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Original Article

Mercury Content Status in Soil at the Gold Mining Site in Paya Teuk Village, Pasie Raja District, Aceh Regency

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Abstract

Artisanal and small-scale gold mining (ASGM) can pollute the environment through the use of mercury (Hg) in the amalgamation process, since released mercury may accumulate in soil and pose risks to environmental quality and public health. This study aimed to determine the status of mercury content in soil at a gold mining site in Gampong Paya Teuk, Pasie Raja District, South Aceh Regency, compare it with the applicable environmental quality standard, and describe the potential environmental health risks. A quantitative approach with a descriptive-analytic design was employed. Soil samples were collected using a circular quadrant method at four points representing the amalgamation processing area, tailings disposal area, community land area, and control area, then analyzed at the BSPJI Banda Aceh laboratory using the SNI 8910:2021 method, with the mean mercury content compared to the soil quality standard of 0.3 mg/kg. The research results show that the mercury concentrations in the soil at all four sampling points (Quadrants I, II, III and IV) were below the laboratory detection limit of 0.0005 mg/kg; consequently, no identifiable differences in concentration were found between the sampling points. These values are well below, and therefore comply with, the environmental quality standard of 0.3 mg/kg. However, these results do not automatically prove that mercury is absent from the study site or that the risk of mercury exposure is entirely non-existent. Therefore, any interpretation must take into account the detection limitations of the analytical method as well as the possibility of exposure via other environmental media.

Keywords: Environmental Health, Environmental Pollution, Gold Mining, Mercury.

1. Introduction

Mercury (Hg) is one of the heavy metals that occurs naturally in the environment, yet it has a high level of toxicity toward living organisms. In the classification of hazardous chemicals, mercury belongs to the group of Hazardous and Toxic Materials (B3) because of its persistent nature, its tendency to accumulate easily, and its potential to give rise to serious impacts on human health and environmental balance; even at relatively low concentrations, continuous exposure to mercury can produce significant biological effects (Sugiana et al., 2023). Mercury is also known as quicksilver, the only metal that is liquid at room temperature, and it is commonly utilized in the production of chlorine gas and caustic soda, the extraction of gold and silver from ore, battery components, dental amalgam, thermometers, barometers, and even electrical switches (Zumaidar et al., 2022). The World Health Organization (WHO) affirms that the use of mercury in the gold amalgamation process is highly dangerous because mercury can enter the human body through respiration, digestion, and skin contact, then accumulate in vital organs such as the brain, kidneys, and liver, thereby giving rise to health

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disorders, especially in the nervous system, with a blood mercury threshold above 5-10 µg/L already declared to exceed the safe limit (Bagia et al., 2023).

Small-scale gold mining or Artisanal and Small-Scale Gold Mining (ASGM) is one of the main sources of mercury pollution in developing countries, including Indonesia. In practice, mercury is used in the amalgamation process because it is considered economical and effective in separating gold from ore, yet it is generally not accompanied by adequate waste management, so that the residue from ore washing and amalgam residues are discharged directly into the soil and waters (Agustiani, Sulistia, Suciati, et al., 2025). The amalgam burning process also releases mercury vapor into the atmosphere without emission control, which is then deposited back into the soil and widens the spread of pollution; the latest systematic studies even show that ASGM activity is the largest contributor to mercury emissions globally, surpassing even the large industrial sector (Ali et al., 2025). Globally, mercury circulates in various reservoirs (the atmosphere, lithosphere, biosphere, and hydrosphere) sourced from anthropogenic as well as natural emissions, with the atmosphere identified as the dominant pathway of its distribution even though a portion is stored locally on land surfaces and in waters (Brocza et al., 2024).

Within the soil, mercury pollution occurs through several main mechanisms, one of which is the disposal of waste from gold processing directly onto the soil surface, which generally has a high mercury content, aggravated by high rainfall that accelerates the movement of mercury through surface runoff and infiltration into deeper soil layers (Manullang et al., 2021). Another mechanism is atmospheric deposition, namely mercury vapor from amalgam burning that settles back into the soil through rain or dust particles, so that soil becomes the main medium of mercury accumulation in the terrestrial environment; several studies at gold mining sites in Indonesia show that the highest mercury levels are generally found in soil around ore processing areas and tailings disposal sites (Nuryanty et al., 2024). The presence of mercury in soil can reduce the porosity and the soil's capacity to store water, disrupt the balance of nutrients, and act toxically toward soil microorganisms that play an important role in the decomposition of organic matter, so that soil exposed to mercury over the long term tends to undergo a degradation of environmental quality that is difficult to restore without special remediation efforts (Kusnarta et al., 2024).

Mercury that pollutes the soil around gold mining areas has the potential to enter the human body through various exposure pathways, one of which is the inhalation of mercury-laden soil dust and direct contact, especially for communities who frequently carry out activities around mining sites such as miners, farmers, and children (Robles et al., 2025). Another pathway occurs through the food chain, when food crops absorb mercury through their roots or when mercury moves into groundwater and waters and then accumulates in aquatic organisms; the consumption of contaminated fish is one of the most dominant exposure pathways in cases of chronic mercury exposure (Agustiani, Sulistia, Sudaryanto, et al., 2025). Mercury that enters the human body tends to accumulate and can cause disturbances of motor function, decline in memory, and even damage to the reproductive system, with higher risk in vulnerable groups such as children and pregnant women because mercury can disrupt fetal development (Arifin et al., 2024).

Mercury contamination in soil surrounding artisanal and small-scale gold mining (ASGM) sites varies depending on mining activities and environmental conditions. Previous studies have reported mercury concentrations in soil around ASGM sites reaching 2–10 mg/kg, indicating the potential for substantial contamination in areas affected by gold processing activities (Ali et al., 2025). In Indonesia, the Ministry of Health Regulation No. 2 of 2023 specifies a soil environmental health quality standard for mercury of ≤0.3 mg/kg

(Peraturan Menteri Kesehatan Republik Indonesia Nomor 2 Tahun 2023 Tentang Peraturan Pelaksanaan Peraturan Pemerintah Nomor 66 Tahun 2014 Tentang Kesehatan Lingkungan, n.d.). This value is used as the reference for comparing the mercury concentrations measured in the present study. Control measures include periodic environmental monitoring and remediation approaches, such as phytoremediation, biochar-based immobilization, and soil stabilization to reduce mercury mobility (Kusnarta et al., 2024).

Small-scale gold mining (ASGM) has been identified as one of the sources of mercury pollution in soil. Agustiani, Sulistia, Suciati, et al. (2025) found high concentrations of mercury in the soil and environmental media around the ASGM site in Sukabumi, along with indications of health risks to the local community. Findings Nuryanty et al. (2024) indicates that mercury concentrations in the soil around the processing and tailings areas in Simpenan, Sukabumi, have exceeded the quality standards used in the study. The results of the study Ali et al. (2025), and Manullang et al. (2021), also reinforces the findings regarding mercury contamination in soil in gold mining areas, including the high levels of Hg in soil at former mining sites compared with soil on oil palm plantations. Furthermore, Kusnarta et al. (2024), demonstrates the potential of biochar to reduce the mobility of mercury in soil contaminated by ASGM activities, whilst Huisa-Mamani et al. (2025), identified the distance from the source of pollution, soil texture, organic matter content and natural dilution processes as factors associated with variations in mercury concentrations in the soil. Mulyadi et al. (2025), also found that mercury exposure resulting from traditional amalgamation processes can be detected in various environmental and biological media, including sediments, hair and blood. In line with this, FAO and FAOLEX (2022) as well as Yuliyanti and Aminuddin (2023) emphasises the importance of remediation and ongoing monitoring, given the persistent nature of mercury and its ability to move between environmental media.

On the basis of the results of those previous studies, it can be concluded that small-scale gold mining activity consistently becomes the main source of mercury pollution in the soil medium, with mercury levels around gold processing sites and tailings disposal generally exceeding the environmental quality standard. Nevertheless, those studies were generally conducted outside the South Aceh region or placed greater emphasis on other environmental media and remediation efforts, so they have not yet portrayed the specific conditions in the community gold mining area in Gampong Paya Teuk, Pasie Raja District, South Aceh Regency. It is this gap that underlies this study, which is arranged on the basis of a theoretical framework of the causal relationship among small-scale gold mining activity, soil environmental quality, and public health (Wandayantolis et al., 2023), in order to specifically examine the status of mercury content in soil at active mines in that area and to link it with an environmental health perspective based on primary health care, thereby differentiating it from previous studies, most of which took the form of post-mining land studies or literature reviews.

Most of the studies reviewed focused on Sulawesi, Java, the Maluku Islands and Nusa Tenggara. In Aceh, geochemical studies of soil mercury are available for Aceh Jaya (Aflah et al., 2023), whilst data on soil mercury levels in South Aceh, particularly in Gampong Paya Teuk, Pasie Raja Sub-district, remain limited. However, local conditions (distance from processing sites, topography and waste disposal practices) will influence the distribution of mercury. This study addresses this gap by determining the status of mercury in soil at the Paya Teuk gold mine site, comparing it with applicable quality standards, and describing the potential environmental health risks.

This study aims to determine the status of mercury content in soil at the gold mining site in the area of Gampong Paya Teuk, Pasie Raja District, South Aceh Regency, to compare it

with the applicable environmental quality standard, to analyze differences in mercury concentration among sampling points, and to describe the potential environmental health risks that arise. The novelty of this study lies in its focus of examination on an active gold mine in the working area of UPTD Puskesmas Rasian, which has never been studied before, so that its results are expected to become a scientific basis and a real contribution to efforts to control pollution, protect environmental health, and serve as a basis for policy on mercury monitoring based on primary health care in the local area.

2. Literature Review

2.1. Small-scale gold mining and the use of mercury

Small-scale gold mining (artisanal and small-scale gold mining, or ASGM) is one of the world's largest sources of anthropogenic mercury emissions. Ansari et al. (2026) state that this sector accounts for approximately 37 per cent of mercury emissions into the atmosphere from all anthropogenic sources and supplies around 20 per cent of the world's gold. In Indonesia, more than 1,200 ASGM sites were recorded in 2017, and the use of mercury continues despite plans to phase it out (Ansari et al., 2026). Meutia et al. (2023) estimate that around 900,000 miners work in this sector, with approximately 2,645 illegal mining sites. The majority of these sites use mercury amalgamation without adequate waste management. Similar conditions have been found in other Southeast Asian countries, such as Myanmar, as studied by Soe et al. (2022), and in Colombia (Caballero-Gallardo et al., 2022). In Indonesia, Meutia et al. (2022) demonstrated in their narrative review that the issues surrounding ASGM are multidimensional, encompassing environmental, health, legal and socio-economic aspects.

During the amalgamation process, ore is ground together with mercury in a tube or trommel until an amalgam forms, which is then burnt to separate the gold. This process causes mercury to evaporate into the air, be discharged with the tailings, and contaminate the soil and water bodies surrounding settlements (Meutia et al., 2023). Consequently, soil becomes one of the primary environmental compartments harbouring mercury contamination at mining sites.

2.2. The Distribution and Behaviour of Mercury in Soil

Mercury concentrations in soil generally decrease with increasing distance from gold processing sites. Aflah et al. (2023) mapped the distribution of mercury around artisanal gold mining sites in Aceh Jaya using geochemical methods and found that the distance from the processing site determines the level of Hg concentration. AAS analysis results showed that 13 samples exceeded the critical threshold. Another finding from the study was the discrepancy between AAS and XRF results for soil samples, which underscores the importance of selecting the appropriate analytical method.

Mercury also moves via surface runoff and erosion. In the small-island ecosystem of Obi Island, North Maluku, Ansari et al. (2026) demonstrated that steep slopes and rainwater runoff accelerate the transport of tailings and mercury to downstream zones, resulting in wetlands and sedimentation zones becoming areas of accumulation. Distribution patterns around waste retention ponds were also reported by Rachman et al. (2021) at a traditional gold mine in Kulon Progo. Thus, the distribution of mercury depends not only on the distance from the source, but also on topography, hydrology and waste disposal practices.

2.3. Mercury Concentrations in the Soil at Gold Mining Sites

Research conducted at various locations across Indonesia has revealed a very wide range of soil mercury concentrations, depending on the scale, duration and processing techniques. Ansari et al. (2026) reported that total mercury in soil in the active mining zone on Obi Island reached 18.37 mg/kg, far exceeding the forest background level of just 0.18 mg/kg. In Sukabumi, West Java, mercury contamination from artisanal and small-scale mining (ASGM) in Simpenan Sub-district was reported by Nuryanty et al. (2024). Astuti et al. (2021) identified risks associated with Hg and Pb in soil in Pangkep Regency, South Sulawesi. In a cross-site compilation, Meutia et al. (2022) noted that soil mercury concentrations in Bone Bolango (Gorontalo) far exceeded regulatory limits, whilst in Sukabumi some samples were below and others above the threshold. A study in Aceh Jaya (Aflah et al., 2023) adds to the evidence that soil around artisanal gold mining sites in Aceh has been exposed to mercury. Nevertheless, Meutia et al. (2023) noted that in some cases residents' drinking water remained below the threshold, whilst soil and sediments already showed signs of contamination. This means that soil conditions need to be assessed separately and cannot be adequately determined solely on the basis of water quality.

The assessment of soil mercury status is carried out by comparing laboratory analysis results with applicable quality standards or threshold values. In the Indonesian literature, the value of 0.3 mg/kg, which refers to Government Regulation No. 101 of 2014 on the Management of Hazardous and Toxic Waste, is frequently used as a benchmark (Ansari et al., 2026; Meutia et al., 2023). Soil samples are generally analysed using Cold Vapour Atomic Absorption Spectrophotometry (CV-AAS) following acid digestion, in accordance with US EPA Method 7471B or an equivalent SNI standard (Ansari et al., 2026).

2.4. Potential Environmental Health Risks

Mercury in soil can affect humans through several routes of exposure. Ansari et al. (2026) cite the inhalation of mercury vapour, the consumption of water and food grown in contaminated soil, and accumulation through the food chain. They also emphasise that children are a particularly vulnerable group. Consequently, former mining sites that have been converted into agricultural land require careful monitoring. Ansari et al. (2026) state that the use of land with high soil mercury concentrations for food crops should be postponed until studies on plant uptake and risk zoning have been carried out.

There is already substantial evidence of health impacts in Indonesia. Meutia et al. (2023) reported that at the ASGM sites they studied, the potential threat to public health was classified as high. Miners complained of headaches, difficulty swallowing, blurred vision, weight loss and other symptoms suspected to be related to mercury exposure, although the authors noted the need for further confirmation. Mercury concentrations in hair and blood at several sites were also at levels ranging from a cause for concern to high. Similar findings come from Colombia, where occupational exposure to mercury amongst ASGM communities was found to be significant (Calao-Ramos et al., 2021). Soe et al. (2022) demonstrated similar patterns of contamination and exposure in South-East Asia. The impact of ASGM on soil and agriculture has also been confirmed in Ghana (Fagariba et al., 2024). Environmental health risk assessments typically integrate concentrations in environmental media with population exposure patterns to estimate risk, as carried out by Astuti et al. (2021) for soil in Pangkep.

Control of mercury pollution in soil includes source prevention through the reduction of mercury use, tailings management, and the remediation of contaminated land. Kusnarta et al. (2024) tested various sources of biochar to immobilise mercury in soil from ASGM areas in West Sumbawa. Ansari et al. (2026) noted that methods such as thermal desorption and phytoextraction are costly and time-consuming when applied on a large scale; consequently,

they proposed a microbial bioremediation approach and risk-based zoning. From a governance perspective, Meutia et al. (2023) emphasised that repressive approaches have not been effective and that a more comprehensive management of ASGM is required.

3. Methods

This study uses a quantitative approach with a descriptive-analytic design in order to portray the actual condition of mercury pollution in the soil medium at the gold mining site in Gampong Paya Teuk. The data produced take the form of mercury concentration values that are analyzed and compared with the applicable environmental quality standard (Nuryanty et al., 2024). The study was carried out in April-May 2026 in the gold mining area of Gampong Paya Teuk, Pasie Raja District, South Aceh Regency.

The study site is located in Gampong Paya Teuk, Pasie Raja Sub-district, South Aceh Regency, with estimated geographical coordinates of 3°06′ N and 97°18′ E, as shown on the study site map. Four sampling zones were identified using purposive sampling based on environmental characteristics and their proximity to mining activities. Subsequently, the circular quadrant method was used to determine the sampling areas within each of the selected zones.

The study samples consist of soil taken at four points using the circular quadrant method, namely Quadrant I (the amalgam processing/burning area), Quadrant II (the tailings disposal area), Quadrant III (the community land area), and Quadrant IV (the control area, relatively far from mining activity). The determination of sampling points was carried out by purposive sampling on the basis of distance from the pollution source and the intensity of mining activity (Agustiani, Sulistia, Suciati, et al., 2025).

Primary data were obtained from the results of the collection and examination of soil samples at a depth of ±10 cm at the four points, while secondary data were obtained from UPTD Puskesmas Rasian and the South Aceh Regency Health Office. The examination of mercury content was carried out at the Testing Laboratory of the Center for Standardization and Industrial Services (BSPJI) Banda Aceh using the SNI 8910:2021 method with an Atomic Absorption Spectrophotometer (AAS) instrument.

The data were analyzed descriptively and quantitatively by calculating the mean value of mercury content, then comparing it with the mercury quality standard in soil of 0.3 mg/kg (WHO/EPA/SNI). The pollution status is declared to meet requirements if the measurement result is ≤ the quality standard, and not to meet requirements if it is > the quality standard.

4. Results and Discussion

4.1. Research Results

4.1.1. General Description of the Study Site

The study site is a small-scale gold mining area utilized by the surrounding community to carry out mining activities, covering the process of excavating material, processing gold ore, and separating the mining product. The environmental conditions around the study site consist of the mining area, community land, and areas that still have vegetation. The mining activity taking place has the potential to exert an influence on environmental quality if the management of waste from gold processing is not carried out properly. This study was carried out in the gold mining area within the territory of Gampong Paya Teuk, Pasie Raja District, South Aceh Regency (Figure 1), more precisely in Paya Teuk Village. Soil sampling was carried

out at four points determined using the circular quadrant method in order to obtain a picture of mercury content in various zones with differing levels of mining activity, namely the processing area, the waste disposal area, the transition area/community land, and the control area.

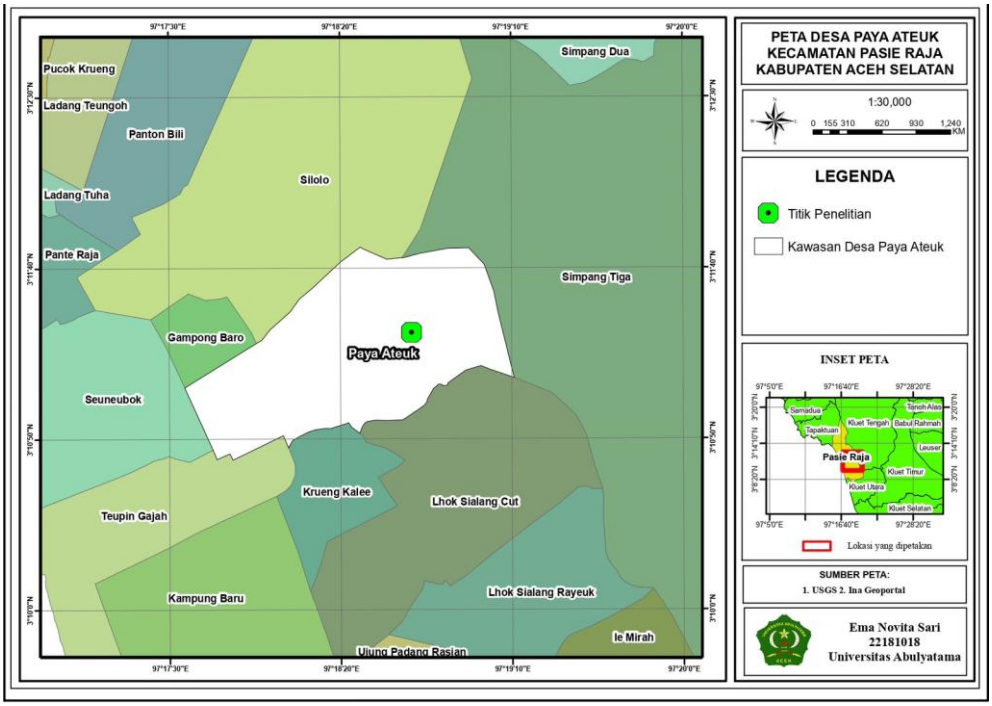


Figure 1. Map of the Study Site in Gampong Paya Teuk, Pasie Raja District, South Aceh Regency

The study site was divided into four sampling zones based on their characteristics and proximity to gold mining activities. Quadrant I represented the amalgam processing and burning area, Quadrant II represented the tailings disposal area, Quadrant III represented the community garden or land area, and Quadrant IV served as the control area located relatively far from mining activities. These zones were selected to provide a general representation of different land-use conditions surrounding the mining site. The characteristics of each sampling zone and the corresponding mercury concentrations are presented in Table 1.

4.1.2. Characteristics and Results of the Examination of Mercury Content in Soil

On the basis of the results of field observation, the four sampling points were selected to portray the variation of environmental conditions around the gold mining site, as presented in Table 1.

Table 1. Characteristics and Results of the Examination of Mercury Content in Soil

Sampling Point	Site Characteristics	Hg Content (mg/kg)	Quality Standard (mg/kg)	Remarks
Quadrant I (A)	Amalgam processing/burning area	< 0.0005	0.3	Meets requirements
Quadrant II (B)	Tailings disposal area	< 0.0005	0.3	Meets requirements

Sampling Point	Site Characteristics	Hg Content (mg/kg)	Quality Standard (mg/kg)	Remarks
Quadrant III (C)	Community garden/land area	< 0.0005	0.3	Meets requirements
Quadrant IV (D)	Control area (far from mining activity)	< 0.0005	0.3	Meets requirements
Mean (n=4)	All points	< 0.0005	0.3	Meets requirements

The examination of mercury content was carried out at the Testing Laboratory of the Center for Standardization and Industrial Services (BSPJI) Banda Aceh using the SNI 8910:2021 method. On the basis of Table 1, all soil samples from the four points (Quadrant I/the amalgam processing and burning area, Quadrant II/the tailings disposal area, Quadrant III/the community garden or land area, and Quadrant IV/the control area relatively far from mining activity) show a mercury (Hg) content of less than 0.0005 mg/kg, far below the environmental quality standard of 0.3 mg/kg, so that all samples are declared to meet environmental quality requirements. Because all samples have the same test result value, the mean mercury content in soil across the four samples (n = 4) is also declared to be less than 0.0005 mg/kg, with no meaningful difference in concentration among the points, whether in the processing area, the tailings disposal area, the community land, or the control area. This condition indicates that mercury pollution in the soil at the study site has not yet been detected significantly, or is still below the detection limit of the testing method used by the laboratory.

4.2. Discussion

On the basis of the laboratory test results, the soil condition at the study site is still relatively safe according to the mercury parameter. When compared with various studies in other gold mining areas that show mercury levels exceeding the quality standard, the results of this study display a better condition in terms of soil environmental quality. All soil samples at the study site show a mercury (Hg) level of < 0.0005 mg/kg, a value that still lies far below the mercury quality standard in soil of 0.3 mg/kg, so that it is declared to meet environmental quality standards and does not yet show the existence of significant mercury pollution. This low mercury content is presumed to be influenced by several factors, among others the limited use of mercury, the natural washing process by rainwater that carries mercury along with the flow of water and mud, topographic conditions, the characteristics of the soil in binding heavy metals, the relatively shallow depth of sampling (±10 cm), and the distance of the sampling points from the main pollution sources such as the amalgam burning area and the tailings disposal area.

Measurement results showing mercury concentrations below 0.0005 mg/kg do not in themselves prove that there has not yet been a significant release or spread of mercury at the study site. These results merely indicate that the mercury concentrations in the analysed soil samples were reported to be below 0.0005 mg/kg. Therefore, the findings of this study must be interpreted strictly in relation to the analysed soil samples and cannot be used to conclude that the entire study site is free from mercury contamination.

Factors suspected of influencing the low mercury concentrations in the soil at this study site, such as leaching by rainwater, topographical conditions, soil characteristics, and the distance of sampling points from pollution sources, should be understood as hypotheses that still require further verification. This study did not specifically measure rainfall intensity, the physical and chemical characteristics of the soil, the movement of mercury in the environment, or the relationship between the distance from the source of contamination and mercury

concentrations. Therefore, these factors cannot yet be established as the direct causes of the low measured mercury concentrations. These factors can only be proposed as possible explanations based on considerations of environmental processes and the findings of previous studies. Further research involving the measurement of relevant environmental parameters is required to test these hypotheses and elucidate the factors contributing to mercury concentrations at the study site.

The results of this study are in line with the study by Amri et al. (2020), which discusses soil characteristics and mercury content in former small-scale gold mining land, showing that soil conditions in former mining areas are influenced by environmental characteristics and mining activity that took place previously. This can be linked with the results of the study in Gampong Paya Teuk, where the mercury content obtained is still very low, thus showing that the amount of mercury within the soil is not determined only by the existence of mining activity, but also by the soil and environmental conditions around the study site. The results of this study also have correspondence with Mulyadi et al. (2025), who studied mercury content in sediment resulting from the amalgamation activity of traditional gold mining, showing that mercury exposure is not always visible in the soil medium, but can be found in other environmental media related to gold processing activity. This supports the results of the study in Gampong Paya Teuk, because even though the mercury content in the soil lies below the detection limit, that does not mean the presence of mercury in other environmental media can be disregarded, so that monitoring of other media such as water and sediment remains important to carry out.

The study by Nuryanty et al. (2024) shows that small-scale gold mining activity can affect the presence of mercury in the environment, especially in processing areas and tailings disposal areas. The results of that study serve as a comparison for this study because both examine mercury content in the gold mining environment. However, the results obtained in Gampong Paya Teuk show a different condition, namely that all samples have an Hg level of < 0.0005 mg/kg. That difference in results may relate to site conditions, the intensity of mining activity, the distance of the sampling points from the pollution source, and the environmental conditions of each area. Thus, the results of this study show that the existence of mining activity does not always produce the same soil mercury level at every site. The results of this study can also be linked with the study by Kusnarta et al. (2024) concerning mercury in soil in small-scale gold mining areas, which explains that soil characteristics can affect the presence and movement of mercury within the soil. This accords with the conditions in the study in Gampong Paya Teuk, where the low mercury level is likely influenced by soil characteristics as well as natural processes occurring in the environment; the washing process by rainwater can cause mercury to move from one location to another so that the concentration at a particular point becomes lower.

The study by Agustiani, Sulistia, Sudaryanto, et al. (2025) shows that small-scale gold mining activity has a relationship with mercury pollution as well as public health risk, with mercury being found in various environmental media in mining areas. If linked with this study, the low results in Gampong Paya Teuk show that at the time the study was conducted, no accumulation of mercury in the soil exceeding the quality standard had been found. However, those results do not mean that the study site is entirely free from the potential for pollution, because factors of distance from the pollution source, environmental conditions, the intensity of mining activity, and waste management can cause mercury levels to differ between one location and another. Huisa-Mamani et al. (2025) explain that the factors of distance from the pollution source, soil texture, organic matter content, and natural dilution processes play a role in the low concentration of mercury in soil. In addition, Mulyadi et al. (2025) also show

that the risk of mercury exposure is more often found in biological media such as the hair and blood of community members than in soil, especially as a result of exposure from the gold processing process. Although the study results show that soil mercury levels are still low, Brocza et al. (2024) as well as FAO and FAOLEX (2022) affirm that gold mining activity still needs to be monitored because mercury is persistent in nature and can move into other environmental media such as water, sediment, and biota.

These findings indicate that the mining activity taking place at the study site has not yet given rise to significant mercury pollution impacts on the soil medium at the sampling points examined. The low concentrations of mercury measured in this study may be related to several factors, such as the intensity of mercury use, soil characteristics, the transport of mercury via rainwater runoff, and the distance of the sampling points from the source of contamination. However, these factors remain hypothetical as they were not measured directly in this study. Consequently, the relationship between these factors and the low mercury concentrations found cannot yet be confirmed. No meaningful difference in mercury levels was found at the four sampling points; all samples show results of less than 0.0005 mg/kg. That condition shows that the distribution of mercury at the study site is relatively even and still at a very low level, so that the spread of mercury into the soil environment has likely not yet occurred extensively or is still at a very small concentration and therefore not yet detected quantitatively by the laboratory testing method.

The presence of mercury (Hg) in the environment is influenced not only by the amount of mercury that enters the soil, but also by processes of environmental dynamics such as movement, changes in chemical form, binding by soil particles, and natural processes occurring in the environment. Mercury originating from gold mining activity can enter the soil through the disposal of waste from gold processing, residues of the amalgamation process, and the deposition of mercury vapor from the amalgam burning process. Once within the soil, mercury can undergo adsorption by soil minerals, become bound with organic matter, move through water flow, and undergo changes in form through the activity of soil microorganisms. On the basis of that theory of environmental dynamics, the low mercury content found in this study can be explained in that the processes of entry and spread of mercury at the study site have likely not yet taken place significantly, so that the process of mercury accumulation in the soil medium is still very low.

The persistent nature of mercury means that this metal still needs to be a matter of attention even though the measurement results remain below the quality standard, because mercury can move from one environmental medium to another such as soil, water, sediment, and living organisms through food chain processes. Therefore, environmental conditions that at present still meet standards do not preclude the possibility of an increase in mercury content if mining activity and waste management are not carried out properly, so that periodic environmental monitoring remains necessary in order to ascertain changes in mercury content over the long term. On the basis of the study results obtained, there are two main assumptions that can be made the basis of explanation: first, gold mining activity at the study site is assumed not yet to have produced a release of mercury in large amounts that would cause accumulation in the soil; second, environmental conditions such as rainfall, soil characteristics, and the distance of the sampling locations from the source of gold processing activity are assumed to contribute to influencing the low mercury levels found. Thus, the results of this study answer the research objective, namely that the status of mercury content in soil at the gold mining site in Gampong Paya Teuk still lies within the safe category, yet periodic monitoring of environmental quality, community education, and the application of

more environmentally friendly mining practices remain necessary as a step to prevent mercury pollution in the future.

5. Conclusion

Based on the research findings, the mercury (Hg) concentrations in all soil samples from the four sampling points (Quadrants I, II, III and IV) at the gold mining site in Gampong Paya Teuk, Pasie Raja Sub-district, South Aceh Regency, were below the detection or reporting limit of 0.0005 mg/kg. Consequently, the mercury concentrations in all samples could not be quantified with certainty, including the average value, and were below the soil quality standard of 0.3 mg/kg used as a reference in this study. No differences were found in the measured mercury concentrations between the amalgam processing area (Quadrant I), the tailings disposal area (Quadrant II), community land (Quadrant III) and the control area (Quadrant IV). However, these results must be interpreted whilst taking into account the limitations of the measurement methods, the number of sampling points and the scope of the study area. Mercury concentrations below the limit of detection do not necessarily prove that mercury release or dispersion has not occurred. Therefore, the results of this study indicate that the mercury concentrations in the analyzed soil samples were below the limit of detection used; however, this is not sufficient to conclude that the entire study area is free from mercury contamination.

The public and gold mining operators are advised to avoid discharging gold processing waste directly into the soil and water bodies, and to implement more controlled tailings management and more environmentally friendly gold processing practices. The Ujung Padang Rasian Community Health Centre (UPTD Puskesmas), together with relevant agencies, is advised to improve education regarding the risks of mercury exposure and to support regular environmental quality monitoring. Future research should expand the number of sampling points and the scope of sampling, consider taking samples at various soil depths, and analyze other environmental media, such as water, sediment and food crops, to obtain a more comprehensive picture of mercury distribution.

5.1. Conflict of Interest Statement

The authors declare that they have no known financial or personal relationships that could be perceived as competing interests in connection with this article. Neither BSPJI Banda Aceh nor the South Aceh Regency Health Office had any role in the design of the study, the interpretation of the analytical results, or the decision to publish.

5.2. Author Contributions

L.L.: Conceptualization, Methodology, Investigation, Formal Analysis, Writing – Original Draft, Project Administration.
P.R.K.: Investigation, Data Curation, Validation, Writing – Review & Editing.
R.S.T.B.B.: Investigation, Data Curation, Visualization, Writing – Review & Editing.

5.3. Funding Statement

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

5.4. Informed Consent

Informed consent was not required. The study involved no human participants; data collection was limited to environmental soil sampling at the mining site, supported by secondary health-office data aggregated at the population level.

5.5. Ethical Approval

Not applicable. The research involved no human or animal subjects and no collection of personal data. Fieldwork was limited to soil sampling at the study site, carried out with the permission of the local community and relevant local authorities.

5.6. Data Availability

The analytical results underlying this study are presented in Table 1 of the article. The laboratory test reports issued by BSPJI Banda Aceh, including the detection limit and method reference (SNI 8910:2021), may be obtained from the corresponding author [L.L.] upon reasonable request, subject to the issuing laboratory's data-release provisions.

5.7. Declaration of Generative AI and AI-assisted Technologies

During the preparation of this manuscript, the authors utilized Claude (Anthropic) for language editing and clarity improvement. All outputs generated with the assistance of the tool were critically reviewed and revised by the authors to ensure factual accuracy, faithful representation of the analytical results, and adherence to academic standards. The authors assume full responsibility for the integrity and content of this manuscript.

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