origin	No.	Station 1	Station 2	Station 3
Water	1	0.024	0.005	0.077
Water	2	0.018	0.034	0.062
Water	3	0.020	0.023	0.138
	Average	0.021	0.021	0.092
	STDEV	0.003	0.015	0.040
Sediment	1	0.073	0.079	0.006
Sediment	2	0.232	0.024	0.000
Sediment	3	0.420	0.015	0.004
	Average	0.242	0.039	0.003
	STDEV	0.174	0.035	0.003

Table 3. Fish morphometrics and mercury concentration in fish samples in the waters of South Central Tabukan District

Scientific name	Local name	Number of samples	Average lenght (cm)	Average weight (g)	Mercury accumulation (μg/g)		Quality standards (μg/g)
					Range	Average	
Rastreligger sp.	Kembung	3	20.5	109.4	45366.0	10.8	0.5*
Neoniphon aurolineatus	Tupai	3	20.3	193.1	45399.0	12.0	0.5*
Scarus sp.	Kakatua	3	23.1	243.3	21033.0	32.3	0.5*
Ctenochaetus striatus	Botana lurik	3	22.0	220.2	30133.0	53.0	0.5*
Upeneus sulphureus	Kuniran	3	16.8	83.2	15–79	65.0	0.5*
Decapterus macarellus	Layang biru	3	33.8	452.7	59–81	69.7	0.5*
Loligo sp.	Cumi–cumi	3	44.8	201.67	2–330	122.33	0.5*
Litopenaeus vannamei	Udang vanamei	3	18.5	133.58	22–357	201.33	0.5*

Note: (*) Quality standards based on SNI 7387:2009 regarding the maximum limit of mercury heavy metal contamination in fish.

vannamei. All samples of fish caught were contaminated with mercury with an average concentration ranging from 10.8–201.3 μg/g with an average of 70.79 μg/g. The highest levels of mercury accumulation in fish samples were sequentially found in the types of *Litopenaeus vannamei* (201.33 μg/g), *Loligo* sp. (122.33 μg/g), *Decapterus macarellus* (69.666 μg/g), *Upeneus sulphureus* (65 μg/g), *Ctenochaetus striatus* (53 μg/g), Scarus sp. (32.33 μg/g), *Neoniphon aurolineatus* (12 μg/g) and *Rastreligger* sp. (10.66 μg/g).

Based on Table 3, it can be seen that the accumulation of mercury in fish samples has exceeded the SNI 7387:2009 standard limit of 0.5 μg/g. The level of mercury accumulation in fish was found to differ spatially and based on each type of fish caught. Suppose each type's mercury accumulation is compared with the standard. In that case, it can show the multiple concentrations between the mercury content in the organism's body and the standard. When compared with the standard, the mercury concentration in *Litopenaeus vannamei* shrimp is 403 times greater, *Loligo* sp. 245 times greater, *Decapterus macarellus* 139 times greater, *Upeneus sulphureus* 130 times greater, *Ctenochaetus striatus* 106 times greater, Scarus sp. 65 times greater, *Neoniphon aurolineatus* 24 times greater, and *Rastreligger* sp. 22 times greater. The most minor multiple concentration is found in the *Rastreligger* sp. fish species, with an increase of 13 times.

Each fish species has a varying average length, and the average length of *Upeneus sulphureus* is the smallest, at 16.8 cm. Still, this type does not have the highest mercury accumulation among all fish species. The type with the most extended length is *Loligo* sp. 44.75 cm long, but the most significant body length does not make *Loligo* sp. have the largest average mercury concentration. *Loligo* sp., with the most considerable body length, is the type of fish with the second-largest average mercury concentration after *Litopenaeus vannamei.*

The average weight of the fish from the largest in order is *Decapterus macarellus* (452.7 g), Scarus sp. (243.3 g), *Ctenochaetus striatus* (220.2 g), *Loligo* sp. (201.6 g), Neoniphon aureolineatus (193.1 g), *Litopenaeus vannamei* (133.5 g), *Rastreligger* sp. (109.3 g) and *Upeneus sulphureus* (83.2 g). The average weight of the largest fish was *Decapterus macarellus*. Still, the mercury accumulation of this type was not the largest among the types of fish whose mercury accumulation was analyzed. *Upeneus sulphureus* is a type of fish with the smallest weight. Still, the most negligible weight does not make *Upheneus sulphurous* have the most insignificant mercury accumulation because the minor mercury accumulation was found in the *Neoniphon aurolineatus* type of fish.

Each type of fish has a different diet where *Rastreligger* sp. eats phytoplankton and zooplankton, and when the larvae usually eat *Cheilio inermis* during the first feeding larval stage. Likewise with *Rastreligger* sp., *Decapterus macarellus* also consumes zooplankton. *Upeneus sulphureus*, amphipods, small shrimp, and *Ctenochaetus striatus* are herbivorous fish that eat algae. *Neoniphon aurolineatus* is a mesophotic fish where mesophotic fish can eat plankton and invertebrates. *Scarus* sp. is a herbivorous fish. *Loligo* sp. is a predator that eats fish, cephalopods and crustaceans. The study stated that *Litopenaeus vannamei* is an omnivore that consumes animals and plants.

The magnitude of the BCF and BAF values

The average BCF and BAF values are presented in Table 4. The highest average BCF values in the sequence are station 1 (5351.9), station 2 (3565.8) and station 3 (368.4). *Litopenaeus vannamei* is the species with the highest BCF value at station 1 (17271.41) and station 2 (11842.11), while for station 3, the species with the highest BCF is *Ctenochaetus striatus* (888.4). The highest average BAF values in the sequence are station 3 (9760.7), station 2 (1710.6) and station 3 (457.1). *Litopenaeus vannamei* is the species with the highest BAF value at all stations, namely station 1 (1475.1), station 2 (5680.9) and station 3 (6315.8).

BCF value >1000 is categorized as very high, BCF of 100–1000 as high, 30–100 as moderate, and BCF < 30 as low. Based on the BCF value, *Litopenaeus vannamei* is the organism with the highest heavy metal accumulation at station 1 (17271.4) and station 2 (11842.1) with a very high category because the BCF value>1000, while for station 3, the highest BCF is in *Ctenochaetus striatus* (888.4) with a high BCF category because it is still in the range of 100–1000. The lowest BCF value at station 1 is in the *Neoniphon aurolineatus* fish (193.5) and station 2 in the *Rastreligger* sp. fish (157.9). Hence, the types of fish with the lowest BCF values at stations 1 and 2 are still in the range of 100-1000, namely high heavy metal accumulation. The lowest BCF value at station 3 was found in the *Scarus* sp. fish species (86.67389), so with this BCF value, it is categorized as moderate heavy metal accumulation because it is still in the range of BCF values 30–100. The highest BAF values at station 1 (1475.1), station 2 (5680.9) and station 3 (6315.8) are categorized as organisms that can accumulate heavy metals because the BAF value > 1. The lowest BAF value at station 1 was found in the *Neoniphon aurolineatus* species (16.5), station 2 in the *Rastreligger* sp. species (75.7) and station 3 in the *Loligo* sp. species (574.2) so even though these types of fish are the types of fish with the lowest BAF values at each station, they are still categorized as organisms with the ability to accumulate heavy metals because the BAF value of each type is more than 1.

Health risk analysis

The pattern of fish consumption caught by the community in Tabukan Selatan Tengah District is presented in Table 5. The level of fish consumption by the Tabukan Selatan Tengah District community ranges from 0.221 to 0.307 g/day, with an average daily consumption of 0.262 g.The highest level of fish consumption was found in the community at station 3 (0.307 g/day), followed by station 1 (0.258 g/day) and station 2 (0.221 g/day). Based on the calculation of the mercury intake value through fish consumption in the community, it is known that the mercury intake value ranges from 0.000606164–0.000842466 kg/day with an average of 0.00071918 kg/day. The highest mercury intake value was found at station 3 (0.000842466 kg/day), station 2 (0.000708904 kg/day) and station 1 (0.000606164 kg/day).

Differences in fish consumption patterns at each station in Tabukan Selatan Tengah District are influenced by differences in the frequency of fish consumption and the amount of fish consumed by the community. Fish consumption at all research locations is relatively low because it is less than 71.2 g/day, so it needs to be categorized as insufficient. In comparison, it is included in the sufficient category if fish consumption is more than or equal to 71.2 g/day (Ministry of Marine

Table 4. BCF and BAF values

Scientific name	BCF			BAF		
	Station 1	Station 2	Station 3	Station 1	Station 2	Station 3
Ctenochaetus striatus	338.7	3684.2	888.4	28.9	1767.4	23540.7
Decapterus macarellus	3338.2	4263.2	639.2	285.1	2045.1	16937.8
Neoniphon aurolineatus	193.5	894.7	162.5	16.5	429.2	4306.2
Rastreligger sp.	677.3	157.9	162.5	57.8	75.7	4306.2
Scarus sp.	2757.6	1684.2	86.7	235.5	807.9	2296.7
Upeneus sulphureus	2273.8	4157.9	747.6	194.2	1994.6	19808.6
Loligo sp.	15965.17	1842.1	21.7	1363.6	883.9	574.2
Litopenaeus vannamei	17271.4	11842.1	238.4	1475.1	5680.9	6315.8
Average	5351.9	3565.8	368.4	457.1	1710.6	9760.7

Table 5. Mercury consumption patterns and intake rates

Location	Number		Weight (kg)	Consumption patterns (g/day)	Intake rate (kg/day)
	Man	Woman			
Station 1	12	8	56.7	0.258	0.000606164
Station 2	6	14	63.3	0.221	0.000708904
Station 3	10	10	63.9	0.307	0.000842466
Average			61.3	0.262	0.00071918

Affairs and Fisheries of the Republic of Indonesia, 2004). The tolerable rate of mercury intake is 0.47μg/kg/day. The highest mean risk quotient (RQ) values in the sequence are at station 2 (6.54), station 1 (5.68), and station 3 (0.0003). A risk quotient value ≤ 1 indicates a safe level, while a value > 1 signifies an unsafe level of health risk. Based on the RQ value obtained, the risk level of consuming fish contaminated with mercury at stations 1 and 2 is categorized as unsafe because the RQ value exceeds 1. Non-carcinogenic Intake values and RQ of mercury are presented in Table 6.

Station 3 has the lowest RQ value of 0.00205, attributed to the shorter duration of community residence compared to stations 1 and 2, where immigrants predominantly reside in station 3. The length of stay of respondents affects the intake value. This intake value is then used to calculate the RQ value, causing a relatively significant difference in the RQ value between station 1 and station 2 with station 3.

DISCUSSION

The lack of notable differences in mercury concentrations in sediment and water across stations may be attributed to the proximity of the stations, which are approximately 1 km apart. The moderate movement of sediment leads to an even distribution across the area. The sedimentation rate in the coastal waters of the PETI area in the Tabukan Selatan Tengah District exhibits relatively low sediment transport. Further research is necessary to understand the influencing factors of sediment transport, such as the impact of rainfall, currents, and oceanographic conditions on sedimentation patterns. Tidal influences, variations in density and wind, and wind patterns at the sea surface all have an impact on the current. Therefore, the influence of ocean currents is a contributing factor to the lack of significant differences observed between research stations (Fagherazzi and Wiberg, 2009).

The overall mercury levels seen are a result of a variety of factors, including water temperature, pH levels, and other environmental parameters. Temperature impacts how easily pollutants like mercury dissolve, change form in the environment, interact with natural substances, remain stable, and affect the metabolism of organisms (Gworek et al., 2020). Changes in water pH influence mercury solubility in aquatic environments. An increase in pH correlates with reduced mercury solubility, whereas a decrease in pH enhances mercury solubility, leading to the conversion of mercury into the more toxic methyl mercury (Ravichandran, 2004).

When examining mercury concentration in water samples, it is important to consider the influence of temperature and pH on the observed levels. Notably, the highest mercury concentration occurs at station 3, which exhibits the lowest average temperature among all locations. Station 2, exhibiting the lowest concentration, demonstrates the highest average temperature. Meanwhile, the pH levels across all research locations remain within quality standards. This phenomenon may be attributed to additional factors, such as current patterns. Tidal current patterns affect the dilution of heavy metals in water (de Melo et al., 2015). Metal ions move to sediment through

Table 6. Non-carcinogenic intake and risk quotient (RQ) of mercury

Location	Non carcinogenic intake			RfD	Risk quotient (RQ)		
	Min	Mean	Max		Min	Mean	Max
Station 1	0.00059	0.08369	0.62132	0.0001	0.191208	5.676628	17.0225
Station 2	0.00059	0.00065	0.00581	0.0001	0.730594	6.541493	58.1849
Station 3	0.01315	0.01587	0.27671	0.0001	0.001735	0.000281	0.0020

a process called water-sediment partitioning or adsorption, resulting in mercury buildup in the sediment. Tidal movements and ocean currents influence heavy metal concentrations (Förstner, 2020), which may explain the lack of correlation between temperature and mercury contamination values in seawater across different stations.

The high mercury concentration in sediment samples at Station 1 is directly linked to the nearby PETI waste disposal site, highlighting the environmental impact of human activities in the area. The location receiving Hg waste disposal from the mining area exhibits the highest mercury concentration in sediment. All locations exhibit uniform sediment composition, specifically mud (Johnson et al., 2015). This particular sediment type has a high concentration of organisms, particularly decomposing microbes, and pH also affects the concentration of mercury in sediment (Hsu-Kim et al., 2013). An increase in pH correlates with reduced mercury solubility in water, as mercury tends to settle at the bottom and is subsequently deposited with sediment (Uddin et al., 2024). Based on this, although the pH at all locations is still within the safe limits of the quality standards, the type of sediment in mud causes high mercury accumulation in sediment at station 1 and the accumulation of mercury at stations 2 and 3. Mercury easily dissolves and changes from a carbonate to a hydroxide state, forming bonds with particles in water. In these settings, mercury can be absorbed by sediments due to biological factors associated with microbial activity, including methyl mercury (CH_3Hg^+), dimethyl mercury ($(CH_3)_2Hg$), and Hg (Namieśnik and Rabajczyk, 2010).

The size, weight, and diet of the fish are some factors that affect mercury accumulation among various fish species (Jia et al., 2017). Size and diet have an impact on mercury concentrations in fish, with larger fish having a greater capacity for mercury accumulation (Dang et al., 2012). The complex dynamics of the food chain, rather than the specific physical characteristics of the fish, primarily influence the relationship between fish weight and length and their mercury levels. Mercury is introduced into aquatic organisms via three primary mechanisms: the food chain, gill absorption, and skin surface diffusion (de Almeida Rodrigues, 2019). Approximately 90% of toxic heavy metal mercury accumulates in fish through the food chain, highlighting the predominant pathway for mercury intake in aquatic organisms. As one ascends the food chain, the concentration of heavy metals in organisms increases. Methyl mercury ions undergo a multiplication or transformation process within this system. Therefore, the specific food chain associated with each fish species must be analyzed, as it significantly influences mercury accumulation in their bodies. Gewurtz et al. (2021), who also found no positive relationship between mercury levels and fish dimensions in their research, support the lack of correlation between fish length and weight with mercury concentration. This observation encompasses the effects of eutrophication and disrupted food chains in various aquatic systems, indicating a lack of balance between mercury concentration and fish size.

Higher trophic levels in organisms are associated with higher concentrations of heavy metals in their bodies, which has an impact on heavy metal accumulation in the food chain (Ali and Khan, 2019). The fact that Litopenaeus vannamei, an omnivorous species, has a significant mercury accumulation indicates a relatively high trophic level in comparison to non-omnivorous fish. Furthermore, Lino et al. (2019) note that plankton consume methyl mercury-containing water and sediment, which causes mercury accumulation in small fish that eat plankton, which are then preyed upon by larger fish, facilitating methyl mercury accumulation in fish tissue. The species Neoniphon aurolineatus exhibits minimal mercury accumulation despite being omnivorous, suggesting variability in the accumulation capabilities among different fish species. Although the food chain in fish is extensive, mercury accumulation remains low, attributable to the differing bioaccumulation and absorption capacities of each fish type (Xu et al., 2018).

According to the BCF value, variations in heavy metal accumulation among various fish species and research stations are a result of different mercury concentrations in the water at each location. Elevated metal concentrations in water facilitate the accumulation of these metals, posing a toxic risk to fish. Additionally, the concentration of heavy metals in sediments influences the bioaccumulation of these substances in fish tissue. The research centers on mercury levels in sediments, which impact the bioaccumulation factor (BAF) results for different fish types at each research site. High trophic levels within the food chain have an impact on the BAF, which affects the presence of mercury in organisms. Larger organisms tend to exhibit higher BAF values. Bioconcentration occurs when the levels of Hg_2^+ and CH_3Hg^+ in organisms surpass those in the water and reach a stable state. In this study, the lack of correlation between organism size and the BAF value is noteworthy as it challenges the typical expectation of an increase in the BAF value with organism size. Specifically, Litopenaeus vannamei, although not the predominant fish species, demonstrates the highest BAF value among all fish types examined. This indicates that fish size does not influence the BAF value at the research site (Junes et al., 2014).

The long-term accumulation of mercury poses significant health risks due to its association with environmental pollution, impacting human health in various ways. The effects of mercury on humans are toxic, with its poisonous properties linked to the sensitivity of the nervous system. Individuals with high mercury intake may exhibit early signs such as tingling skin, unsteadiness, hearing loss, speech difficulties, and, in severe cases, fatal outcomes, highlighting the range of health effects linked to elevated mercury exposure. Accumulating mercury over time poses serious health hazards, especially for people living in stations 1 and 2, where there are higher RQ values (Tamalawe, 2024).

CONCLUSIONS

The study of water quality and mercury accumulation in the Tabukan Selatan Tengah District reveals significant environmental concerns. The water temperature and pH levels were within acceptable limits, but TSS exceeded quality standards, potentially impacting mercury concentrations. Mercury levels in water and sediment were found to be above safe limits, indicating contamination, particularly near waste disposal sites. Fish samples showed alarming mercury accumulation, exceeding national safety standards, with variations among species and locations. The health risk analysis highlighted unsafe consumption levels of contaminated fish, particularly at stations 1 and 2, where residents face higher health risks due to elevated mercury exposure.

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