Indonesian Journal of Chemical Research

http://ojs3.unpatti.ac.id/index.php/ijcr Indo. J. Chem. Res., 13 (3), 206-211, 2026

Study of Mercury and Arsenic Contamination in Gold Processing Tailings from Gunung Botak, Buru Island – Maluku

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Received: September 2025
Received in revised: December 2025
Accepted: January 2026
Available online: January 2026

Abstract

Buru Island in Maluku Province is one of the sites of unlicensed gold mining activities (Illegal Gold Mining, IGM), which may lead to environmental pollution due to improper waste management. This study aimed to analyze the concentrations of mercury (Hg) and arsenic (As) as hazardous pollutants (Hazardous and Toxic Materials, HTM) in gold processing tailings from Dafa and Debowae Villages, Buru Island. Tailings samples were collected from three different sites. Mercury concentrations were determined using Cold Vapor AAS, while As was analyzed using Hydride-Generation AAS based on the APHA-AWWA-WEF standard method (2005). The results showed that Hg levels in tailings from Debowae Village (Location 1 and 2) were 399.18 mg/kg and 286.39 mg/kg dry weight, respectively, whereas Dafa Village (Location 3) reached 1182.51 mg/kg dry weight. Arsenic concentrations ranged from 0.59 to 0.74 mg/kg dry weight across all locations. According to Indonesia Government Regulation PP No. 22 of 2021 on Hazardous Waste Management, Hg concentrations in all study sites exceeded the quality standard, whereas As levels remained below the permissible limits. These findings highlight the serious potential risk of mercury contamination in artisanal gold mining areas on Buru Island.

Keywords: heavy metals, mercury, arsenic, tailings, waste

INTRODUCTION

Maluku Province is one of the Indonesian provinces with the largest number of islands. The abundance of islands makes Maluku rich in natural resources, one of which is gold. Gold reserves in Maluku are relatively high, resulting in both large-scale industrial mining and small-scale artisanal mining activities spread across the province, including Gunung Botak in Buru Island. Gold mining has positive economic impacts, such as improving community welfare and regional income due to the relatively high selling price of gold. However, in addition to these benefits, gold mining also poses negative impacts on the environment and surrounding communities, particularly due to the generation of mining waste (tailings) that may cause severe environmental contamination. This has been confirmed in multiple Artisanal and Small-Scale Gold Mining (ASGM) sites across Indonesia where environmental degradation and health threats are pronounced (Meutia et al., 2023). Artisanal mining practices are often considered the main cause of environmental degradation because miners commonly use mercury (Hg) for gold extraction, a heavy metal categorized as hazardous and toxic materials (HTM) waste. Similar findings were also reported in Gunung Pongkor, West Java, where mercury contamination exceeded safe limits and posed health risks (Agustiani et al., 2025). Other heavy metals such as cadmium (Cd), arsenic (As), and chromium (Cr) may also be released as by-products of gold mining processes and are strongly associated with human health, agriculture, and ecosystem.

Gold mining activities in Gunung Botak, particularly in Dafa and Debowae Villages (Wamsait Hamlet), are categorized as unlicensed artisanal or illegal gold mining (IGM). These activities are generally carried out using the amalgamation method, a technique in which Hg is applied as a chemical element to bind gold using trommel equipment, producing tailings as waste. Tailings are classified as HTM because they contain heavy metals that can contaminate the environment (Fakaubun et al., 2020; Rumatoras et al., 2016). Heavy metals included in the HTM category, such as Hg and As, tend to accumulate in living organisms, such as humans, animals, and plants. Additionally, it persists for long periods, exerting toxic effects. Similar bioaccumulation has been reported for chromium (Cr) in marine sponges from Ambon Bay, demonstrating that heavy metals can persist and concentrate within aquatic organisms (Siahaya et al., 2021)

The toxicity of mercury, particularly in the form of methyl mercury (CH_3Hg), is highly dangerous for living organisms (Mariwy et al., 2021). A well-known case occurred in Minamata Bay, Japan, where local residents exposed to mercury suffered from severe disabilities and even death. The pollution was caused by mercury sulfate ($HgSO_4$) waste discharged from the Shin Nippon Chisso Fertilizer Co. Ltd. A similar case in Indonesia occurred in Buyat Bay, where contamination originated from gold ore processing (Lasut et al., 2010). In addition to mercury, arsenic (As) is another hazardous by-product of mining. Arsenic is a highly toxic pollutant to humans. According to National Institute for Occupational Safety and Health (NIOSH), inorganic arsenic compounds can damage the liver, kidneys, skin, lungs, and lymphatic system, with these being the primary target organs when exposed. Furthermore, arsenic is classified as a carcinogenic substance.

An arsenic contamination case occurred in Bangladesh in 1998, where arsenic naturally present in geological formations was mobilized due to human activities, contaminating water sources and affecting public health. Health impacts included melanosis, keratosis, gangrene, and skin cancer, with approximately 7,000 patients reported. Consequently, the World Health Organization (WHO) established a limit of arsenic in drinking water at no more than 0.01 ppm (1 part in 100 million parts) (Ahmad et al., 2005).

Recent broader assessments in Indonesia show that mining and processing of metals including gold are having measurable negative health and environmental impacts (Wahyono et al., 2024). Heavy metals are unique contaminants because they cannot be degraded biologically, physically, or chemically into less toxic forms. Instead, they tend to undergo transformations that may increase their mobility and toxicity (Abbas et al., 2018). One of the major causes of soil contamination by heavy metals is illegal gold mining (IGM). This is due to the natural presence of heavy metals such as As and Hg in the ore processed by miners. Observations in Dafa and Debowae Villages show that IGM activities are carried out near residential areas, with tailings disposed of directly into the environment. Therefore, the purpose of this study is to determine the concentrations of Hg and As in tailings around Dafa and Debowae Villages and to compare the results with Government Regulation PP No. 22 of 2021 concerning Hazardous Waste Management.

METHODOLOGY

Materials and Instrumentals

The materials used in this study were tailing samples obtained from artisanal gold mining sites in Gunung Botak, Buru Regency. Reagents included concentrated nitric acid (HNO_3), hydrochloric acid (HCl), potassium permanganate ($KMnO_4$), hydroxylamine hydrochloride, and stannous chloride dihydrate ($SnCl_2 \cdot 2H_2O$), all of analytical grade (Merck). Distilled water was used throughout the procedures. The instruments employed were a Cold Vapor Atomic Absorption Spectrophotometer (CV-AAS) Varian Spectra AA-20 Plus VGA (1996) for mercury (Hg) analysis, and a Hydride Generation AAS Varian Spectra AA-20 Plus Hydride (1996) for arsenic (As) analysis.

Sampling

Tailings were collected from three sampling points in Gunung Botak, Waelata Sub-district, Buru Regency. Two points were located in Debowae Village, Wamsait Hamlet, and one point in Dafa Village. The sampling coordinates are shown in Table 1 and Figure 1.

Table 1. Sampling locations and coordinates

Location	Coordinates
Debowae (1)	3°24’36.25” S; 127°2’36.13” E
Debowae (2)	3°24’35.60” S; 127°2’35.95” E
Dafa (3)	3°24’1.74” S; 127°1’49.38” E

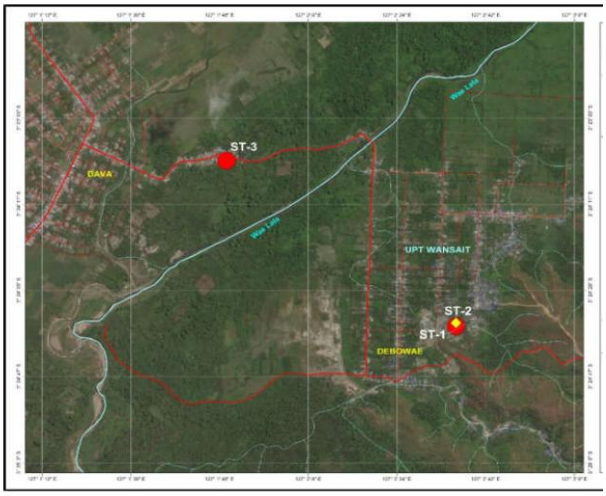

Figure 1. Map of sampling locations in Debowae and Dafa Villages, Gunung Botak, Buru Island

Sample Preparation

For the determination of arsenic (As), one gram of each tailing sample was digested with a mixture of nitric acid (HNO_3) and hydrochloric acid (HCl) in a ratio of 1:3 and allowed to react for one hour. The mixture was then evaporated to dryness before 15 mL of distilled water was added. The digested sample was subsequently boiled, cooled, and filtered into a 100 mL volumetric flask, and the final volume was adjusted with distilled water to 100 mL. The resulting filtrate was analyzed for As using Hydride-Generation Atomic Absorption Spectrophotometry (AAS) in accordance with the APHA-AWWA-WEF standard method (2005, Part No. 3114).

For mercury (Hg) analysis, ten grams of each sample were digested with HNO_3 and HCl (1:3), heated at 70 °C, cooled, and diluted with 15 mL of distilled water. The mixture was filtered into a 100 mL volumetric flask, and from this solution, a 10 mL aliquot was taken. The aliquot was treated with 0.1 mL of 10% potassium permanganate ($KMnO_4$), homogenized, and subsequently reduced with 0.1 mL of hydroxylamine hydrochloride, followed by the addition of 0.5 mL of stannous chloride dihydrate ($SnCl_2{\cdot}2H_2O$). The prepared solution was then analyzed for Hg using Cold Vapor Atomic Absorption Spectrophotometry (CV-AAS).

Data Analysis

The concentrations of Hg, and As obtained from instrumental analysis were expressed in mg/kg dry weight. These results were then compared with the permissible limits established in Government Regulation PP No. 22 of 2021 concerning Hazardous Waste Management.

RESULTS AND DISCUSSION

Mercury (Hg) concentration in tailings from Debowae and Dafa Villages

Tailings are residues from gold processing after the target mineral is separated, and typically consist of various particle sizes, such as sand, silt, and clay fractions. Improper disposal of tailings into the environment poses a significant risk of pollution because, in addition to containing mercury (Hg), they may also contain other heavy metals such as arsenic (As), which is consistent found in gold tailings from North Sumatra Province (Sigiro, 2016). In this study, sampling was conducted at three sites: two in Debowae Village, Wamsait Hamlet (Location 1 and 2), and one in Dafa Village (location 3).

The results showed that the Hg concentration at Location 1 was 399.18 mg/kg dry weight, while Location 2 had a much lower concentration of 86.39 mg/kg dry weight, despite the short distance of approximately 10 m between the two sites. These values are comparable to Hg contamination levels previously reported in soils and plants in Simpenan, Sukabumi (Nuryanty et al., 2024). The lower Hg level at Location 2 is likely due to the cessation of amalgamation activities at this site in mid-2016, whereas Location 1 remained active. At Location 2, the mercury (Hg) concentration is relatively high compared to arsenic (As) due to fundamental differences in their sources and geochemical behavior during artisanal gold processing.

Mercury at artisanal mining sites is introduced directly and intentionally through the amalgamation process. Even if amalgamation activities have ceased or reduced, residual mercury can remain strongly adsorbed onto fine tailing particles such as clays and organic matter. Mercury is known for its high affinity for sulfide minerals and fine-grained sediments, which allows it to persist locally at elevated concentrations even after mining activity declines.

In contrast, arsenic at the study site is primarily of geogenic origin, released naturally from arsenic-bearing minerals present in the host rock rather than being added deliberately during gold extraction. Arsenic mobility is strongly influenced by redox conditions, pH, and hydrological transport. Under the relatively oxidizing and well-drained conditions at Location 2, arsenic tends to remain dissolved and can be more easily transported away from the tailings area, resulting in lower residual concentrations in solid tailings.

Therefore, the observed pattern—high Hg but low As at Location 2—reflects the anthropogenic dominance of mercury input combined with the higher environmental mobility of arsenic, rather than a shared accumulation mechanism.

The highest Hg concentration was observed at Location 3 (Dafa Village), reaching 1182.51 mg/kg dry weight. although reported concentrations in environmental media generally remain below several hundred mg/kg (Agustiani et al., 2025). This elevated value can be attributed to continuous trommel operation from 2016 until 2019, with four processing cycles conducted daily, and the use of approximately 400 cc of mercury per cycle. Similar observations were reported by Mirdat (2012), who found that high Hg concentrations in tailings were strongly influenced by the amount of Hg applied during gold extraction. In line with widespread mercury contamination across soil, water, and crops has also been reported in Sukabumi, Indonesia (Yuliyanti & Aminuddin, 2023).

The proximity of gold processing facilities to residential areas in Location 3, only about four meters from the nearest household, exacerbates the environmental risk. Tailings are stored in open ponds without further treatment, and heavy rainfall could lead to overflow, contaminating nearby soil and even local groundwater sources used for domestic purposes direct human exposure to mercury has been documented in Gorontalo, where elevated levels were detected in residents' hair samples (Metaragakusuma et al., 2023). According to Government Regulation PP No. 22 of 2021 concerning Hazardous Waste Management, tailings containing mercury above 10 µg/g fall into Hazardous Waste Category 1. The results of this study demonstrate that Hg concentrations at all three sites far exceeded the permissible limit of 0.3 µg/g for hazardous waste category 1, indicating that these tailings require urgent management interventions. Comparisons with the United States Environmental Protection Agency (USEPA, 1994) standard, which sets the threshold for Hg in sludge at 17 µg/g, also confirm that Hg levels at all sites exceeded international safety guidelines. This highlights the serious ecological and health hazards posed by artisanal gold mining in the study area.

Mercury is of particular concern because inorganic Hg in the environment can undergo methylation to form methylmercury (CH_3Hg^+) through microbial processes in sediments and aquatic systems (Wu et al., 2024). Methylmercury is more toxic and lipophilic than inorganic Hg, enabling it to cross biological membranes such as the blood–brain barrier and causing neurological disorders. The potential for methylation in the study area suggests an increased risk of bioaccumulation and biomagnification within local ecosystems.

Arsenic (As) concentration in tailings from Debowae and Dafa Villages

The concentrations of As in tailings were 0.59 mg/kg at locations 1 and 3, and 0.74 mg/kg at Location 2. The slightly higher concentration at Location 2 may be attributed to the limited number of tailings ponds at this site, which could reduce sedimentation and retention, resulting in greater As mobilization. The slightly higher arsenic (As) concentration observed at Location 2 can be linked to the limited number of tailings ponds, which affects sediment retention and metal distribution within the site.

A limited number of tailings ponds reduces the system's capacity for particle settling and geochemical stabilization. As a result, fine-grained tailings—where arsenic is preferentially associated—tend to accumulate within fewer confined areas instead of being distributed across multiple settling zones. Arsenic commonly adsorbs onto iron oxyhydroxides and clay minerals, and insufficient pond capacity can enhance localized accumulation of these fine fractions.

Moreover, restricted pond volume may promote periodic overflow or re-suspension of sediments, particularly during rainfall events. This process can facilitate arsenic re-deposition in nearby tailings rather than long-term burial, leading to slightly elevated concentrations in solid samples despite overall values remaining below regulatory thresholds.

Thus, the observed increase in arsenic concentration at Location 2 is not indicative of excessive contamination, but rather reflects hydrodynamic and sedimentological effects caused by limited tailings pond infrastructure.

Arsenic is recognized as a highly toxic by-product of gold mining and is classified as a hazardous pollutant due to its carcinogenic effects (Oladimeji et al., 2024).When compared with the permissible limit of 20 mg/kg for As under PP No.22 of 2021, the measured concentrations at all three sites were far below the regulatory threshold. This indicates that, unlike Hg, arsenic contamination in the study area is still within safe levels according to Indonesian standards. Nevertheless, the presence of As, even at low concentrations, remains a concern due to its persistence and potential long-term accumulation in soils and water resources.

All the measurement results are shown in Table 2.

Table 2. Concentrations of Hg and As in tailings from Debowae and Dafa Villages

Code	Location	Hg (mg/kg)	As (mg/kg)
SS_1	Debowae Village (Loc.1)	399.18	0.59
SS_2	Debowae Village (Loc.2)	86.39	0.74
SS_3	Dafa Village (Loc.3)	1182.51	0.59

CONCLUSION

The results of this study showed that mercury (Hg) concentrations in gold processing tailings were highest at Location 3 in Dafa Village (1182.51 mg/kg), followed by Location 1 in Debowae Village, Wamsait Hamlet (399.18 mg/kg), and lowest at Location 2 in Debowae Village (86.39 mg/kg). Arsenic (As) concentrations were 0.74 mg/kg at Location 2, slightly higher than those at Location 1 and 3, which were both 0.59 mg/kg. When compared with Government Regulation PP No.22 of 2021 concerning Hazardous

Waste Management, Hg levels in all locations exceeded the permissible limit of 0.3 mg/kg, classifying these tailings as Category 1 hazardous waste. This is aligned with findings from national studies assessing risk of mercury exposure linked to mining and processing in Indonesia (Wahyono et al., 2024). In contrast, as concentrations remained below the threshold value of 20 mg/kg, indicating that arsenic contamination in the study area has not yet reached hazardous levels. These findings highlight the urgent need for proper management and control of mercury contamination from artisanal gold mining activities in Buru Island.

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