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Multi-matrix assessment of mercury contamination, sediment retention, fish bioaccumulation, and human biomonitoring in an artisanal and small-scale gold mining – impacted riverine area of Indonesia

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ABSTRACT

Mercury contamination from artisanal and small-scale gold mining (ASGM) remains a major concern in riverine environments and exposed communities. This study applied a multi-matrix approach in an ASGM-impacted area of Bungo District, Jambi Province, Indonesia, integrating mercury analysis in water, sediment, fish muscle, and human hair with kidney-related biomarkers. Mercury was not detected in the analyzed water samples, whereas sediment mercury was detected at several sites, with mean concentrations ranging from 0.02 to 0.10 mg/kg. Mercury was detected in all fish samples, with mean concentrations ranging from 0.05 to 0.17 mg/kg. Among 50 residents, hair mercury ranged from 0.17 to 6.15 mg/kg, with a mean of 1.01 ± 0.98 mg/kg; 10.0% of participants had concentrations ≥2.0 mg/kg. The mean UACR was 16.31 ± 32.55 mg/g, the mean eGFR was 107.76 ± 40.62 mL/min/1.73 m², and 18.0% of participants had at least one altered kidney-related indicator. These findings indicate that water-only monitoring may underestimate mercury relevance in ASGM-affected river systems because mercury can be retained in sediments and detected in biological matrices even when surface-water mercury is below the analytical detection limit. The results support a multi-matrix monitoring approach using sediment, fish, and human biomarkers to improve interpretation of contamination persistence, bioaccumulation potential, and exposure significance. However, because the study was cross-sectional, based on total mercury analysis, and limited in sample size for fish and human health interpretation, the findings should be interpreted as evidence of a plausible environmental–food chain–human exposure continuum rather than proof of causality.

Keywords: artisanal and small-scale gold mining, mercury contamination, sediment retention, fish bioaccumulation, human biomonitoring, multi-matrix monitoring.

INTRODUCTION

Mercury contamination remains one of the most serious environmental and public health concerns associated with artisanal and small-scale gold mining (ASGM) (Wibowo et al., 2022). In many mining-affected regions, mercury is still widely used during gold amalgamation because it is inexpensive, accessible, and effective for separating gold from ore (Fornasaro et al., 2025). However, uncontrolled mercury use, open burning of amalgam, and direct disposal of mining residues can release mercury into the surrounding air, soil, sediment, and aquatic systems (Basu, 2023; Pant et al., 2024). Once released into the environment, mercury can persist, move across environmental compartments, and undergo transformation into more toxic and bioavailable forms.

In aquatic ecosystems, inorganic mercury may be converted by microbial processes into methylmercury, a highly neurotoxic form that readily accumulates in aquatic organisms and biomagnifies through food webs (Basu, 2023; Hsu-Kim et al., 2013). This process creates a pathway through which environmental contamination can be transferred from mining sites to fish and ultimately to humans through dietary exposure or other forms of environmental contact. Therefore, mercury contamination in ASGM-impacted areas should be understood not only as a localized mining problem, but also as a complex environmental–food chain–human health issue.

Previous studies have extensively documented mercury contamination in ASGM regions, particularly in environmental media such as water, soil, sediment, and aquatic biota (Agustiani et al., 2025; Mulenga et al., 2024; Saim, 2021). Fish are frequently used as bioindicators of mercury contamination because they integrate exposure from surrounding water, sediment-associated food sources, and trophic interactions (Oros, 2025). Mercury accumulation in fish is influenced by multiple ecological and biological factors, including habitat type, trophic level, feeding behavior, body size, age, lipid and protein composition, and the degree of contamination in the aquatic environment (Al-Sulaiti et al., 2022; Oros, 2025). Predatory and higher-trophic-level fish generally contain higher mercury concentrations because of bioaccumulation and biomagnification processes (Liu et al., 2011). In addition to its ecological consequences, mercury-contaminated fish are a major human health concern because fish consumption is one of the dominant exposure pathways for methylmercury in many communities. Human biomonitoring using biological samples such as hair, blood, or urine provides a direct indication of internal mercury burden and can complement environmental monitoring by linking external contamination with human exposure (Esteban-López et al., 2022; Peña-Fernández et al., 2021; Santonen et al., 2022). Kidney-related biomarkers, including albuminuria and estimated glomerular filtration rate, may also provide relevant information because mercury exposure has been associated with renal toxicity, oxidative stress, and tubular or glomerular dysfunction.

Despite increasing scientific attention to mercury pollution in ASGM-affected regions, several important gaps remain. Many studies have examined environmental mercury contamination, fish contamination, or human biomonitoring separately, whereas fewer have integrated these components within a single environmental–food chain–human health framework. As a result, the pathway linking mercury contamination in environmental media, accumulation in aquatic organisms, and internal mercury burden in exposed communities remains insufficiently characterized, particularly in Indonesian ASGM settings. Moreover, human health implications are often discussed from a general toxicological perspective without concurrent biomarker data. Studies that simultaneously evaluate mercury levels in environmental matrices, fish, human biomarkers, and kidney-related indicators remain limited. This integrated approach is important because mercury exposure in mining-affected communities may arise through multiple overlapping pathways, including contaminated environmental media, aquatic food-chain transfer, and indirect residential exposure. A more holistic assessment is therefore needed to better understand how mercury moves through environmental systems and contributes to potential human health risks.

The novelty of this study lies not merely in combining multiple sample types, but in using a single field dataset to trace a coherent mercury continuum from environmental retention to aquatic bioaccumulation, internal human exposure, and supportive kidney-related indicators in an Indonesian ASGM setting. Compared with many previous studies that assessed only one compartment at a time, the present study integrates water, sediment, fish muscle, human hair, and objective clinical biomarkers to evaluate whether a non-detectable water profile can coexist with detectable mercury in ecologically and clinically relevant matrices. This design provides a stronger environmental interpretation of mercury transfer than water-only or single-matrix monitoring and is particularly relevant for mining-impacted tropical river systems, where particle-bound mercury, sediment retention, and time-integrated biological uptake may dominate over instantaneous dissolved-water signals. The study further contributes context-specific evidence from Indonesia, where integrated environmental–biomonitoring datasets in ASGM-affected communities remain limited. By linking sediment contamination, fish mercury, human hair mercury, and kidney-related biomarkers within one analytical framework, this study advances

a practical multi-matrix monitoring model for environmental risk interpretation, surveillance prioritization, and public health follow-up in mercury-impacted riverine communities.

By integrating environmental matrices, aquatic biota, human mercury biomonitoring, and kidney-related clinical indicators within a single field-based framework, this study provides an applied monitoring perspective for ASGM-affected riverine systems. The approach is particularly relevant for settings where surface-water mercury may be below the analytical detection limit, while sediment retention and biological accumulation continue to indicate environmental and exposure relevance. This multi-compartment framework allows the study to move beyond water-only assessment and to evaluate mercury contamination as a linked environmental, food-chain, and human biomonitoring issue. The conceptual contribution of this study is not to prove a complete causal transfer pathway from sediment to fish to humans, but to demonstrate how mercury occurrence differs among environmental and biological compartments within the same ASGM-affected area. By comparing water, sediment, fish muscle, human hair, and kidney-related biomarkers, the study evaluates whether mercury that is not detectable in surface water may still be retained in solid environmental matrices and reflected in biological samples. The resulting interpretation is therefore based on compartment-specific evidence, co-occurrence across matrices, and environmentally plausible exposure pathways, rather than on a fully established directional transfer sequence.

Therefore, this study aimed to characterize mercury contamination across environmental, aquatic biota, and human biomonitoring matrices in an ASGM-impacted area and to interpret the resulting environmental–food chain–human exposure continuum. Specifically, this study evaluated mercury levels in water and sediment, assessed mercury accumulation in edible fish muscle, characterized internal human mercury burden using hair biomonitoring, and described kidney-related biomarkers as supportive indicators of potential health relevance. The findings are expected to provide a more realistic basis for mercury surveillance in mining-affected landscapes by showing why sediment, fish, and human biomarkers may be more informative than water alone for interpreting contamination persistence, bioaccumulation, and exposure significance.

MATERIALS AND METHODS

Study design and research framework

This study was designed as an integrated environmental monitoring, aquatic biota assessment, and human biomonitoring study in an ASGM-impacted area of Indonesia. The research framework focused on objective laboratory-based measurements rather than questionnaire-derived exposure determinants. Mercury measurements in environmental and fish samples were integrated with human mercury biomonitoring and kidney-related clinical biomarkers to evaluate potential environmental transfer and the health relevance of mercury contamination in a mining-affected setting.

The conceptual framework of this study was based on the transfer of mercury from ASGM activities into surrounding environmental compartments, followed by potential accumulation in aquatic biota and internal exposure in humans. Environmental samples were used to characterize mercury contamination in the affected ecosystem, fish samples were used to evaluate aquatic food-chain relevance, and human biological samples were used to determine internal mercury burden. Kidney-related biomarkers were included to provide supportive clinical information because mercury exposure has been associated with renal tubular and glomerular injury.

Importantly, the present study was not designed to establish causal relationships between environmental mercury contamination, fish mercury accumulation, human mercury burden, and kidney-related biomarker alterations. Instead, it was designed to provide a descriptive and integrative assessment of mercury occurrence across multiple matrices within the same ASGM-affected setting. Therefore, the interpretation of the findings is based on environmental plausibility, matrix-specific mercury distribution, and consistency across compartments rather than on causal inference. The observed pattern was used to evaluate whether non-detectable mercury in surface water could coexist with detectable mercury in sediments, fish muscle, and human hair, thereby supporting a sediment-mediated and food-chain-relevant exposure hypothesis that requires further confirmation through longitudinal, larger-scale, and mercury-speciation studies.

Study area

The study was conducted in Bungo District, Jambi Province, Indonesia, an area affected by

artisanal and small-scale gold mining activities (Figure 1). ASGM activities in this region may contribute to mercury release through amalgamation, amalgam burning, improper tailings disposal, and redistribution of contaminated materials into surrounding terrestrial and aquatic environments. Mercury released from mining activities can be transported through runoff, river flow, atmospheric deposition, and sediment-associated processes. These mechanisms may increase the likelihood of mercury accumulation in environmental matrices and aquatic organisms, thereby creating potential exposure pathways for nearby communities.

Sampling locations were selected to represent environmental and biological matrices potentially affected by ASGM-related mercury contamination. Environmental sampling focused on matrices available in the field dataset, particularly soil- and sediment-related samples, whereas fish samples represented aquatic biota relevant to food-chain exposure. Human biomonitoring data were used to characterize internal mercury burden among individuals living in the mining-affected area. Available documented sampling coordinates were recorded during fieldwork and are provided in Supplementary Table S1 to support field traceability and reproducibility. These coordinate records were compiled as part of the field validation materials and describe the spatial distribution of documented environmental sampling points within the ASGM-affected area.

Environmental sample collection and preparation

Environmental samples were collected from selected locations within the ASGM-affected area to assess mercury contamination in the surrounding environment. Soil and sediment samples were obtained from locations potentially influenced by mining activities, riverine transport, or deposition of mining-related materials. Sampling was conducted using clean stainless-steel or acid-washed tools to minimize cross-contamination. Each sample was placed in a clean, labeled polyethylene container and transported to the laboratory for preparation and analysis.

In the laboratory, visible debris such as stones, plant residues, and roots was removed manually. Solid environmental samples were air-dried or oven-dried at a controlled temperature, homogenized, gently disaggregated, and sieved before digestion. Homogenized samples were stored in clean containers until chemical

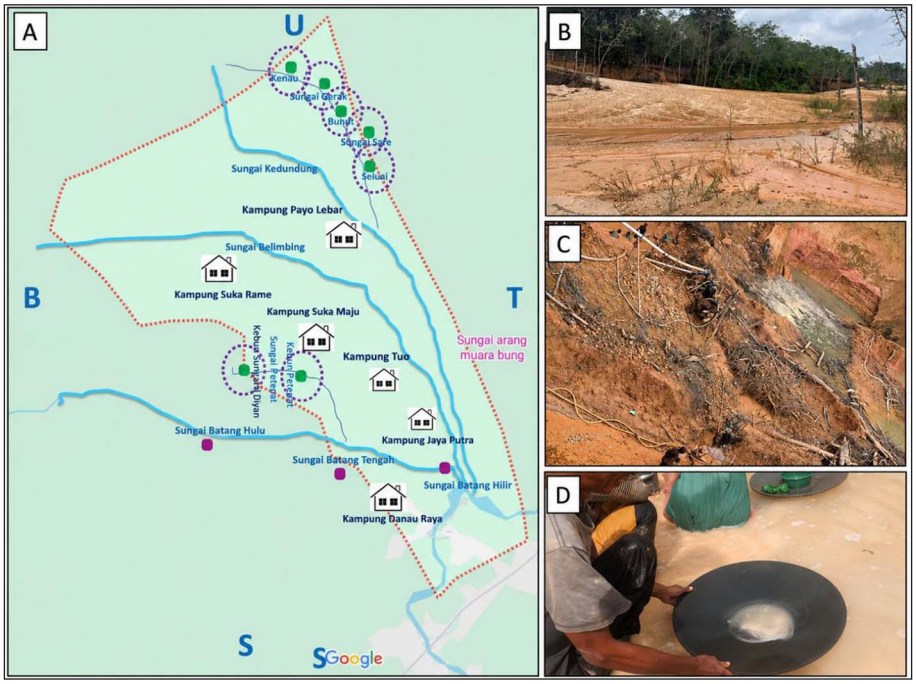

Figure 1. Study area, sampling framework, and representative field conditions in the ASGM-impacted area of Bungo District, Jambi Province, Indonesia; (a) map of the study area showing major rivers, settlements, and sampling locations; (b) disturbed landscape and sediment-laden surface runoff in the mining-affected environment; (c) active artisanal and small-scale gold mining excavation area; (d) traditional gold panning activity in a water-filled mining site

analysis. Mercury concentrations in solid environmental samples were reported as mg/kg dry weight. Water samples were collected from selected river locations using pre-cleaned polyethylene bottles. Samples were preserved and transported under cold conditions before laboratory analysis. Mercury concentrations in water were expressed as mg/L or µg/L according to the analytical report. Non-detectable results were reported as ND when concentrations were below the instrumental detection limit.

Fish sample collection and preparation

Fish samples were collected to evaluate mercury accumulation in aquatic biota and its relevance to food-chain transfer. Fish specimens were obtained from aquatic environments associated with the ASGM-affected area. Each fish sample was identified by local name and, when possible, taxonomic classification. Morphometric information, including body weight and length, was recorded when available because mercury accumulation in fish may be influenced by size, age, trophic level, and feeding behavior. Fish samples were transported to the laboratory in an ice box to preserve sample integrity. In the laboratory, edible muscle tissue was dissected using clean stainless-steel instruments on contamination-free working surfaces. Muscle tissue was selected because it represents the portion most relevant to human consumption and dietary mercury exposure. All dissection instruments were cleaned between samples using detergent, deionized water, dilute acid solution, and ultrapure water to prevent cross-contamination.

Representative fish specimens were photographed before tissue preparation using a ruler as a scale reference and geotagged/time-stamped documentation to support sample traceability. These photographs (Figure 2) were used only as verification of specimen handling and morphometric documentation, not as formal taxonomic voucher confirmation. The collected muscle tissues were homogenized prior to analysis. Samples were analyzed either on a wet-weight basis or after drying to constant weight, depending on the analytical protocol. When drying was performed, moisture content was calculated from the difference between wet and dry weights. Mercury concentrations in fish were expressed as mg/kg, with the reporting basis specified as wet weight or dry

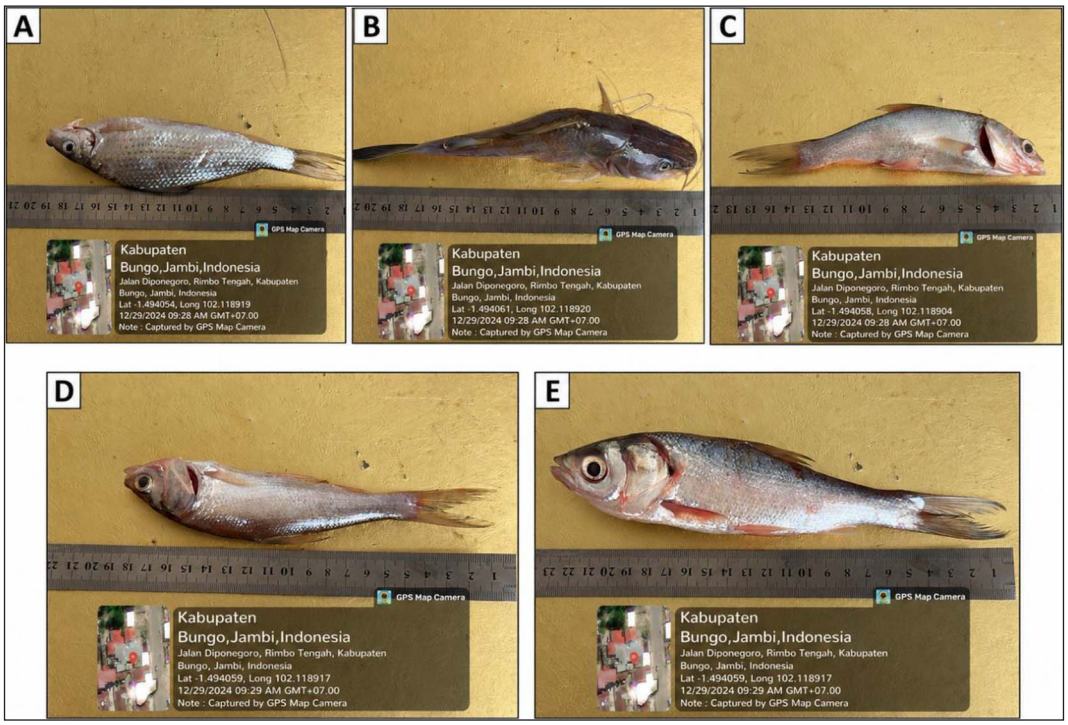

Figure 2. Representative fish specimens documented prior to muscle tissue preparation for mercury analysis. (A–E) Fish specimens photographed with a ruler as a scale reference and GPS/time-stamped field documentation to support sample traceability. The photographs were included to verify specimen handling before dissection and edible muscle tissue preparation. They should be interpreted as biological sample documentation rather than formal taxonomic voucher confirmation or evidence of species-level ecological representativeness

weight. If necessary, dry-weight concentrations were converted to wet-weight concentrations using measured moisture content or moisture ratio.

Human hair sampling and mercury biomonitoring

Human hair samples were used as a biomarker of internal mercury burden. Hair is suitable for mercury biomonitoring because mercury incorporated into keratin during hair growth can reflect cumulative exposure over time. Hair samples were collected from the occipital region of the scalp using clean stainless-steel scissors. Approximately 1–2 cm of hair closest to the scalp was collected, placed in clean labeled containers or polyethylene bags, and stored under dry conditions prior to analysis.

Before analysis, hair samples were prepared according to laboratory procedures to minimize the influence of external contamination. Samples were washed, dried, cut into small fragments, homogenized as far as possible, and digested before instrumental measurement. Mercury analysis in hair was performed using inductively coupled plasma mass spectrometry (ICP-MS). According to the laboratory certificate from PT Saraswanti Indo Genetech, mercury analysis was conducted using method 18-13-14/MU (ICP-MS). Results were expressed as mg/kg hair.

Sample digestion and mercury determination

Solid samples, including environmental samples, fish muscle, and hair, were subjected to acid digestion before mercury determination. A known mass of homogenized sample was accurately weighed using an analytical balance and transferred into clean digestion vessels. Concentrated ultrapure nitric acid was used as the main digestion reagent, and additional oxidizing reagents such as hydrogen peroxide may be used depending on the sample matrix and laboratory protocol. After digestion, sample solutions were cooled to room temperature, transferred quantitatively into volumetric tubes, and diluted to a known final volume using ultrapure water. Procedural blanks were included to monitor potential contamination from reagents and laboratory handling. Digested solutions were stored in acid-cleaned tubes until instrumental analysis.

Samples were digested before ICP-MS determination. Mercury analysis was performed using ICP-MS according to laboratory method 18-13-14/MU. Calibration standards were prepared from certified mercury standard solutions using an acid-matched diluent. A multi-point calibration curve was established over the expected analytical range. Instrument optimization and calibration verification were performed before and during analysis to ensure analytical stability. Quality-control procedures included reagent blanks, method blanks, duplicate measurements, and calibration verification standards. When available, certified reference materials and spike-recovery samples were included to assess analytical accuracy and matrix effects. Mercury concentrations in hair and solid matrices were expressed as mg/kg.

The mercury concentrations reported in this study represent total mercury (THg). Mercury speciation was not performed; therefore, the analytical results do not distinguish inorganic mercury from methylmercury or other mercury species. Consequently, any discussion of methylation, methylmercury formation, or bioavailability is presented as a plausible environmental mechanism based on established mercury biogeochemistry rather than as a process directly measured in the present study. This distinction is particularly important for fish and human biomonitoring interpretation because methylmercury is the dominant toxicologically relevant form associated with fish consumption and human internal exposure.

Kidney-related biomarker assessment

Representative analytical documentation of the biological sample workflow is presented in Figure 3 to support laboratory traceability from coded sample handling, pre-analytical processing, and aliquoting to active instrument-based measurement. The figure is used to support the methodological reliability of the biomarker workflow rather than as a descriptive photograph of equipment or biological specimens. Clinical chemistry measurements were performed using an automated Abbott Alinity clinical analyzer system. The Alinity c/i platform was used for automated laboratory testing, and the clinical chemistry component supported biochemical measurements relevant to kidney function assessment. Urinary albumin, urinary creatinine, and serum creatinine were analyzed according to the manufacturer's reagent protocols and internal clinical laboratory procedures. Calibration, internal quality control, and instrument maintenance were performed

Figure 3. Analytical traceability of biological sample processing and kidney-related biomarker measurement; (a) Coded biological samples arranged during laboratory registration and pre-analytical handling, (b) Blood sample centrifugation as part of the pre-analytical preparation workflow, (c) Aliquoting and preparation of biological specimens before instrument-based analysis; (d) Abbott Alinity c/i system monitor showing active analytical processing during the measurement run. The figure was revised to demonstrate the dynamic laboratory workflow from sample preparation to instrument operation rather than merely showing biological specimens or laboratory equipment

according to laboratory standards before sample analysis. eGFR was expressed as mL/min/1.73 m². UACR and eGFR were interpreted descriptively using established clinical categories. These biomarkers were not used to establish causality but were included as supportive health indicators in the integrated environmental-health interpretation of mercury exposure.

Data processing and descriptive interpretation

All laboratory data were compiled, checked for consistency, and organized according to sample type. Mercury concentrations were summarized descriptively for environmental matrices, fish samples, and human hair samples using minimum, maximum, mean, and standard deviation or median and range where appropriate. Kidney-related biomarkers were also summarized descriptively. No questionnaire-derived variables were included in the present manuscript, and no inferential statistical testing was performed. Environmental mercury concentrations were compared with relevant environmental quality standards or international guideline values where applicable. Fish mercury concentrations were compared with food safety limits for mercury in fish. Human hair mercury concentrations were interpreted in relation to recognized biomonitoring reference values. UACR and eGFR results were interpreted using clinical classification categories for albuminuria and kidney function.

The environmental-health interpretation was developed using an integrated pathway approach. Mercury contamination in environmental samples was interpreted as evidence of external contamination, fish mercury levels were interpreted as indicators of aquatic bioaccumulation and food-chain relevance, and hair mercury concentrations were interpreted as evidence of internal human mercury burden. Kidney-related biomarkers were discussed as supportive indicators of potential health concern, with careful attention to the descriptive and cross-sectional nature of the dataset. Terminology was standardized throughout the

manuscript by using "ASGM-affected area" to refer to the specific study setting in Bungo District and "ASGM-affected riverine systems" when discussing broader implications. Percentages were reported together with their denominators to improve clarity. For example, elevated hair mercury was expressed as 5 of 50 participants (10.0%), and altered kidney-related indicators were expressed as 9 of 50 participants (18.0%). Non-detectable mercury results were reported as below the instrumental detection limit where this information was available. When the exact detection limit was not provided in the available laboratory report, non-detectable results were interpreted cautiously and described as below the reporting threshold of the applied analytical method.

Ethical considerations

Human biomonitoring and clinical data collection were conducted in accordance with ethical principles for research involving human participants. Ethical approval was obtained from the relevant institutional ethics committee prior to sample collection. Informed consent was obtained before biological sample collection. Participant confidentiality was maintained throughout the study, and personal identifiers were removed from the dataset before analysis. Results were reported only in aggregate form.

RESULTS AND DISCUSSION

Environmental mercury contamination in ASGM-affected sites

Environmental mercury assessment was conducted to characterize the occurrence of mercury in aquatic and terrestrial matrices within the ASGM-affected area. The monitoring results showed that mercury was not detected in the analyzed water samples, whereas detectable concentrations were observed in several sediment- or soil-related samples. Previous studies have also shown that mercury may be undetectable in water while still accumulating in sediments and soils because these compartments can act as mercury sinks (Nelson et al., 2022). In an artisanal gold-mining area in North Sumatra, Indonesia, mercury in wells and river water was below the analytical detection limit, whereas sediments and soils showed the highest accumulation (Astika et al., 2021). This pattern indicates that mercury in the study area was more clearly retained in solid environmental compartments than in the aqueous phase. Such a distribution is environmentally relevant because mercury released from ASGM activities can rapidly partition onto suspended particles, fine sediments, organic matter, and mineral surfaces rather than remain dissolved in surface water. Consequently, water samples may show non-detectable mercury levels even when surrounding sediment or soil contains measurable mercury residues.

As shown in Table 1, mercury was not detected in any of the analyzed water samples, whereas detectable concentrations were observed in several sediment samples. Mean sediment mercury concentrations ranged from 0.02 to 0.10 mg/kg, indicating that mercury in the study area was more clearly retained in solid environmental compartments than in the water column. The highest mean sediment mercury concentration was observed at the upstream site of Sungai Bathin III Ulu without direct human activity, followed by Sungai Gerak, Kebun Seluai, and downstream sites of Sungai Bathin III Ulu. Overall, detectable mercury concentrations in solid matrices ranged from 0.02 to 0.10 mg/kg across the investigated locations. Mercury was detected in samples from Sungai Petepat, Kebun Bunut, Sungai Gerak, Kebun Seluai, and several locations along Sungai Bathin III Ulu. The presence of mercury at multiple locations suggests that contamination may not be restricted to a single point source but may reflect broader environmental redistribution within the mining-affected landscape. In ASGM environments, mercury can be transported through erosion of contaminated soil, resuspension of fine particles, surface runoff, riverine sediment transport, and atmospheric deposition from amalgam burning. Therefore, detectable mercury in solid matrices may represent an integrated record of past and ongoing contamination processes.

The absence of detectable mercury in water samples should be interpreted cautiously and should not be taken as evidence that mercury was absent from the aquatic environment. A non-detect result may reflect several factors, including the analytical detection limit, dilution by river flow, sampling timing, short-term hydrological variability, and the mercury fraction captured by the sampling and analytical procedure. Mercury in ASGM-affected river systems may occur predominantly in particle-bound or sediment-associated forms rather than as dissolved mercury in

Table 1. Mercury concentrations in environmental samples collected from the ASGM-affected area. Water samples were non-detectable at all locations, whereas sediment mercury was detected at several sites

No.	Location	Water Hg	Sediment Duplicate 1 (mg/kg)	Sediment Duplicate 2 (mg/kg)	Mean Sediment Hg (mg/kg)
1	Sungai Petepat	ND	0.02	0.02	0.02
2	Sungai Kedudung	ND	ND	ND	ND
3	Kebun Bunut	ND	0.05	0.04	0.045
4	Sungai Gerak	ND	0.09	0.08	0.085
5	Kebun Seluai	ND	0.07	0.07	0.07
6	Sungai Sare	ND	ND	ND	ND
7	Sungai Belimbing	ND	ND	ND	ND
8	Kebun Kenalu	ND	ND	ND	ND
9	Sungai Diyan	ND	ND	ND	ND
10	Sungai Batang Bungo (hilir)	ND	ND	ND	ND
11	Sungai Batang Bungo (tengah)	ND	ND	ND	ND
12	Sungai Batang Bungo (hulu)	ND	ND	ND	ND
13	Sungai Bathin III Ulu (aktivitas manusia) hilir	ND	0.05	0.05	0.05
14	Sungai Bathin III Ulu (aktivitas manusia) tengah	ND	0.02	0.02	0.02
15	Sungai Bathin III Ulu (tanpa aktivitas manusia) hilir	ND	0.07	0.07	0.07
16	Sungai Bathin III Ulu (tanpa aktivitas manusia) tengah	ND	0.04	0.04	0.04
17	Sungai Bathin III Ulu (tanpa aktivitas manusia) hulu	ND	0.10	0.10	0.10

Note: *ND: not detected; below the instrumental detection limit.

the water column. Therefore, a single-time-point water measurement may fail to capture episodic or particulate mercury transport, especially during rainfall, runoff, flooding, or sediment resuspension events. In this context, water monitoring remains important, but water data should be interpreted together with sediment and biological matrices to avoid underestimating mercury persistence and exposure relevance.

Mercury often partitions strongly into suspended particles and sediments rather than remaining dissolved in water (Han et al., 2004). Hydrology and high-discharge events can control mercury transport in rivers, especially by moving sediment-bound mercury (Moreno-Brush et al., 2020). This interpretation is also consistent with broader evidence that sediments can function as important reservoirs and future secondary sources of metal contamination in impacted aquatic systems (Gumbo and Kapenge, 2025). In tropical mining-affected catchments, high rainfall, runoff, and sediment mobilization may further enhance the transfer of mercury from water columns into sediments and floodplain deposits. Therefore, sediment or soil-associated mercury may provide a more stable indicator of contamination than a single water measurement. This finding supports the importance of including solid environmental matrices when evaluating mercury contamination in ASGM-impacted aquatic systems.

The relatively high sediment mercury concentration at the upstream site categorized as without direct human activity should not be interpreted as evidence of natural background contamination alone. In mining-affected catchments, locations without visible local activity may still receive mercury through upstream transport, historical deposition, erosion of contaminated materials, or hydrological connectivity with disturbed areas. Historical mining sediments can remain stored in floodplains and later be eroded and transported downstream (Leigh, 1994). From an environmental-health perspective, mercury in sediment is important because these compartments can act as both sinks and secondary sources. Sediments can retain mercury for long periods but may later release it through remobilization (Ramalhosa et al., 2006). Under suitable biogeochemical conditions, retained mercury may be transformed into methylmercury and enter aquatic food webs, creating ecological and public health relevance even when total sediment concentrations are relatively low.

Mercury accumulation in fish and aquatic food-chain relevance

Mercury was detected in all analyzed fish samples, indicating measurable mercury occurrence in the edible fish muscle collected from the ASGM-affected aquatic environment. However, the fish dataset was limited to one specimen per species/local name; therefore, the results should be interpreted as preliminary descriptive evidence of mercury presence in fish rather than as a basis for ecological generalization. The dataset does not allow reliable conclusions regarding species-specific accumulation, trophic transfer, biomagnification, or differences among fish taxa. Accordingly, the discussion of fish mercury in this study is restricted to its role as an indicator of food-chain relevance and potential dietary exposure, while broader ecological interpretation requires larger sample sizes, repeated sampling, and trophic-level assessment (Table 2).

Because only total mercury was measured in fish muscle, the present study cannot determine the proportion of methylmercury in the analyzed fish samples. This is an important limitation because methylmercury is generally the mercury species of greatest toxicological relevance for fish consumption and human exposure. Therefore, the detection of total mercury in fish should be interpreted as evidence of mercury occurrence in edible tissue and potential food-chain relevance, rather than as direct evidence of methylmercury exposure or biomagnification. Future studies should include mercury speciation in fish muscle to better assess dietary exposure and toxicological risk.

Mean mercury concentrations in fish ranged from 0.05 to 0.17 mg/kg. The highest concentration was observed in Lambak, followed by Lampam, Baung, and Seluang. Although the number of fish samples was limited, the detection of mercury across all analyzed species provides important evidence that mercury contamination had entered the aquatic biotic compartment. This finding is environmentally relevant because fish integrate mercury exposure from water, sediment-associated food sources, benthic organisms, and trophic interactions. Therefore, fish mercury concentrations may reflect cumulative exposure within the aquatic ecosystem more effectively than a single water measurement. Previous studies have shown that fish mercury is strongly influenced by age, diet, trophic position, and ecosystem conditions (Bartz et al., 2023). In addition, benthic feeding can increase mercury transfer from sediments into fish (Rizzo et al., 2014).

The contrast between non-detectable mercury in water and detectable mercury in fish supports the concept that aquatic mercury exposure is not determined solely by dissolved mercury in the water column. Mercury can bind to suspended particles and sediments, persist in these compartments, and become biologically available through sediment–water and food-web pathways (Xu et al., 2022). Under suitable conditions, especially in organic-rich or particle-rich systems, microorganisms can convert inorganic mercury into methylmercury, a more bioavailable form that is efficiently absorbed and biomagnified in aquatic food webs (Gascón Díez et al., 2016; Lehnherr, 2014). Once incorporated into fish tissue, mercury can be retained and increase through bioaccumulation and biomagnification along the food chain (Chen et al., 2008; Gentès et al., 2021).

Although Lambak, Lampam, and Baung showed higher mercury concentrations than Seluang in the present dataset, this pattern should be interpreted cautiously because only one specimen was analyzed for each species/local name. The observed differences may reflect individual-level variation, fish size, habitat history, feeding behavior, sampling location, or analytical variability rather than true species-specific differences. Therefore, the present data cannot be used to rank fish species according to mercury accumulation potential or to infer biomagnification

Table 2. Mercury concentrations in fish samples collected from the ASGM-affected aquatic environment

No.	Fish species/local name	Weight (g)	Length (cm)	Hg Duplicate 1 (mg/kg)	Hg Duplicate 2 (mg/kg)	Mean Hg (mg/kg)
1	Baung	98	22	0.13	0.15	0.14
2	Lambak	69	19	0.17	0.17	0.17
3	Seluang	47	18	0.05	0.05	0.05
4	Lampam	110	24	0.15	0.16	0.16

patterns. A reliable ecological interpretation would require a larger number of specimens per species, broader size-class coverage, repeated seasonal sampling, and supporting trophic information such as stable isotope analysis. Fish that interact more closely with sediments or consume benthic organisms may have greater exposure to sediment-associated mercury, whereas higher-trophic-level species may accumulate more mercury through prey consumption (He et al., 2022; Sarasiab et al., 2014). Previous studies have shown that fish mercury varies with species, body size, trophic level, habitat, feeding behavior, and local contamination conditions (Le Croizier et al., 2019; Mille et al., 2021). Accordingly, interspecies differences should be interpreted as the combined result of environmental exposure and ecological traits rather than as a simple reflection of dissolved mercury in water.

From a food-chain perspective, mercury in edible fish muscle is important because fish consumption is a major human exposure pathway for methylmercury (Chen and Driscoll, 2018). Although fish mercury concentrations in the present study were below commonly used international limits, the finding remains relevant for public health because repeated consumption of locally caught fish may contribute to chronic low-dose mercury intake over time, especially in ASGM-affected communities where mercury inputs can persist and fish may be a regular protein source (Gibb and O'Leary, 2014; Salazar-Camacho et al., 2017). Studies in ASGM regions have shown that fish consumption is a significant predictor of human mercury biomarkers (Calao-Ramos et al., 2021; Wyatt et al., 2017).

Overall, the fish results provide preliminary evidence that mercury was present in edible fish muscle from the ASGM-affected aquatic environment despite non-detectable mercury in water samples. This finding supports the inclusion of fish as a relevant biological matrix in mercury monitoring programs. However, because of the limited number of fish specimens, the results should not be interpreted as evidence of species-specific bioaccumulation, trophic transfer, or biomagnification. Future studies should include larger fish sample sizes, replicate specimens per species, fish age or size stratification, seasonal sampling, and trophic-position analysis to better characterize mercury accumulation within the aquatic food web.

Sediment-mediated mercury bioaccumulation: Explaining mercury detection in fish despite non-detectable water mercury

The detection of mercury in fish despite non-detectable mercury in water is an important observation, but it should be interpreted within the methodological limitations of water sampling. Non-detectable mercury in water may result from concentrations below the analytical detection limit, short-term dilution, sampling outside high-flow or resuspension periods, or the predominance of particle-bound mercury that was not fully represented in the analyzed water fraction. Therefore, the present findings do not indicate that water monitoring is unimportant. Rather, they show that single-time-point water measurements alone may be insufficient to characterize mercury contamination in ASGM-affected aquatic systems, particularly when mercury is retained in sediments or transferred into biological matrices over time. The proposed sediment-mediated mercury bioaccumulation pathway is illustrated in Figure 4.

In the present study, mercury was not detected in any analyzed water sample, whereas sediment mercury was detected at several locations and mercury was found in all analyzed fish samples. This pattern suggests that mercury in the study area was retained more strongly in solid environmental compartments and biological tissues than in the water column. Mercury released from ASGM activities can rapidly partition from the aqueous phase onto suspended particles, fine sediments, organic matter, and mineral surfaces. Once bound to particulate material, mercury may settle into riverbed sediments or floodplain deposits, creating a long-term environmental reservoir (Hošek et al., 2020). As a result, the water column may show non-detectable mercury concentrations while sediments and aquatic organisms still contain measurable mercury.

Sediment plays a central role in mercury cycling because it can act as both a sink and a secondary source. It can retain mercury derived from mining residues, runoff, erosion, and atmospheric deposition, while sediment-associated mercury can later be remobilized during flooding, resuspension, flow changes, or bioturbation (Brown et al., 2015; García-Ordiales et al., 2020; Meyer and Medeiros, 2017). Under suitable biogeochemical conditions, inorganic mercury retained

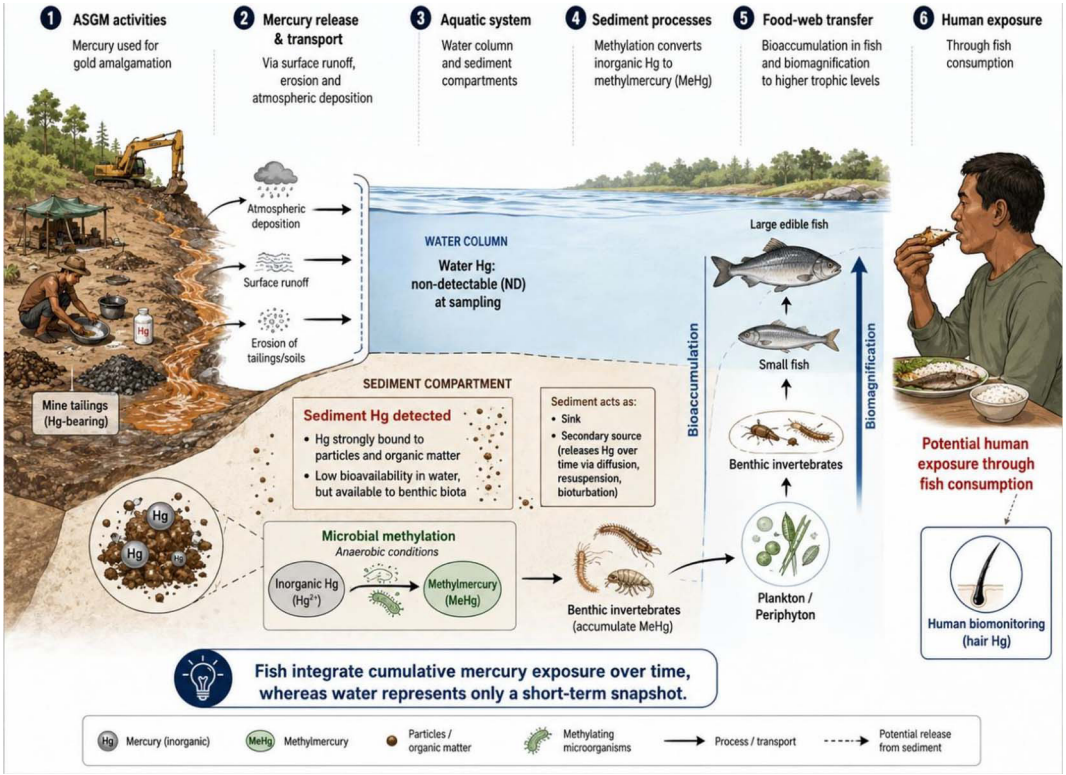

Figure 4. Conceptual illustration of a plausible sediment-mediated and food-chain-relevant mercury pathway in an ASGM-affected aquatic ecosystem. The methylation and bioavailability steps are shown as established environmental processes that may occur under suitable biogeochemical conditions, but they were not directly measured because the present study analyzed total mercury only

in sediment may be transformed by microorganisms into methylmercury, a more bioavailable and bioaccumulative mercury species (Ullrich et al., 2001). However, the present study measured only total mercury and did not include mercury speciation in sediment, fish, water, or human biological samples. Therefore, methylation and methylmercury-related bioavailability should be interpreted as plausible mechanisms that may explain mercury transfer in ASGM-affected aquatic systems, not as directly demonstrated processes in this dataset.

Fish mercury concentrations are therefore not determined solely by mercury levels in the water column. In general, fish can accumulate mercury through dietary uptake, benthic food-web interactions, and long-term exposure within contaminated habitats (Bigham et al., 2016; Prasad et al., 2005). However, because the present study analyzed only one specimen per species/local name and did not include trophic-position analysis, these mechanisms should be considered plausible background processes rather than directly demonstrated pathways in the present dataset. Because methylmercury binds strongly to proteins in fish muscle and is eliminated slowly, fish can retain mercury over extended periods. This explains why mercury may be detectable in fish even when single-time-point water samples show non-detectable concentrations. In this context, fish act as biological integrators of mercury exposure rather than direct indicators of instantaneous water quality.

The observed pattern also highlights the limitation of relying solely on water samples to assess mercury contamination in ASGM-affected aquatic systems. Water mercury levels may fluctuate substantially with rainfall, dilution, hydrological conditions, suspended sediment load, and sampling timing. In contrast, sediment and fish provide more stable and cumulative information about mercury contamination and exposure. Sediment reflects longer-term retention of mercury within the aquatic environment, whereas fish reflects biological uptake and food-chain transfer. Therefore, integrated monitoring involving water, sediment, and biota is essential for evaluating mercury risk in mining-affected river systems. From a food-chain perspective, the presence of mercury in fish muscle is particularly important because edible fish tissue represents a direct route of human exposure. Even when measured

concentrations remain below international food safety limits, repeated consumption of contaminated fish may contribute to chronic low-dose mercury intake, especially in communities living near mining-affected rivers. The detection of mercury in all analyzed fish samples therefore supports the need for continued biomonitoring of aquatic biota and careful interpretation of environmental mercury data. Non-detectable mercury in water should not be interpreted as evidence of ecological safety when sediment and fish compartments show mercury accumulation.

Overall, the present findings indicate a sediment-mediated mercury bioaccumulation pathway in the ASGM-affected aquatic environment. Mercury appears to be more clearly retained in sediments and transferred into fish than detected in the water column. This finding emphasizes that sediment and fish are critical matrices for assessing mercury contamination and potential human exposure in mining-impacted ecosystems. The integration of environmental and biological matrices provides a more realistic understanding of mercury transfer than water monitoring alone.

Human mercury biomonitoring profile

Human mercury biomonitoring was conducted using hair mercury concentration as an indicator of internal mercury burden among residents living in the ASGM-affected area. Hair mercury is widely used in environmental health studies because mercury incorporated into hair keratin reflects cumulative exposure over time, particularly exposure to methylmercury from aquatic food-chain pathways and other environmental sources (Souza et al., 2025). In the present study, mercury was detected in all analyzed hair samples, indicating measurable internal mercury exposure among the study population.

Table 3. Distribution of hair mercury concentrations among residents living in the ASGM-affected area

Parameter	Value
Mean hair Hg concentration (mg/kg)	1.01 ± 0.98
Median hair Hg concentration (mg/kg)	0.76
Minimum hair Hg concentration (mg/kg)	0.17
Maximum hair Hg concentration (mg/kg)	6.15
Participants with hair Hg <1.0 mg/kg	36 (72.0%)
Participants with hair Hg 1.0–<2.0 mg/kg	9 (18.0%)
Participants with hair Hg ≥2.0 mg/kg	5 (10.0%)

The distribution of hair mercury concentrations is summarized in Table 3. Hair mercury concentrations ranged from 0.17 to 6.15 mg/kg, with a mean concentration of 1.01 ± 0.98 mg/kg and a median of 0.76 mg/kg. Most participants had hair mercury concentrations below 1.0 mg/kg, while a smaller subgroup showed higher concentrations. Based on the 2 mg/kg reference threshold used for elevated exposure classification, 5 participants, corresponding to 10.0% of the study population, had elevated hair mercury concentrations. In addition, 9 participants had concentrations between 1.0 and <2.0 mg/kg, indicating that 28.0% of participants had hair mercury concentrations above 1.0 mg/kg.

The detection of mercury in all hair samples indicates that mercury exposure was not limited to environmental compartments or fish tissue but was also reflected in human biological samples. This finding is important because hair mercury represents cumulative internal exposure rather than short-term environmental contact. A previous study in Canada also reported hair-to-blood mercury relationships above World Health Organization reference levels in part of the study population (Packull-McCormick et al., 2022). In the context of the present study, measurable hair mercury concentrations are consistent with the detection of mercury in sediment and fish, supporting the interpretation that mercury contamination in the ASGM-affected environment may contribute to human exposure through multiple pathways.

The mean hair mercury concentration remained below the 2 mg/kg threshold; however, the presence of individuals exceeding this level indicates that a vulnerable high-exposure subgroup exists within the study population. The maximum concentration of 6.15 mg/kg demonstrates substantial inter-individual variability in mercury burden. Such variability may reflect differences in duration of residence, dietary exposure through fish, proximity to contaminated environmental media, occupational or household contact with mining-related materials, and individual toxicokinetic factors. Because questionnaire-derived variables were intentionally excluded from the present manuscript, these potential determinants are discussed only as plausible exposure pathways rather than as directly tested explanatory factors.

The distribution pattern also suggests that population averages alone may underestimate exposure concern. Although the overall mean was moderate, elevated individual values indicate that some

residents had mercury burdens substantially higher than the group average. This is important because mercury-related health risks are often concentrated in vulnerable or highly exposed subgroups, such as frequent fish consumers, miners, children, or pregnant women, rather than being distributed evenly across the population (Baeuml et al., 2011; Cullen et al., 2014). Human biomonitoring therefore provides essential information on internal exposure that cannot be inferred from environmental measurements alone. Integrating hair mercury data with environmental and fish results strengthens the evidence for an environmental–food chain–human exposure continuum in the study area. Mercury was not detected in water, but it was detected in sediment, fish, and human hair. This pattern supports the interpretation that mercury exposure may be mediated through long-term sediment retention, transfer into aquatic organisms, and eventual accumulation in humans. The hair mercury findings therefore provide biological confirmation that environmental mercury contamination in the ASGM-affected area has relevance beyond environmental matrices and may translate into measurable internal exposure among residents.

Overall, the human biomonitoring results indicate measurable mercury exposure among residents in the ASGM-affected area, with a subset of individuals showing elevated hair mercury concentrations. These findings highlight the importance of combining environmental monitoring with human biomonitoring to better characterize mercury exposure in mining-affected communities. Continued biomonitoring is needed to identify high-exposure individuals, evaluate temporal trends, and support targeted environmental health interventions.

Kidney-related biomarkers and potential health implications

Kidney-related biomarkers were evaluated as descriptive clinical indicators to complement the human mercury biomonitoring profile. In the present study, urinary albumin-to-creatinine ratio (UACR) and estimated glomerular filtration rate (eGFR) were used to describe kidney-related status among residents living in the ASGM-affected area. These biomarkers were included to provide a preliminary health-context layer, not to establish mercury-induced kidney effects. No statistical association analysis was performed between hair mercury concentration and UACR or eGFR, and the study did not adjust for clinical or demographic confounders such as age, hypertension, diabetes, hydration status, infection, medication use, nutritional status, or pre-existing kidney disease. Therefore, the kidney-related findings should be interpreted strictly as co-occurring biomarker alterations within a population where internal mercury exposure was also detected, rather than as evidence that mercury exposure caused kidney dysfunction.

The distribution of kidney-related biomarkers is summarized in Table 4. The mean UACR value was 16.31 ± 32.55 mg/g, with values ranging from 1.61 to 174.46 mg/g. Most participants had UACR values within the normal category; however, 5 participants, corresponding to 10.0% of the study population, showed UACR values ≥30 mg/g, indicating the presence of albuminuria. For eGFR, the mean value was 107.76 ± 40.62 mL/min/1.73 m², with values ranging from 39.22 to 190.15 mL/min/1.73 m². A total of 6 participants, corresponding to 12.0% of the study population, had eGFR values <60 mL/min/1.73 m². When UACR ≥30 mg/g or eGFR <60 mL/min/1.73 m² was considered as an altered kidney-related profile, 9 participants, or 18.0% of the study population, had at least one altered kidney-related indicator. These findings indicate that a subset of participants had kidney-related biomarker

Table 4. Distribution of kidney-related biomarkers among residents living in the ASGM-affected area

Parameter	Value
Mean UACR (mg/g)	16.31 ± 32.55
Median UACR (mg/g)	4.60
Minimum–maximum UACR (mg/g)	1.61–174.46
Participants with UACR <30 mg/g	45 (90.0%)
Participants with UACR 30–300 mg/g	5 (10.0%)
Participants with UACR >300 mg/g	0 (0.0%)
Mean eGFR (mL/min/1.73 m²)	107.76 ± 40.62
Median eGFR (mL/min/1.73 m²)	109.60
Minimum–maximum eGFR (mL/min/1.73 m²)	39.22–190.15
Participants with eGFR ≥90 mL/min/1.73 m²	30 (60.0%)
Participants with eGFR 60–89 mL/min/1.73 m²	14 (28.0%)
Participants with eGFR 45–59 mL/min/1.73 m²	5 (10.0%)
Participants with eGFR 30–44 mL/min/1.73 m²	1 (2.0%)
Participants with eGFR <30 mL/min/1.73 m²	0 (0.0%)
Participants with UACR ≥30 mg/g or eGFR <60 mL/min/1.73 m²	9 (18.0%)

alterations, but the cross-sectional and descriptive nature of the study prevents attribution of these alterations to mercury exposure.

The presence of albuminuria in a subset of participants is clinically relevant because UACR is commonly used as an early indicator of kidney damage. Albuminuria may reflect increased glomerular permeability, tubular dysfunction, vascular injury, or inflammatory processes affecting the kidney (Comper et al., 2022). In the context of mercury exposure, renal effects are biologically plausible because mercury can accumulate in renal tissue, induce oxidative stress, disrupt cellular redox balance, and affect tubular and glomerular structures (Bridges and Zalups, 2017; Salazar-Flores et al., 2019). However, albuminuria is not specific to mercury exposure and may also be influenced by other conditions such as hypertension, diabetes, infection, dehydration, age-related kidney changes, and other environmental or occupational exposures. Therefore, the UACR findings should be interpreted as evidence of kidney-related vulnerability within the population rather than direct proof of mercury-induced renal injury.

The eGFR results showed that most participants had preserved filtration function, as indicated by eGFR values ≥60 mL/min/1.73 m². Nevertheless, 12.0% of participants had eGFR values below 60 mL/min/1.73 m², suggesting reduced kidney filtration in a minority of individuals. This finding is important because reduced eGFR may indicate impaired kidney function, although interpretation in cross-sectional environmental studies requires caution. eGFR can be influenced by age, muscle mass, hydration status, nutritional condition, chronic disease, and methodological differences in serum creatinine measurement. Therefore, reduced eGFR observed in this study should be considered a signal for further clinical evaluation rather than a definitive diagnosis of mercury-related kidney disease.

The combined interpretation of UACR and eGFR provides a broader view of kidney-related status than either biomarker alone. Some individuals may show increased UACR while maintaining normal eGFR, reflecting early kidney injury or increased renal permeability before filtration decline becomes apparent. Conversely, reduced eGFR may occur without elevated albuminuria, depending on the underlying mechanism of kidney impairment. In the present study, 18.0% of participants had at least one altered kidney-related indicator, suggesting that kidney health monitoring may be relevant in communities affected by ASGM-related mercury contamination.

When interpreted together with the human hair mercury data, the kidney-related biomarker results indicate co-occurrence rather than a demonstrated exposure–effect relationship. The study identified measurable mercury concentrations in all hair samples and detected altered kidney-related indicators in a subset of participants. However, because no correlation, regression, stratified analysis, or confounder-adjusted model was performed, these findings cannot be used to infer that mercury exposure contributed to the observed UACR or eGFR alterations. The kidney biomarker data should therefore be viewed as preliminary clinical-context information that supports the need for follow-up health surveillance, rather than as evidence of mercury-related renal injury.

Overall, the kidney-related biomarker results show that most participants had UACR and eGFR values within normal clinical categories, while a smaller subgroup showed albuminuria, reduced filtration function, or at least one altered kidney-related indicator. These findings do not demonstrate mercury-induced kidney dysfunction. Instead, they indicate that kidney-related biomarker alterations co-occurred in part of the study population where internal mercury burden was also measurable. This co-occurrence supports the value of integrating exposure biomonitoring with basic clinical screening in ASGM-affected communities, but causal interpretation requires future studies with larger sample sizes, repeated biomarker measurements, individual exposure assessment, and multivariable adjustment for relevant clinical confounders.

Integrated environmental–food chain–human exposure interpretation

The integrated interpretation presented in this section should be understood as a pathway-based synthesis rather than a causal model. Because the study used a cross-sectional design and did not include mercury speciation, repeated seasonal sampling, individual dietary intake assessment, or longitudinal kidney-function follow-up, the observed relationships among sediment mercury, fish mercury, hair mercury, and kidney-related biomarkers cannot be interpreted as direct cause–effect associations. Nevertheless, the simultaneous assessment of environmental, aquatic biota, and human biological matrices provides a stronger

descriptive basis than single-matrix monitoring for identifying environmentally plausible mercury transfer pathways in the ASGM-affected area. The integrated findings show that mercury contamination in the ASGM-affected area cannot be understood adequately from a single matrix. Mercury was not detected in water at the time of sampling, yet it was detected in sediment, fish muscle, and human hair. This pattern supports an exposure continuum driven by solid-phase retention, aquatic food-chain transfer, and cumulative internal exposure rather than persistent dissolved mercury in the water column.

The environmental data showed that sediment was a more informative matrix than water for detecting mercury contamination. Although all water samples were non-detectable, sediment mercury concentrations ranged from 0.02 to 0.10 mg/kg at several locations. This indicates that mercury released from mining-related activities may have been retained in riverbed sediments, floodplain deposits, or soil-associated materials. In ASGM-affected systems, mercury can bind strongly to fine particles, organic matter, and mineral surfaces, allowing sediments to function as long-term reservoirs. These reservoirs may subsequently contribute to biological exposure through resuspension, diffusion, benthic uptake, and microbial transformation into methylmercury.

The detection of mercury in all analyzed fish samples provides evidence that mercury had entered the aquatic biotic compartment. Fish mercury concentrations ranged from 0.05 to 0.17 mg/kg, indicating measurable accumulation in edible muscle tissue. This finding is important because fish integrate mercury exposure over time through multiple pathways, including contaminated prey, benthic food webs, and habitat-specific exposure (Lepak et al., 2019; Oros, 2025). Unlike water samples, which represent short-term environmental conditions, fish tissue reflects cumulative exposure and biological retention. Therefore, fish serve as a critical link between environmental contamination and potential human exposure.

Human biomonitoring results further support the relevance of environmental and food-chain mercury transfer. Mercury was detected in all analyzed hair samples, with concentrations ranging from 0.17 to 6.15 mg/kg. Although the mean hair mercury concentration remained below the elevated exposure threshold, a subset of participants had concentrations ≥2.0 mg/kg. This finding indicates that mercury contamination in the surrounding environment has potential biological relevance for residents living in the ASGM-affected area. Hair mercury represents cumulative internal exposure and may reflect long-term contact with mercury through dietary, environmental, or other local exposure pathways (Višnjevec et al., 2013; Boerleider et al., 2017). Because behavioral and questionnaire-derived variables were excluded from this manuscript, the present interpretation does not assign exposure to specific individual behaviors but instead emphasizes the environmental plausibility of mercury transfer from contaminated ecosystems to humans.

The kidney-related biomarker results add another layer to the integrated environmental health interpretation. Most participants had UACR and eGFR values within normal clinical categories; however, a measurable subgroup showed albuminuria, reduced filtration function, or at least one altered kidney-related indicator. These findings do not establish a causal relationship between mercury exposure and kidney dysfunction. Nevertheless, the coexistence of measurable internal mercury burden and altered renal indicators in part of the study population supports the need for continued health surveillance in mining-affected communities. The kidney is a biologically plausible target organ for mercury toxicity because mercury can accumulate in renal tissues and contribute to oxidative stress, tubular injury, and glomerular dysfunction (Bridges and Zalups, 2017; Salazar-Flores et al., 2019).

Taken together, the present results are consistent with a plausible environmental–food chain–human exposure framework, but they should not be interpreted as evidence of a confirmed directional continuum or causal pathway. Mercury released from ASGM activities may be transported through runoff, erosion, atmospheric deposition, and particle movement into aquatic and sedimentary compartments. Sediment-associated mercury may persist and, under suitable environmental conditions, may become more bioavailable through microbial transformation. Mercury detected in fish muscle indicates food-chain-relevant accumulation, while mercury detected in human hair indicates internal mercury burden among residents. However, because this study did not include mercury speciation, stable isotope-based trophic analysis, individual fish-consumption data, occupational exposure assessment, longitudinal biomonitoring, or multivariable adjustment for clinical confounders, the observed

pattern should be interpreted as environmentally plausible and hypothesis-generating rather than causal. Similarly, the kidney-related biomarker findings indicate the presence of altered renal indicators in a subset of participants, but they do not demonstrate that these alterations were caused by mercury exposure.

This integrated pattern has important implications for environmental monitoring strategies. Monitoring water alone may underestimate mercury risk in ASGM-affected ecosystems because mercury can be non-detectable in the water column while still being retained in sediments and accumulated in biota. Similarly, environmental data alone may not fully capture human exposure unless paired with biomonitoring. The findings therefore support a multi-matrix monitoring approach that includes sediments, fish, and human biomarkers. Such an approach is more suitable for identifying persistent contamination, food-chain transfer, and potential health relevance in mining-affected environments.

Overall, the study shows that mercury in ASGM-affected communities should be interpreted through an integrated environmental–food chain–human exposure framework. The detection of mercury in sediment, fish, and human hair despite non-detectable water mercury highlights the importance of cumulative and matrix-specific assessment for environmental surveillance and risk interpretation.

Environmental and public health implications

The findings have practical implications for environmental monitoring and health surveillance in ASGM-affected communities. The detection of mercury in sediment, fish, and human hair despite non-detectable water mercury indicates that water-only monitoring may underestimate contamination relevance. A surveillance strategy that includes sediment, aquatic biota, and human biomarkers is therefore more appropriate for identifying persistent contamination and exposure significance. The combined assessment of sediment, fish, human hair, UACR, and eGFR provides an applied surveillance framework for ASGM-affected communities, although the clinical biomarker results should be interpreted as preliminary supportive indicators rather than diagnostic evidence of mercury-related disease.

From an environmental perspective, sediment should be considered a priority matrix for mercury monitoring in mining-affected river systems. Sediments can retain mercury over long periods and may act as secondary sources under changing hydrological and biogeochemical conditions (Selin, 2009). During rainfall events, flooding, erosion, or sediment resuspension, sediment-bound mercury can be redistributed across aquatic and floodplain environments (Baudo, 2020; Schwab et al., 2022). In addition, microbial methylation in sediment can transform inorganic mercury into methylmercury, increasing the potential for biological uptake (Regnell and Watras, 2019; Zhao et al., 2024). Therefore, periodic sediment monitoring is needed to evaluate contamination persistence, identify hotspot areas, and assess the potential for long-term ecological exposure.

Fish monitoring is equally important because fish represent a direct link between environmental contamination and potential human exposure. The detection of mercury in edible fish muscle indicates that mercury had entered the aquatic food-chain compartment. Although the measured concentrations were relatively low to moderate, repeated consumption of locally caught fish may still contribute to chronic exposure, particularly in communities dependent on riverine fish as a regular protein source. Public health programs in ASGM-affected areas should therefore include routine fish mercury assessment, identification of species with higher accumulation potential, and risk communication regarding safer fish consumption practices. Such guidance should be locally adapted and should avoid discouraging fish consumption indiscriminately, because fish also provide important nutritional benefits. Instead, risk communication should focus on species selection, consumption frequency, and avoidance of fish from highly contaminated locations when necessary.

The human biomonitoring findings further emphasize the importance of direct exposure surveillance (Albertini et al., 2006). Hair mercury analysis provides evidence of internal mercury burden and can help identify individuals or groups requiring follow-up. In the present study, a subset of participants had hair mercury concentrations exceeding the elevated exposure threshold, indicating that population-level averages may underestimate high-end exposure concerns. Community-based biomonitoring can therefore support early identification of elevated exposure, evaluation of temporal trends, and assessment of intervention effectiveness. Such programs are particularly relevant in ASGM areas where mercury use may be ongoing and exposure pathways

may involve both occupational and non-occupational routes.

The presence of altered kidney-related biomarkers in some participants suggests that environmental health surveillance should not stop at exposure measurement alone. Although the present study does not establish causality between mercury and kidney dysfunction, UACR and eGFR data provide useful clinical indicators for identifying individuals who may benefit from medical follow-up. Integrating mercury biomonitoring with basic kidney health screening may improve early detection of potential health concerns in mining-affected communities. This approach is especially important because chronic mercury exposure may produce subtle or subclinical effects before overt disease becomes apparent.

The results also support the need for preventive environmental management in ASGM-affected regions. Reducing mercury exposure requires controlling mercury release at the source through safer mining practices, reduction or elimination of mercury use, improved tailing management, and separation of ore-processing activities from residential and aquatic environments. Environmental remediation strategies should prioritize areas where sediments accumulate mercury and where aquatic biota are harvested for local consumption. In addition, practical decision-support tools and environmental self-assessment systems may help companies and local operators identify priority risks and impacts earlier, thereby strengthening environmental management capacity in resource-limited settings (Onambele et al., 2025). Community-level interventions should be supported by collaboration among environmental agencies, public health authorities, local governments, laboratory networks, and community leaders.

For monitoring programs, the present findings indicate that a multi-matrix approach is essential. Water sampling alone may fail to detect mercury contamination if mercury has partitioned into sediments or accumulated in organisms. Therefore, environmental surveillance should include repeated measurements of sediment and fish, alongside human biomonitoring when feasible. Seasonal sampling is also recommended because mercury mobilization may vary with rainfall, river flow, sediment disturbance, and mining intensity. Longitudinal monitoring would provide stronger evidence regarding temporal trends, exposure persistence, and the effectiveness of interventions.

Overall, the study highlights that mercury contamination in ASGM-affected areas should be addressed as an integrated environmental and public health problem. The combined detection of mercury in sediment, fish, and human hair supports the need for coordinated action involving environmental monitoring, food-chain assessment, biomonitoring, clinical screening, and source control. Such integrated strategies are necessary to reduce mercury exposure, protect aquatic ecosystems, and safeguard the health of communities living near mining-affected environments.

Study limitations and future research

Several limitations should be considered when interpreting these findings. First, the study used a cross-sectional environmental and human biomonitoring design. The results therefore provide an integrated snapshot of mercury occurrence across environmental, aquatic biota, and human biological matrices, but they cannot establish temporal sequence, directionality, or causality. In particular, the observed coexistence of sediment mercury, fish mercury, hair mercury, and altered kidney-related biomarkers should not be interpreted as proof that sediment mercury caused fish accumulation, that fish mercury caused human exposure, or that mercury exposure caused kidney-related alterations. Longitudinal studies with repeated environmental sampling, dietary and occupational exposure assessment, mercury speciation, and multivariable adjustment for clinical confounders are required to evaluate causal pathways more rigorously.

Second, mercury analysis in environmental and biological samples was limited to total mercury. Although total mercury provides useful information on the overall contamination burden, it does not distinguish inorganic mercury from methylmercury or other mercury species. This limitation is critical because methylmercury is the dominant toxicologically relevant species in fish muscle and is closely associated with dietary exposure and human health risk. Therefore, the present study cannot determine the degree of mercury methylation in sediment, the methylmercury fraction in fish, or the specific mercury species reflected in human hair. Mechanistic explanations related to methylation, bioavailability, and food-chain transfer should therefore be interpreted as plausible background processes rather than directly measured findings. Future studies

should include mercury speciation in water, suspended particulate matter, sediment, fish muscle, and human biological samples to better characterize mercury mobility, bioavailability, and toxicological relevance.

Third, the ecological representativeness of the fish data was limited because only one specimen was analyzed for each fish species/local name. Although mercury was detected in all analyzed fish samples, this small sample size prevents reliable ecological generalization regarding species-specific accumulation, trophic transfer, or biomagnification. The apparent differences in mercury concentration among fish should therefore be interpreted as descriptive differences among individual specimens rather than as true interspecies patterns. Future studies should include replicate specimens for each species, broader taxonomic and size-class coverage, seasonal sampling, and trophic-position analysis using stable isotopes such as $\delta^{15}N$ and $\delta^{13}C$. Such data would allow stronger evaluation of mercury bioaccumulation and biomagnification within the aquatic food web.

Fourth, the study did not include stable isotope analysis or direct trophic-level determination. Consequently, interpretation of food-chain transfer was based on mercury distribution across environmental compartments and fish muscle rather than on direct evidence of trophic biomagnification. Stable isotope analysis using $\delta^{15}N$ and $\delta^{13}C$ would provide stronger evidence of trophic position, feeding sources, and biomagnification patterns. Integrating mercury analysis with stable isotope data would enable a more detailed understanding of how mercury moves through aquatic food webs in ASGM-affected ecosystems.

Fifth, environmental sampling was limited to the available matrices and time points. Mercury concentrations in water were non-detectable, whereas sediment mercury was detected at several locations. However, mercury concentrations in aquatic systems can vary substantially with rainfall, river discharge, suspended sediment load, hydrological disturbance, and mining intensity. Single-time-point water sampling may therefore underestimate contamination if mercury is mainly particle-bound or transported episodically during runoff and flooding events. Future research should include seasonal water and sediment sampling, suspended particulate matter analysis, porewater mercury measurement, and hydrological characterization to better understand mercury mobility in mining-affected river systems.

In addition, the interpretation of non-detectable mercury in water was limited by the available analytical and sampling information. The present study did not include repeated seasonal water sampling, suspended particulate mercury analysis, filtered versus unfiltered water comparison, porewater mercury measurement, or event-based sampling during rainfall and high-flow conditions. Therefore, the non-detectable water results may reflect detection-limit constraints, temporal variability, dilution, or the absence of particle-bound mercury in the analyzed fraction rather than the complete absence of mercury from the aquatic system. Future monitoring should include both dissolved and particulate mercury fractions, repeated sampling across hydrological seasons, and sediment–water interface measurements to better characterize mercury mobility in ASGM-affected rivers.

Sixth, questionnaire-derived exposure determinants, including fish consumption frequency, occupational history, knowledge, and behavioral factors, were intentionally excluded to maintain alignment with journal requirements that restrict questionnaire-based studies. Consequently, the study did not directly quantify individual dietary intake, occupational exposure intensity, or behavioral determinants of mercury exposure. Human exposure pathways were therefore interpreted using objective environmental, fish, and biomonitoring data rather than self-reported information. Future studies submitted to journals that allow exposure questionnaires could integrate dietary assessment, occupational history, and residential exposure data with biomarker measurements to provide a more individualized exposure assessment.

Seventh, kidney-related biomarkers were interpreted descriptively and should not be considered diagnostic evidence of mercury-induced kidney disease. UACR and eGFR can be influenced by many factors, including age, hydration status, muscle mass, hypertension, diabetes, infection, medication use, and other environmental exposures. Because the present study did not include detailed clinical histories or repeated measurements, the observed altered kidney-related profiles should be interpreted as indicators warranting further clinical surveillance rather than as confirmed mercury-related renal effects. Future studies should include repeated renal biomarker measurements, broader panels of tubular injury markers, oxidative stress biomarkers, inflammatory markers, and clinical follow-up to

clarify potential kidney effects of chronic mercury exposure.

Despite these limitations, the study provides an important integrated assessment of mercury contamination and exposure in an ASGM-affected area. By combining environmental matrices, fish mercury data, human hair biomonitoring, and kidney-related biomarkers, it offers a broader environmental-health perspective than single-matrix monitoring alone. Future research should build on this framework by incorporating mercury speciation, larger ecological datasets, seasonal monitoring, trophic-level analysis, and longitudinal human biomonitoring to better characterize mercury transfer, exposure dynamics, and health implications in mining-impacted communities.

CONCLUSIONS

This study shows that mercury contamination in an ASGM-impacted riverine area cannot be interpreted adequately through water monitoring alone. Although mercury was not detected in the analyzed water samples, detectable concentrations were found in sediment, fish, and human hair, indicating sediment retention, aquatic bioaccumulation, and internal human exposure. Sediment mercury ranged from 0.02 to 0.10 mg/kg, fish mercury ranged from 0.05 to 0.17 mg/kg, and hair mercury ranged from 0.17 to 6.15 mg/kg, with 10.0% of participants showing concentrations ≥2.0 mg/kg. A subset of participants also had altered kidney-related biomarkers, which should be interpreted as supportive clinical signals rather than evidence of causality. The kidney-related biomarker findings should be interpreted cautiously. Although altered UACR or eGFR values were observed in a subset of participants, the study did not test statistical associations between mercury biomarkers and kidney outcomes or adjust for clinical confounders. Therefore, the results indicate co-occurrence of measurable internal mercury burden and kidney-related biomarker alterations, not evidence of mercury-induced kidney effects.

This study demonstrates that mercury occurrence differed across environmental and biological compartments in the ASGM-affected area. Mercury was not detected in the analyzed water samples, but it was detected in several sediment samples, all analyzed fish muscle samples, and all human hair samples. These findings support the value of multi-matrix monitoring because sediment, fish, and human biomonitoring provided complementary information that was not captured by water analysis alone. However, the results should be interpreted as compartment-specific evidence and co-occurrence across matrices, not as proof of a complete causal pathway from sediment to fish to humans. The kidney-related biomarker findings also require cautious interpretation because altered UACR or eGFR values were observed in some participants without statistical linkage to mercury biomarkers or adjustment for clinical confounders. Overall, the study provides a descriptive and hypothesis-generating framework for mercury surveillance in ASGM-affected riverine systems and highlights the need for future studies incorporating mercury speciation, larger ecological sampling, longitudinal biomonitoring, and confounder-adjusted health analysis.

From an environmental monitoring perspective, these findings support a practical multi-matrix framework in which sediment, fish, and human biomarkers provide more informative evidence of mercury persistence and exposure significance than water alone in mining-affected tropical river systems. This framework can support monitoring prioritization, risk communication, and targeted follow-up in mercury-impacted communities. Future work should strengthen this approach through repeated seasonal sampling, larger fish datasets, mercury speciation, and longitudinal biomonitoring.

REFERENCES

1. Agustiani, T., Sulistia, S., Suciati, F., Sudaryanto, A., Amandita, F.Y., Efadeswarni, Handika, R., Poku, P.A., Boohene, M., Kobayashi, J., Ishibashi, Y., Morrow, J.S., Anan, Y., Agusa, T., (2025). Comprehensive assessment of mercury contamination and health risks from artisanal and small-scale gold mining (ASGM) in Sukabumi, Indonesia. *Earth 6*, 110.
2. Albertini, R., Bird, M., Doerrer, N., Needham, L., Robison, S., Sheldon, L., Zenick, H., (2006). The use of biomonitoring data in exposure and human health risk assessments. environ. health perspect. 114, 1755–1762.
3. Al-Sulaiti, M.M., Soubra, L., Al-Ghouti, M.A., (2022). The causes and effects of mercury and methylmercury contamination in the marine environment: A review. *Curr. Pollut. Rep. 8*, 249–272.
4. Astika, H., Handayani, S., Damayanti, R., Surono, W., Maryono, Suciyanti, M., Octaviano, H.A., (2021). Characterization of potential mercury

contamination in the ASGM area of Mandailing Natal, North Sumatera. *IOP Conf. Ser. Earth Environ. Sci. 882*, 012062.

5. Baeuml, J., Bose-O'Reilly, S., Gothe, R.M., Lettmeier, B., Roider, G., Drasch, G., Siebert, U., (2011). Human biomonitoring data from mercury exposed miners in six artisanal small-scale gold mining areas in Asia and Africa. *Minerals 1*, 122–143.
6. Bartz, K.K., Hannam, M.P., Wilson, T.L., Lepak, R.F., Ogorek, J.M., Young, D.B., Eagles-Smith, C.A., Krabbenhoft, D.P., (2023). Understanding drivers of mercury in lake trout (*Salvelinus namaycush*), a top-predator fish in southwest Alaska's parklands. *Environ. Pollut. 330*, 121678.
7. Basu, M., (2023). *Impact of Mercury and Its Toxicity on Health and Environment: A General Perspective.* In: Kumar, N. (Ed.), Mercury Toxicity, Environmental Science and Engineering. Springer Nature Singapore, Singapore, pp. 95–139.
8. Baudo, R., (2020). *Sediments: Chemistry and Toxicity of In-Place Pollutants, 1st ed*. CRC Press.
9. Bigham, G.N., Murray, K.J., Masue-Slowey, Y., Henry, E.A., (2016). Biogeochemical controls on methylmercury in soils and sediments: Implications for site management. *Integr. Environ. Assess. Manag. 13*, 249–263.
10. Bridges, C.C., Zalups, R.K., (2017). The aging kidney and the nephrotoxic effects of mercury. *J. Toxicol. Environ. Health Part B 20*, 55–80.
11. Brown, L.E., Chen, C.Y., Voytek, M.A., Amirbahman, A., (2015). The effect of sediment mixing on mercury dynamics in two intertidal mudflats at Great Bay Estuary, New Hampshire, USA. *Mar. Chem. 177*, 731–741.
12. Calao-Ramos, C., Bravo, A.G., Paternina-Uribe, R., Marrugo-Negrete, J., Díez, S., (2021). Occupational human exposure to mercury in artisanal small-scale gold mining communities of Colombia. *Environ. Int. 146*, 106216.
13. Chen, C., Amirbahman, A., Fisher, N., Harding, G., Lamborg, C., Nacci, D., Taylor, D., (2008). Methylmercury in marine ecosystems: Spatial patterns and processes of production, bioaccumulation, and biomagnification. *EcoHealth 5*, 399–408.
14. Chen, C.Y., Driscoll, C.T., (2018). Integrating mercury research and policy in a changing world. *Ambio 47*, 111–115.
15. Chen, C.Y., Driscoll, C.T., Eagles-Smith, C.A., Eckley, C.S., Gay, D.A., Hsu-Kim, H., Keane, S.E., Kirk, J.L., Mason, R.P., Obrist, D., Selin, H., Selin, N.E., Thompson, M.R., (2018). A critical time for mercury science to inform global policy. *Environ. Sci. Technol. 52*, 9556–9561.
16. Comper, W.D., Vuchkova, J., McCarthy, K.J., (2022). New insights into proteinuria/albuminuria. *Front. Physiol. 13*, 991756.
17. Cullen, E., Evans, D., Davidson, F., Burke, P., Burns, D., Flanagan, A., Griffin, C., Kellegher, A., Mannion, R., Mulcahy, M., Ryan, M., Biot, P., Casteleyn, L., Castaño, A., Angerer, J., Koch, H., Esteban, M., Schindler, B., Navarro, C., Kolossa-Gehring, M., Fiddicke, U., Schoeters, G., Hond, E., Sepai, O., Exley, K., Bloemen, L., Knudsen, L., Joas, R., Joas, A., Aerts, D., (2014). Mercury exposure in Ireland: Results of the DEMOCOPHES human biomonitoring study. *Int. J. Environ. Res. Public. Health 11*, 9760–9775.
18. Escobar-Camacho, D., Rosero-López, D., Ruiz-Urigüen, M., Barragán, K.S., Carpintero-Salvador, N., Daza, J.R., Aldous, A., Benítez, S., Tear, T., Encalada, A.C., (2024). Mercury in aquatic ecosystems of two indigenous communities in the Piedmont Ecuadorian Amazon: evidence from fish, water, and sediments. *Ecotoxicology 33*, 440–456.
19. Esteban-López, M., Arrebola, J.P., Juliá, M., Pärt, P., Soto, E., Cañas, A., Pedraza-Díaz, S., González-Rubio, J., Castaño, A., (2022). Selecting the best non-invasive matrix to measure mercury exposure in human biomonitoring surveys. *Environ. Res. 204*, 112394.
20. Fornasaro, S., Fulignati, P., Gioncada, A., Garces, D., Mulas, M., (2025). Geogenic and anthropogenic origins of mercury and other potentially toxic elements in the ponce Enriquez artisanal and small-scale Gold Mining District, Southern Ecuador. *Minerals 15*, 725.
21. García-Ordiales, E., Covelli, S., Braidotti, G., Petranich, E., Pavoni, E., Acquavita, A., Sanz-Prada, L., Roqueñí, N., Loredo, J., (2020). Mercury and arsenic mobility in resuspended contaminated estuarine sediments (Asturias, Spain): A laboratory-based study. *Sci. Total Environ. 744*, 140870.
22. Gascón Díez, E., Loizeau, J.-L., Cosio, C., Bouchet, S., Adatte, T., Amouroux, D., Bravo, A.G., (2016). Role of settling particles on mercury methylation in the oxic water column of freshwater systems. *Environ. Sci. Technol. 50*, 11672–11679.
23. Gentès, S., Löhrer, B., Legeay, A., Mazel, A.F., Anschutz, P., Charbonnier, C., Tessier, E., Maury-Brachet, R., (2021). Drivers of variability in mercury and methylmercury bioaccumulation and biomagnification in temperate freshwater lakes. *Chemosphere 267*, 128890.
24. Gumbo, N., Kapenge, C., (2025). Groundwater contaminated with heavy metals as a threat to population safety and health in developing countries: A scoping review. *Trends Ecol. Indoor Environ. Eng. 3*, 37–45.
25. Gibb, H., O'Leary, K.G., (2014). Mercury exposure and health impacts among individuals in the artisanal and small-scale gold mining community: A comprehensive review. *Environ. Health Perspect. 122*, 667–672.

26. Hahn, J., Breuer, L., Wiederhold, J.G., (2025). Temporal trends and spatial variations of total mercury in sediments of the legacy-contaminated river Elbe (Germany). *Environ. Monit. Assess. 198*, 56.
27. Han, F., Shan, X.-Q., Zhang, S.-Z., Wen, B., (2004). Mercury speciation in China's coastal surface seawaters. *Int. J. Environ. Anal. Chem. 84*, 583–598.
28. He, X., Wallace, W.G., Reinfelder, J.R., (2022). Grass Shrimp (*Palaemonetes pugio*) as a trophic link for methylmercury accumulation in urban salt marshes. *Environ. Sci. Technol. 56*, 8071–8081.
29. Hošek, M., Bednárek, J., Popelka, J., Elznicová, J., Tůmová, Š., Rohovec, J., Navrátil, T., Matys Grygar, T., (2020). Persistent mercury hot spot in Central Europe and Skalka Dam reservoir as a long-term mercury trap. *Environ. Geochem. Health 42*, 1273–1290.
30. Hsu-Kim, H., Eckley, C.S., Achá, D., Feng, X., Gilmour, C.C., Jonsson, S., Mitchell, C.P.J., (2018). Challenges and opportunities for managing aquatic mercury pollution in altered landscapes. *Ambio 47*, 141–169.
31. Hsu-Kim, H., Kucharzyk, K.H., Zhang, T., Deshusses, M.A., (2013). Mechanisms regulating mercury bioavailability for methylating microorganisms in the aquatic environment: A critical review. *Environ. Sci. Technol. 47*, 2441–2456.
32. Le Croizier, G., Schaal, G., Point, D., Le Loc'h, F., Machu, E., Fall, M., Munaron, J.-M., Boyé, A., Walter, P., Laë, R., Tito De Morais, L., (2019). Stable isotope analyses revealed the influence of foraging habitat on mercury accumulation in tropical coastal marine fish. *Sci. Total Environ. 650*, 2129–2140.
33. Lehnherr, I., (2014). Methylmercury biogeochemistry: a review with special reference to Arctic aquatic ecosystems. *Environ. Rev. 22*, 229–243.
34. Leigh, D.S., (1994). Mercury contamination and floodplain sedimentation from former gold mines in north Georgia. *JAWRA J. Am. Water Resour. Assoc. 30*, 739–748.
35. Lepak, R.F., Hoffman, J.C., Janssen, S.E., Krabbenhoft, D.P., Ogorek, J.M., DeWild, J.F., Tate, M.T., Babiarz, C.L., Yin, R., Murphy, E.W., Engstrom, D.R., Hurley, J.P., (2019). Mercury source changes and food web shifts alter contamination signatures of predatory fish from Lake Michigan. *Proc. Natl. Acad. Sci. 116*, 23600–23608.
36. Liu, G., Cai, Y., O'Driscoll, N. (Eds.), (2011). *Environmental Chemistry and Toxicology of Mercury, 1st ed.* Wiley.
37. Martinez, G., McCord, S.A., Driscoll, C.T., Todorova, S., Wu, S., Araújo, J.F., Vega, C.M., Fernandez, L.E., (2018). Mercury contamination in riverine sediments and fish associated with artisanal and small-scale gold mining in Madre de Dios, Peru. *Int. J. Environ. Res. Public. Health 15*, 1584.
38. Meyer, U., Medeiros, C., (2017). Mercury in the Santa Cruz channel, ne Brazil - A potential risk. *Trop. Oceanogr. 45*.
39. Mille, T., Bisch, A., Caill-Milly, N., Cresson, P., Deborde, J., Gueux, A., Morandeau, G., Monperrus, M., (2021). Distribution of mercury species in different tissues and trophic levels of commonly consumed fish species from the south Bay of Biscay (France). *Mar. Pollut. Bull. 166*, 112172.
40. Moreno-Brush, M., McLagan, D.S., Biester, H., (2020). Fate of mercury from artisanal and small-scale gold mining in tropical rivers: Hydrological and biogeochemical controls. A critical review. *Crit. Rev. Environ. Sci. Technol. 50*, 437–475.
41. Mulenga, M., Ouma, K.O., Monde, C., Syampungani, S., (2024). Aquatic mercury pollution from artisanal and small-scale gold mining in Sub-Saharan Africa: Status, impacts, and interventions. *Water 16*, 756.
42. Nelson, S.A.M., Hintelmann, H., Aherne, J., (2022). Mercury in soil, sediment, and lake water in upland headwater catchments in Ireland. *Environ. Earth Sci. 81*, 492.
43. Oros, A., (2025). Bioaccumulation and trophic transfer of heavy metals in marine fish: Ecological and ecosystem-level impacts. *J. Xenobiotics 15*, 59.
44. Onambele, N.L.N., Mouhaman, A., Ghogomu, R.T., (2025). Design of software for self-assessment of risks and environmental impacts. *Trends Ecol. Indoor Environ. Eng. 3*, 28–35.
45. Packull-McCormick, S., Ratelle, M., Lam, C., Napenas, J., Bouchard, M., Swanson, H., Laird, B.D., (2022). Hair to blood mercury concentration ratios and a retrospective hair segmental mercury analysis in the Northwest Territories, Canada. *Environ. Res. 203*, 111800.
46. Pant, R., Mathpal, N., Chauhan, R., Singh, A., Gupta, A., (2024). *A Review of Mercury Contamination in Water and Its Impact on Public Health.* In: Kumar, N. (Ed.), Mercury Toxicity Mitigation: Sustainable Nexus Approach, Earth and Environmental Sciences Library. Springer Nature Switzerland, Cham, pp. 93–115.
47. Peña-Fernández, A., Evans, M.D., Cooke, M.S., (2021). T*oxicology for the Health and Pharmaceutical Sciences, 1st ed*. CRC Press, Boca Raton.
48. Prasad, M.N.V., Sajwan, K.S., Naidu, R. (Eds.), 2005. *Trace Elements in the Environment, 0 ed.* CRC Press.
49. Ramalhosa, E., Pato, P., Monterroso, P., Pereira, E., Vale, C., Duarte, A.C., (2006). Accumulation versus remobilization of mercury in sediments of a contaminated lagoon. *Mar. Pollut. Bull. 52*, 353–356.
50. Regnell, O., Watras, Carl. J., (2019). Microbial mercury methylation in aquatic environments: a critical review of published field and laboratory studies. *Environ. Sci. Technol. 53*, 4–19.
51. Rizzo, A., Arcagni, M., Campbell, L., Koron, N.,

Pavlin, M., Arribére, M.A., Horvat, M., Ribeiro Guevara, S., (2014). Source and trophic transfer of mercury in plankton from an ultraoligotrophic lacustrine system (Lake Nahuel Huapi, North Patagonia). *Ecotoxicology 23*, 1184–1194.

52. Roach, K.A., Jacobsen, N.F., Fiorello, C.V., Stronza, A., Winemiller, K.O., (2013). Gold mining and mercury bioaccumulation in a Floodplain Lake and Main Channel of the Tambopata River, Perú *J. Environ. Prot. 4*, 51–60.
53. Saim, A.K., (2021). Mercury (Hg) use and pollution assessment of ASGM in Ghana: Challenges and strategies towards Hg reduction. *Environ. Sci. Pollut. Res. 28*, 61919–61928.
54. Salazar-Camacho, C., Salas-Moreno, M., Marrugo--Madrid, S., Marrugo-Negrete, J., Díez, S., (2017). Dietary human exposure to mercury in two artisanal small-scale gold mining communities of northwestern Colombia. *Environ. Int. 107*, 47–54.
55. Salazar-Camacho, C., Salas-Moreno, M., Paternina-Uribe, R., Marrugo-Negrete, J., Díez, S., (2021). Mercury species in fish from a tropical river highly impacted by gold mining at the Colombian Pacific region. *Chemosphere 264*, 128478.
56. Salazar-Flores, J., H. Torres-Jasso, J., Rojas- Bravo, D., M. Reyna- Villela, Z., D. Torres- Sanchez, E., (2019). Effects of mercury, lead, arsenic and zinc to human renal oxidative stress and functions: A review. *J. Heavy Met. Toxic. Dis. 4*.
57. Santonen, T., Schoeters, G., Nordberg, M., (2022). *Biological monitoring of metals and biomarkers.* In: Handbook on the Toxicology of Metals. Elsevier, pp. 217–235.
58. Sarasiab, A.R., Hosseini, M., Tadi Beni, F., (2014). Mercury and methyl mercury concentration in sediment, benthic, Barbus Grypus and pelagic, Barbus esocinus fish species, from Musa estuary, *Iran. Int. Aquat. Res. 6*, 147–153.
59. Schwab, L., Rothe, F.M., McLagan, D.S., Alten, A., Kraemer, S.M., Biester, H., Wiederhold, J.G., (2022). Large extent of mercury stable isotope fractionation in contaminated stream sediments induced by changes of mercury binding forms. *Front. Environ. Chem. 3*, 1058890.
60. Selin, N.E., (2009). Global biogeochemical cycling of mercury: A review. *Annu. Rev. Environ. Resour. 34*, 43–63.
61. Souza, C.F.D., Antunes, R.C., Lopes, V.J.S., De Barros, A., Quadros, A.R.B.D., Andrade, R.L.T.D., Souza, J.C.D., (2025). Mercury levels in hair of domestic and wild animals. *Biology 14*, 1497.
62. Ullrich, S.M., Tanton, T.W., Abdrashitova, S.A., (2001). Mercury in the aquatic environment: A review of factors affecting methylation. *Crit. Rev. Environ. Sci. Technol. 31*, 241–293.
63. Višnjevec, A.M., Kocman, D., Horvat, M., (2013). Human mercury exposure and effects in Europe. Environ. *Toxicol. Chem. 33*, 1259–1270.
64. Wibowo, Y.G., Ramadan, B.S., Universitas Diponegoro, Maryani, A.T., Universitas Jambi, Rosarina, D., Universitas Muhammadiyah Tangerang, Arkham, L.O., Institut Teknologi Sumatera, (2022). Impact of illegal gold mining in Jambi, Indonesia. *Indones. Min. J. 25*, 29–40.
65. Wyatt, L., Ortiz, E., Feingold, B., Berky, A., Diringer, S., Morales, A., Jurado, E., Hsu-Kim, H., Pan, W., (2017). Spatial, temporal, and dietary variables associated with elevated mercury exposure in peruvian riverine communities upstream and downstream of artisanal and small-scale gold mining. *Int. J. Environ. Res. Public. Health 14*, 1582.
66. Xu, X., Bryan, A.L., Parks, J.R., Gibson, K.N., (2022). Mercury accumulation in a stream ecosystem: Linking labile mercury in sediment porewaters to bioaccumulative mercury in trophic webs. *Water 14*, 2003.
67. Z. Boerleider, R., Roeleveld, N., T.J. Scheepers, P., Department for Health Evidence, Radboud Institute for Health Sciences, Radboud university medical center, PO Box 9101, 6500 HB Nijmegen, The Netherlands, (2017). Human biological monitoring of mercury for exposure assessment. *AIMS Environ. Sci. 4*, 251–276.
68. Zhao, W., Gan, R., Xian, B., Wu, T., Wu, G., Huang, S., Wang, R., Liu, Z., Zhang, Q., Bai, S., Fu, M., Zhang, Y., (2024). Overview of methylation and demethylation mechanisms and influencing factors of mercury in water. *Toxics 12*, 715.