Analysis and Mitigation of the Impact of Artisanal Gold Mining in Ratatotok Village, Southeast Minahasa Regency

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Abstract

Artisanal gold mining in Ratatotok Village, Southeast Minahasa Regency, is an informally growing economic activity that poses significant environmental impacts, particularly on water quality. The use of hazardous chemicals such as mercury (Hg) and cyanide (CN), along with the potential release of arsenic (As), presents a serious threat to groundwater, springs, and rivers utilized by local communities. This study aims to assess water quality by focusing on three key parameters—mercury, cyanide, and arsenic—based on the quality standards stipulated in Government Regulation No. 2 of 2023 (for clean water) and Government Regulation No. 22 of 2021 (for Class III river water). Spatial analysis was conducted using a 500-meter buffer radius from seven sampling points to map pollutant distribution and identify zones of contamination risk. Laboratory results indicate that although all parameter concentrations remain within regulatory thresholds, the levels of arsenic and cyanide at several locations approach the upper limits, suggesting the onset of contamination. Spatial mapping reveals moderate-risk zones concentrated around mining activity areas, warranting targeted mitigation efforts. As a mitigation strategy, this study recommends the implementation of a modular reactor system with cyanide recirculation. This simple and environmentally friendly waste processing technology enables the reuse of cyanide solution in a closed-loop system.

Through quantitative and spatial approaches, this study is expected to contribute to the formulation of environmental management policies and adaptive water pollution mitigation strategies tailored to the context of artisanal gold mining areas.

Keywords: Artisanal Gold Mining; Mining Impact; Impact Mitigation; Ratatotok Village.

INTRODUCTION

Artisanal gold mining is one of the growing economic activities in various regions of Indonesia, including in Ratatotok Village, Southeast Minahasa Regency. However, the gold extraction process in this region is often carried out without compliance with technical standards or proper environmental management practices. The use of hazardous chemicals such as mercury (Hg) and cyanide (CN) is a major contributor to environmental pollution. In addition, other heavy metals such as arsenic (As) and lead (Pb) are also found in mining waste, which is frequently discharged into the environment with little or no treatment. These practices pose serious threats to the quality of groundwater, surface water, and spring water, all of which are vital for local community use. Exposure to these substances not only harms aquatic ecosystems but also creates long-term health risks for

surrounding populations, particularly vulnerable groups such as children and the elderly.

In an effort to understand the extent of the environmental damage caused by artisanal gold mining, this study focuses on analyzing water quality based on three key parameters: mercury, cyanide, and arsenic. The analysis is conducted with reference to the water quality standards outlined in Government Regulation No. 2 of 2023 for clean water and Government Regulation No. 22 of 2021 for class III river water. This regulatory framework provides a foundation for evaluating the severity of pollution and determining whether water quality in the study area meets acceptable thresholds.

To further assess the environmental impact, this study also adopts a spatial analysis approach using a 500-meter buffer radius around each sampling point. This method enables the identification of pollutant distribution patterns and the classification of contamination risk zones. By mapping these zones, the research highlights areas that require prioritized monitoring and environmental management efforts.

In addition to analyzing the pollution levels and spatial distribution, the study also seeks to identify general mitigation strategies that can be applied to reduce environmental impacts. While the technical details of each method are not discussed in depth, this research emphasizes the importance of promoting environmentally friendly solutions, particularly through the recommendation of a modular reactor system with cyanide recirculation. This system allows cyanide solution to be reused in a closed process, minimizing chemical waste, reducing environmental discharge, and offering a practical solution for small-scale mining operations.

The overall objectives of this research are to analyze the current state of water quality in the artisanal gold mining area of Ratatotok Village, to map pollution distribution patterns using spatial methods, and to identify relevant mitigation strategies that may be implemented. By providing both scientific and practical insights, this study aims to support regulatory compliance, inform policy decisions, and encourage the adoption of sustainable mining practices.

This research is expected to contribute to several key outcomes. First, it provides a scientific overview of the extent of heavy metal and chemical contamination based on nationally accepted regulatory standards. Second, it offers spatial data that can be used by local governments and stakeholders as a foundation for environmental planning and water quality protection policies. Third, it presents initial recommendations for community-based mitigation strategies and waste management technologies, which may serve as a basis for further research or implementation of local environmental action plans. Artisanal gold mining activities in Ratatotok Village are believed to significantly contribute to water pollution in the surrounding area, as indicated by rising levels of mercury and cyanide in local water sources. However, through effective land reclamation, improved mine waste management, strict enforcement of environmental policies, and active community involvement in mitigation efforts, the environmental impacts of mining can be significantly reduced. The integration of these targeted strategies is expected to support sustainable improvements in environmental quality for Ratatotok Village and serve as a model for responsible artisanal mining in other regions.

RESEARCH METHODS

Artisanal gold mining is one of the growing economic activities in various regions of Indonesia, including in Ratatotok Village, Southeast Minahasa Regency. However, the gold extraction process in this region is often carried out without compliance with technical standards or proper environmental management practices. The use of hazardous chemicals such as mercury (Hg) and cyanide (CN) is a major contributor to environmental pollution. In addition, other heavy metals such as arsenic (As) are also found in mining waste, which is frequently discharged into the environment with little or no treatment. These practices pose serious threats to the quality of groundwater, surface water, and spring water, all of which are vital for local community use. Exposure to these substances not only harms aquatic ecosystems but also creates long-term health risks for surrounding populations, particularly vulnerable groups such as children and the elderly.

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RESULTS AND DISCUSSION

This research was carried out in Ratatotok District, Southeast Minahasa Regency, North Sulawesi Province. This area is known as an area with very high potential for mineral resources, especially gold, which makes it one of the centers of Artisanal gold mining activities in eastern Indonesia. Geographically, the Ratatotok area is located on the southern coast of the northern part of Sulawesi Island, with a landscape dominated by hills and mountains rich in metal content, as well as a hydrological system that flows from upstream to downstream to Buyat Bay. Most of the residents of Ratatotok District are Artisanal from the Minahasa tribe who have a strong cultural relationship with nature and the environment. This attachment is reflected in how the community uses local resources for generations, including in the practice of Artisanal gold mining. To support the spatial understanding of the environmental context of the research area, in this section the Land Cover Map of Ratatotok District (Figure 1) is presented. This map is displayed as a visual aid to illustrate the distribution and extent of each type of land use in the study area, as well as to show the direct relationship between mining activities and the conditions of the surrounding environment, especially water bodies that are susceptible to pollution. This information is important to identify strategic locations affected by Artisanal gold mining activities, as well as as a basis for further environmental impact analysis.

Based on the interpretation of land cover maps, the research area includes various types of land cover including residential areas, forests, open pit mines, scrubland, and river networks. Artisanal gold mining areas were identified as widespread especially in the central to southern parts of the region, adjacent to settlements and river routes, indicating a high potential for water contamination due to mining waste flows. Meanwhile, forest areas still dominate the northern and western parts of the Ratatotok region, which serves as an important buffer for the ecosystem.
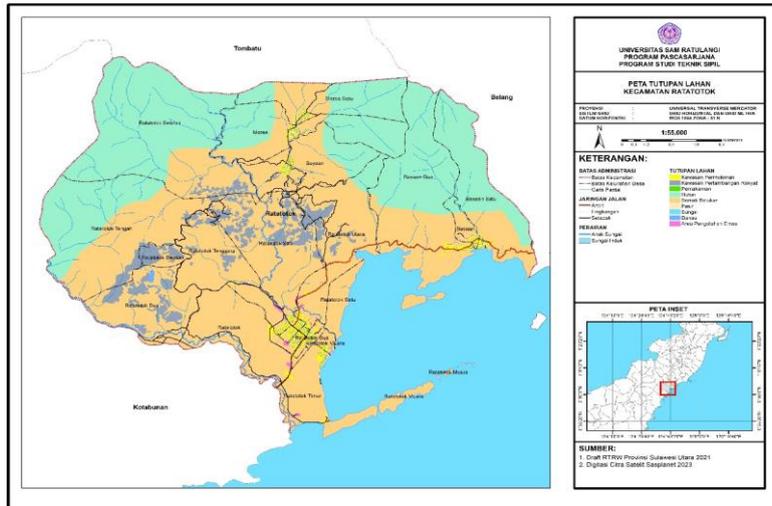
Figure 1. Land Cover Map

The Ratatotok Subdistrict has complex hydrological characteristics with varying groundwater availability, supported by river flow patterns that cross almost all villages and form a good natural drainage system. The Hydrology Map of Ratatotok Subdistrict shows three categories of aquifer productivity—highly productive, moderately productive, and low productivity—with most of the central to southern areas, such as Ratatotok, Ratatotok Satu, and Ratatotok Dua, falling into the highly productive zone with abundant groundwater potential. In contrast, northern areas like Ratatotok Selatan and Basaan Atas have low productivity, requiring deeper exploration technologies to meet water needs. The presence of tributaries flowing from north to south and the even distribution of aquifers indicate that this region has great potential for local water resource development, making hydrological mapping essential to support efficient water management and water security in rural areas of Ratatotok.
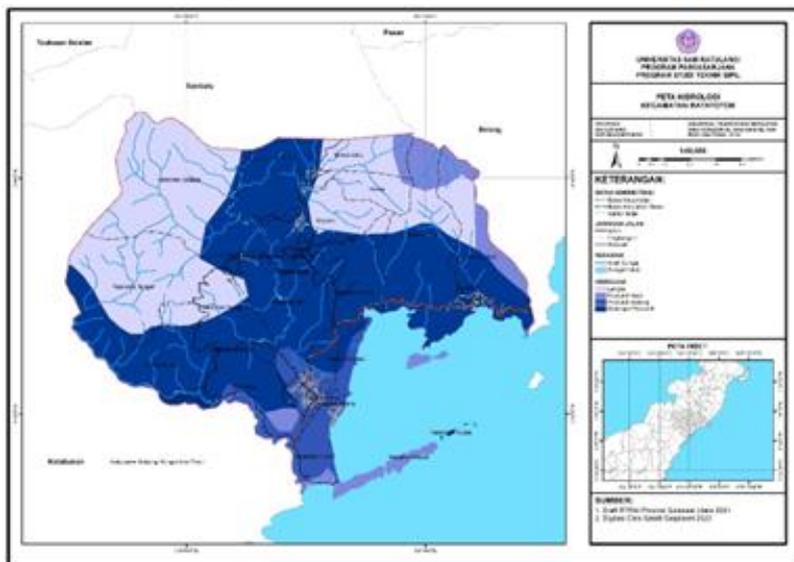

Figure 2. Hydrology Map of Ratatotok Subdistrict

Ratatotok Village has a hydrological system influenced by its geographical, geological, and tropical climate conditions, with water flow patterns following the hilly

topography, allowing rainwater to easily flow toward rivers and natural channels. During the rainy season, river discharge increases, while in the dry season, shallow wells often dry up. The main water sources in the village come from springs, local rivers, and groundwater from wells. Ratatotok District has complex hydrological characteristics with varying groundwater availability, but its natural drainage system is relatively good in areas with gentle to steep contours. Based on the Ratatotok District Hydrology Map, the central to southern areas, such as Ratatotok, Ratatotok Satu, and Ratatotok Dua villages, are classified as highly productive aquifer zones, while northern areas like Ratatotok Selatan and Basaan Atas are in low-productivity zones, requiring deeper water exploration technology. The presence of tributaries flowing from north to south and the distribution of aquifers indicate significant potential for developing local water resources. Therefore, hydrological mapping is essential to support efficient water management strategies and ensure water resilience in rural areas such as Ratatotok.

The test results of the eight samples are as follows:

Sample 1

Sample 1 was collected from a spring in the Waseng area, which serves as both a residential area and a base for gold miners. This spring is the primary water source for the surrounding community's daily needs. Although the water quality from this spring largely meets the required standards, the mining activities nearby pose a potential risk of heavy metal contamination, warranting further monitoring.

Sample 2

Sample 2 was collected from a well located several kilometers from the Waseng spring. This well is commonly used for washing clothes and bathing, but not for drinking purposes. It is situated close to residential areas and small-scale gold processing facilities, which discharge wastewater that could contaminate the groundwater. While the current water quality remains within safe limits, the potential contamination from gold processing activities requires continuous monitoring.

Sample 3

Sample 3 was collected from an upstream section of the river, which is used as a disposal route for wastewater from gold processing activities. The river contains hazardous chemicals such as mercury and cyanide, which pose a serious threat to the environment and the health of communities that rely on the river as a water source.

Sample 4

Sample 4 was collected from the midstream section of the river, which flows near residential areas. Gold processing activities in this vicinity generate waste that is directly discharged into the river. If not properly managed, this waste could exacerbate water pollution, endangering both the ecosystem and the health of local communities dependent on this river.

Sample 5

Sample 5 was collected from a well located near the coast, which is not used by residents for consumption. The well is situated close to gold processing sites, making it susceptible to contamination by hazardous chemicals such as mercury and cyanide. Although most water quality parameters are still within safe limits, continuous monitoring is necessary to ensure water safety.

Sample 6

Sample 6 was collected from the river estuary near a residential settlement. Although it is not directly impacted by gold mining waste, this estuary may still receive runoff from upstream river segments contaminated by mining activities. The interaction between domestic activities and the river water increases the risk of environmental pollution.

Sample 7

Sample 7 was collected from the main river estuary that serves as the primary disposal route for waste from gold processing. Intensive gold processing activities in the surrounding area have caused severe pollution, with extremely high water turbidity due to suspended particles from excavation and gold processing materials. These impacts significantly deteriorate water quality and the surrounding ecosystem.

Sample 8

Sample 8 was collected from gold processing tailings in the Waseng area. This soil contains excessively high levels of heavy metals, including mercury (3.68 mg/kg), arsenic (659.73 mg/kg), lead (0.96 mg/kg), and cadmium (0.54 mg/kg), exceeding safe limits. While the soil pH is neutral, the heavy metal content indicates severe contamination. This soil is unsuitable for agriculture without proper remediation, and the continued use of mercury in gold processing exacerbates its environmental impact.

The following table presents the laboratory test results for each sample collected from various water sources surrounding the gold mining area. These results are used to evaluate the potential contamination caused by mining activities and their impacts on both the environment and public health. The table provides the detailed test results for each sample described above.

Table 1. Laboratory Test Results of Water Samples

No	Parameter	Unit	Spring Water (Sample 1)	Well Water (Sample 2)	River Water (Sample 3)	River Water (Sample 4)	Well Water (Sample 5)	River Water (Sample 6)	River Water (Sample 7)	Test Method
1	Dissolved Arsenic (As)	mg/L	< 0,0002	0.0085	0.0273	0.0239	0.0016	0.0212	0.0259	SNI 06-6989.54-2005
2	Dissolved Mercury (Hg)	mg/L	0.0005	0.0006	0.0006	0.0006	0.0004	0.0005	0.0005	SNI 6989.78:2019
3	Cyanide (CN)	mg/L	< 0.007	< 0.007	0.01	0.04	< 0.009	0.02	0.03	IK-1.35 Spektrofotometri

Source: Author (2025)

Discussion

Spatial and Comparative Evaluation of Water Pollutant Parameters Based on Government Regulation No. 22 of 2021 and Government Regulation No. 2 of 2023 (Summary)

a. **Spatial Analysis in Water Quality Assessment**

Spatial analysis was used in this study to evaluate the distribution of water pollution based on parameters deemed important according to regulations. With the help of GIS software such as ArcGIS, the data from the laboratory test results is mapped into a colored thematic map, which shows the pollution zones from safe to highly polluted. This mapping makes it easier to identify affected sites and supports mitigation strategies, such as the establishment of priority zones for mine waste recovery and control.

The pollution zones are classified into four levels based on the thresholds of Government Regulation No. 22/2021 and Government Regulation No. 2/2023:

1) Safe Zone (Green): Below the threshold; can still be used according to its designation.
2) Medium Zone (Yellow): Slightly over the limit; Need monitoring.
3) High Zone (Orange): Quite high; It needs to be processed before use.
4) Very High Zone (Red): Well above the limit; Not suitable for use without further processing.

Each sampling point is classified based on test results and visualized on a map to facilitate interpretation and data-driven environmental policy-making.

b. **Mapping and Comparison of Sample Data to Quality Standards (Government Regulation No. 22 of 2021 and No. 2 of 2023)**

The analysis of water quality from seven samples, consisting of household water and river water, aims to evaluate whether the water meets the quality standards set by Government Regulation (PP) No. 22 of 2021 and PP No. 2 of 2023. The test results indicate that most water quality parameters—such as arsenic, mercury, cyanide. However, several sampling points reveal potential contamination, particularly in areas adjacent to artisanal gold mining activities. Although the majority of samples comply with the established standards, elevated concentrations of Arsenic and cyanide, at certain locations indicate an environmental risk that requires further monitoring and mitigation.

The arsenic and cyanide parameters in river water samples at Points 4 and 7 exhibit higher concentrations compared to other sampling locations, indicating the impact of small-scale gold processing activities on water quality. These locations are known as areas with a high density of artisanal gold processing units. Spatial mapping further reveals that Points 4 and 7 fall within the yellow zone classification, suggesting moderate pollution risk. Therefore, targeted mitigation efforts and stricter water quality management are required to control contamination. Without timely

intervention, pollution levels in these areas may worsen and pose greater environmental threats in the future.

Spatial Delineation of Areas at Risk of Pollution Due to Artisanal Gold Mining

This study uses spatial analysis to evaluate the spread of water pollution due to Artisanal gold mining activities in Ratatotok District. Visualization was carried out by mapping a radius of 500 meters from seven sampling points, using laboratory data on pollutant parameters such as arsenic, mercury, and cyanide. The results show that all parameters are still below the quality standard threshold based on Government Regulation No. 2 of 2023 (clean water) and Government Regulation No. 22 of 2021 (class III river water). However, some points such as S3, S4, S6, and S7 show higher concentrations of pollutants than natural levels, indicating the potential for initial contamination even though it has not exceeded the regulatory limit.

Based on the classification of risk zones, the regions are divided into three categories: low-risk zones (S1, S2, S5, S3, S6), medium (S3, S4, S6, S7 for arsenic and S4, S7 for cyanide), and no high-risk zones are found. Medium zones indicate an ecologically significant increase in pollutant levels and need to be monitored regularly to prevent further pollution.

a. Spatial Analysis and Visualization of Areas at Risk of Pollution by Heavy Metals and Hazardous Chemicals

1) Arsenic

Arsenic (As) is an important indicator in assessing the risk of pollution from small-scale gold mining activities. Laboratory tests on seven water sampling points (springs, wells, and rivers) referred to Government Regulation (PP) No. 2 of 2023 for clean water and PP No. 22 of 2021 for Class III river water. Three clean water samples (S1, S2, S5) showed arsenic levels below the limit of 0.01 mg/L, with results of <0.0002 mg/L, 0.0085 mg/L, and 0.0016 mg/L, indicating they are safe for use. Four river water samples (S3, S4, S6, S7) were also below the threshold of 0.05 mg/L, ranging from 0.0212 to 0.0273 mg/L. Although none exceeded the quality standard, arsenic concentrations in some points, particularly S3, S4, S6, and S7, were higher than natural levels (<0.001 mg/L), indicating early anthropogenic contamination. Spatial visualization with a 500-meter buffer radius showed that all points remain within the safe zone, but areas with relatively high arsenic levels are recommended for regular monitoring to prevent accumulation and environmental degradation. This analysis emphasizes the need for continuous monitoring as a preventive measure against future pollution risks.
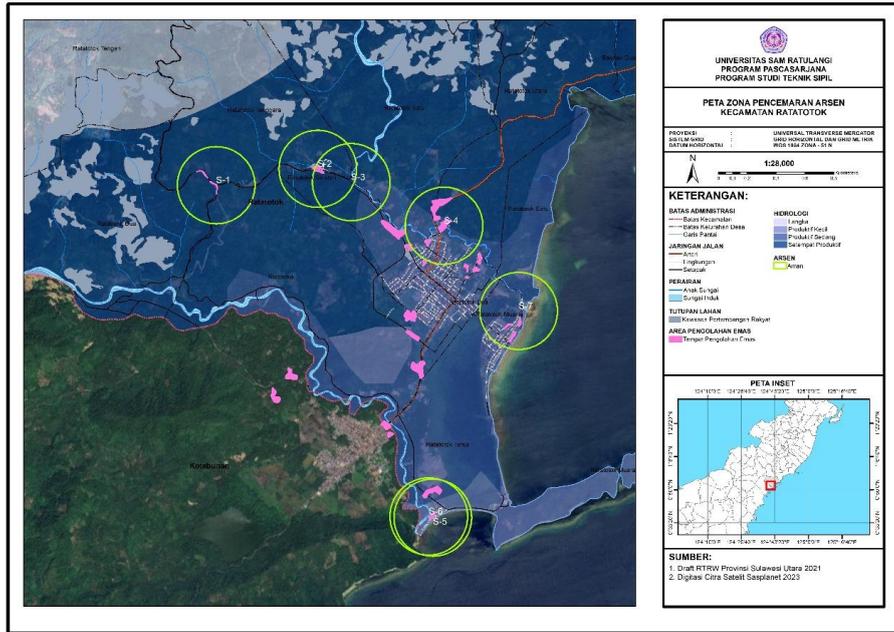
Figure 3. Spatial Visualization of Arsenic Potential Impact Zones

2) Mercury

Mercury (Hg) is a hazardous heavy metal commonly used in gold processing through the amalgamation method, requiring strict monitoring of its distribution and concentration. Tests conducted on seven sampling points (springs, wells, and rivers) referred to Government Regulation (PP) No. 2 of 2023 for clean water and PP No. 22 of 2021 for Class III river water. Laboratory results showed that mercury levels in three clean water samples (S1, S2, S5) were below the threshold of 0.001 mg/L, with values ranging from 0.0004–0.0006 mg/L, while four river water samples (S3, S4, S6, S7) were also below the limit of 0.002 mg/L. Although these levels are legally safe, all samples exhibited mercury concentrations higher than natural background levels (<0.0001 mg/L), indicating potential accumulation from artisanal gold mining activities. Spatial mapping using a 500-meter buffer radius showed safe zones, but points with levels approaching the threshold, such as S2, S3, and S4, are recommended for regular monitoring. Overall, this analysis highlights the need for continuous surveillance and mitigation strategies to prevent the escalation of mercury pollution in mining areas.
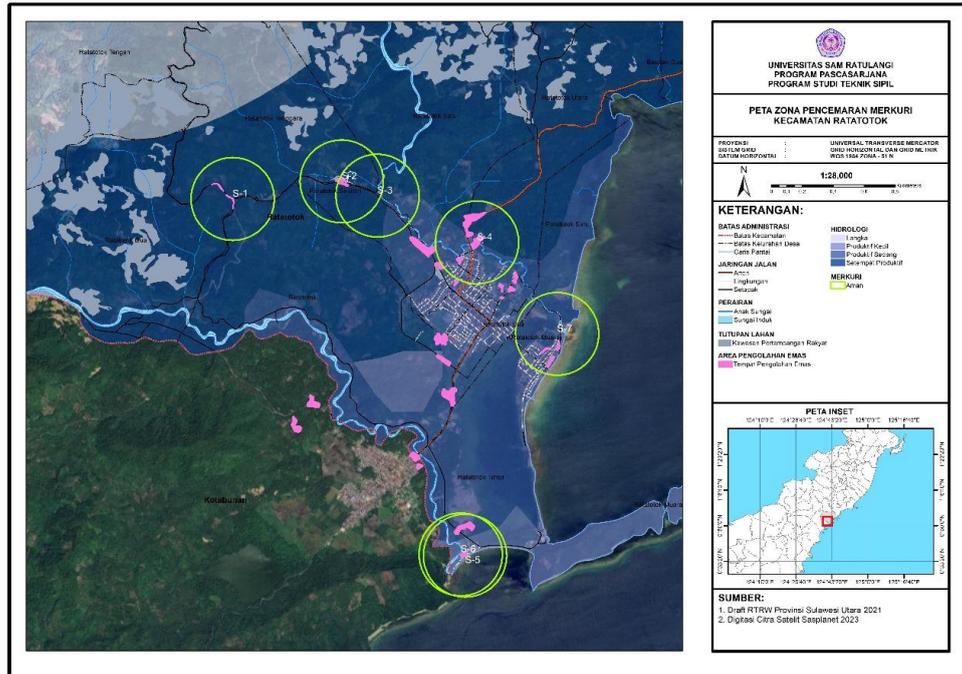
Figure 4. Spatial Visualization of Mercury Potential Impact Zones

3) Cyanide

Cyanide (CN) is a hazardous chemical widely used in gold processing through leaching methods and serves as a key indicator in monitoring the environmental quality of mining areas. Tests on seven water sampling points in Ratatotok Subdistrict, including wells, springs, and rivers, showed that cyanide levels in three clean water points (S1, S2, S5) were well below the threshold set by Government Regulation (PP) No. 2 of 2023 (0.07 mg/L), with results of <0.007 mg/L for S1 and S2 and <0.009 mg/L for S5, placing them all in the safe zone. For the four river water points (S3, S4, S6, S7), analyzed based on PP No. 22 of 2021 (limit of 0.1 mg/L), cyanide levels were also below the standard, ranging from 0.01 to 0.04 mg/L. However, concentrations in S4 (0.04 mg/L) and S7 (0.03 mg/L) were higher than the other points, indicating active contamination from mining activities.

Spatial visualization with a 500-meter buffer radius shows two risk categories: safe zones (S1, S2, S3, S5, S6) and moderate-risk zones (S4 and S7), reflecting localized contamination potential. Although none of the samples exceeded the regulatory limits, cyanide concentrations at certain points are approaching early warning levels and are located near surface water flows and residential areas, requiring regular monitoring to prevent health risks and broader pollution. Overall, while heavy contamination has not yet occurred, the resulting spatial map can be used as a basis for mitigation policies and water quality monitoring strategies in mining areas.
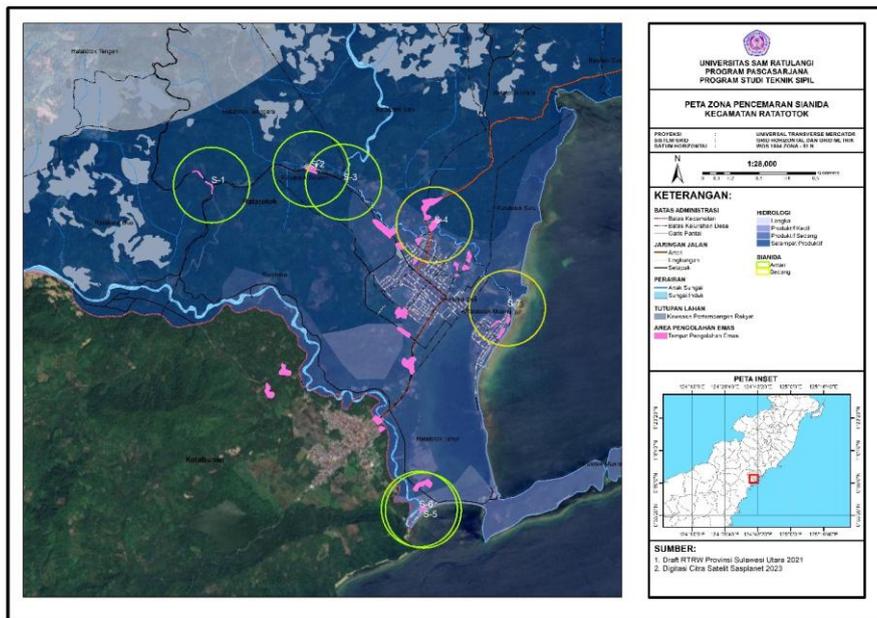
Figure 6. Spatial Visualization of Cyanide Potential Impact Zones

Analysis of the Impact of Artisanal Gold Mining on Water Quality in Ratatotok Village

Laboratory test results from water and tailings soil samples in Ratatotok Village show a significant increase in heavy metal concentrations, particularly mercury (Hg). This increase is not naturally occurring, but rather indicates anthropogenic activity, especially from artisanal gold mining practices that lack proper waste treatment systems. The presence of mercury in the tailings suggests that the mining process contributes directly to contamination of the surrounding environment.

Furthermore, the laboratory analysis revealed a decline in the physical quality of water at several sampling points. Elevated levels of physical parameters—some even exceeding acceptable thresholds—were recorded. In addition, physical discomfort was reported, such as a burning sensation on the skin when in contact with water, especially in samples 4 and 7, indicating potential contamination or chemical irritation.

Significant changes were also found in the chemical parameters of water samples taken from seven different locations. One of the most concerning findings was the consistent presence of cyanide across all samples. In river water samples in particular, the detection of cyanide strongly suggests ongoing gold extraction activities using hazardous chemicals, with direct or indirect discharge into nearby water bodies.

Overall, these chemical alterations confirm that artisanal gold mining activities in Ratatotok Village have led to chemical contamination of local water sources. The rise in harmful substances and the disruption of water's chemical balance pose long-term threats to both public health and the sustainability of aquatic ecosystems in the region.

Mitigation Strategy for the Impact of Artisanal Gold Mining on Water Quality in Ratatotok Village

Artisanal gold mining in Ratatotok Village operates at two main scales: small-scale family-based mining using simple tools, and a growing number of operations using heavy

equipment. However, most miners still face constraints in funding, waste management technology, and environmental awareness. Due to the limited land and resources, flexible, low-cost, and space-efficient solutions are required. One of the dominant processing methods is cyanide-based leaching.

Laboratory tests show that while most heavy metal concentra tions remain below regulatory limits, arsenic and cyanide are elevated and fall within the "yellow zone," indicating a moderate pollution risk. Notably, mercury was also detected in tailings despite its ban, suggesting covert usage. Thus, mercury elimination must be reinforced through education, strict monitoring, and safer processing alternatives.

A key recommendation is the adoption of a Modular Cyanide Processing Reactor, a closed-loop leaching system that is low-cost, portable, and suitable for small-scale miners. This system utilizes closed drums for cyanide leaching, followed by filtration and chemical neutralization of the cyanide using oxidizing agents like hydrogen peroxide (H_2O_2) or sodium hypochlorite (NaOCl).
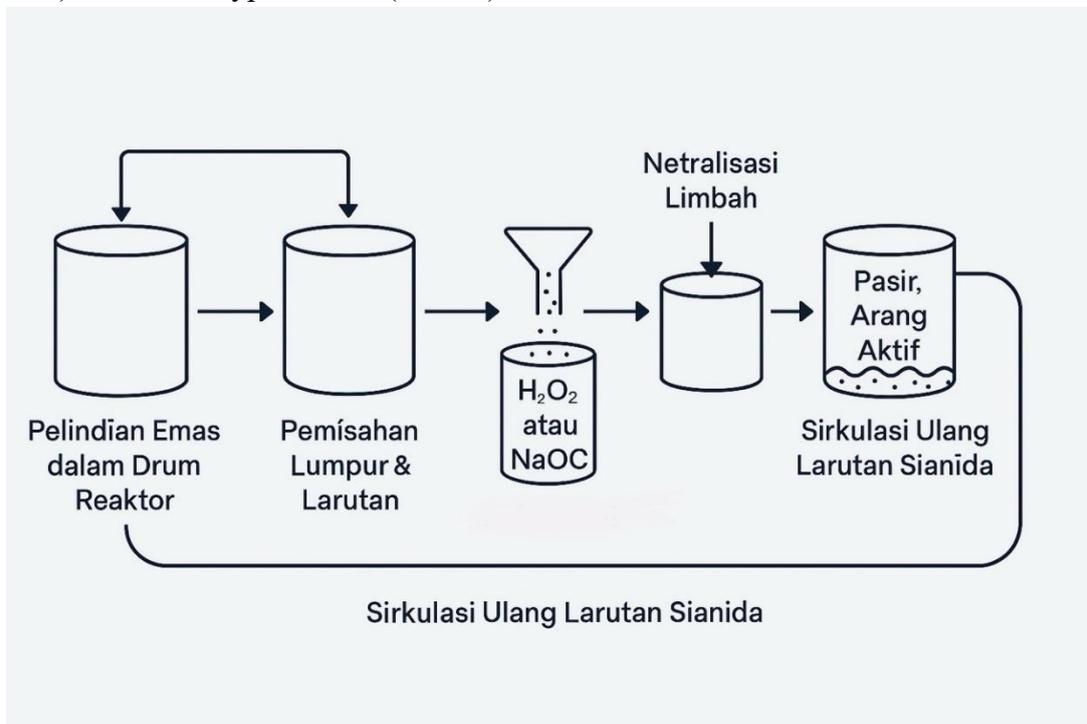
The treated solution is then reused in a circular process, significantly reducing chemical waste and pollution risk.

This modular reactor system offers multiple advantages:
1. Efficient chemical usage through recirculation and filtration;
2. Reduced environmental contamination due to a sealed design;
3. Applicability in limited spaces;
4. Lower implementation costs using locally available materials;
5. Improved gold extraction yield through controlled processing.

As a transition from traditional, environmentally harmful methods, this system provides a technically and economically feasible solution for artisanal miners. Its broader adoption will require collaboration between local communities, technical experts, and

government agencies through training, regulation, and sustained support.

CONCLUSION

This study has investigated the impact of artisanal gold mining activities in Ratatotok Village on local water quality, focusing specifically on the concentrations of mercury (Hg), cyanide (CN^-), and arsenic (As) in clean water and river water sources. Referring to Government Regulation No. 2 of 2023 and No. 22 of 2021, laboratory results from seven water samples and one tailings soil sample showed that while mercury levels remained below regulatory thresholds, all values exceeded natural background levels, indicating contamination from mining activities. Cyanide and arsenic concentrations, particularly at sampling points 4 and 7—located near gold processing zones—were found to be significantly elevated and categorized as yellow zones in spatial risk mapping, signaling moderate pollution and potential escalation if not addressed.

The spatial analysis using a 500-meter buffer radius helped identify pollution risk zones and clarified the geographic distribution of contamination. These results emphasize the need for site-specific and community-based monitoring and environmental management strategies.

As a mitigation measure, the study recommends the adoption of a **Modular Cyanide Processing Reactor**, a closed-loop cyanidation system that allows for chemical recirculation and neutralization. This system is suitable for small-scale miners due to its low cost, adaptability to limited space, and potential to reduce environmental contamination. The continued presence of mercury in tailings samples also highlights the urgent need to strengthen education, enforcement of bans, and the promotion of safer alternatives.

In conclusion, while the current pollution level in Ratatotok remains within regulatory limits, early signs of environmental degradation have emerged. Immediate, low-cost, and adaptive interventions—such as modular treatment systems and stricter monitoring—are critical to prevent long-term ecological and public health consequences in this artisanal mining region.

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