Mercury Contamination in Artisanal Gold Mining Sites in Indonesia and the Remediation

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Abstract. Mercury's mobility, toxicity, and atmospheric residency make it dangerous. Their use in amalgamation, Indonesia's recent gold rush, and the longstanding history of artisanal gold mining have brought environmental issues. Mercury contamination from tailings can harm miners, other workers, and surrounding inhabitants. The socioeconomic aspects of ASGM mining compounded mercury concerns. Environmental health assessments have been conducted to characterize mercury contamination at several ASGM mining sites in Indonesia. A study of mercury contamination at artisanal gold mining sites and remediation is needed to determine the most effective remediation method for mercury-containing waste and contaminated soil.

Keyword: Mercury Contamination, Artisanal Gold Mining Sites, Remediation

1. Introduction

The words "artisanal mining" and "small-scale mining" frequently refer to the same activity. In some regions, however, these two phrases may have different meanings. The term "artisanal mining" refers to small-scale mining carried out by hand, whereas "small-scale mining" refers to mining carried out using technology and sometimes on a larger scale [1]. Artisanal gold mining, abbreviated ASGM, has a long history and various focal points in Indonesia [2]. This mining activity utilizes up to 145 mg of mercury annually [3, 4]. This makes ASGM the second largest mercury consumer in Asia after China. ASGM practice in Indonesia and its mercury consumption have contributed to more than 57.5% of national mercury emissions [5]. Several areas contribute to mercury emissions of more than 100 g/km^2 [6]. ASMG emits 727 (range: 410–1040) tons of mercury emissions annually, or 37% of anthropogenic mercury released into the atmosphere. It is estimated that ASGM releases about 800 tons of mercury annually to soil and water, making it the primary anthropogenic source of mercury that harms the environment [7].

Although the government has promoted legal mining areas (Wilayah Pertambangan Rakyat/WPR), another problem with ASGM practice is the illegal status of most operations [8]. The extent of environmental damage makes legalization of ASGM in alluvial deposits impractical, as is the case for the vast majority of ASGM in Indonesia. ASGM of hard rock has a better chance of obtaining mining rights. Hence, it is unclear who will be liable for environmental risks from mercury released from ASGM.

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Gold mining processes such as extraction, processing, concentration, amalgamation, incineration, and refining may expose miners and people to mercury-related environmental and occupational health risks [7]. Mercury is utilized extensively in ASGM's amalgamation technique to extract gold from ore [9, 10]. According to recent research on the global health impact of mercury in artisanal gold mining, 25 to 33 percent of ASGM miners, or between 3.3 and 6.5 million globally, experience mild chronic mercury vapor poisoning [11]. Around 300,000 to 500,000 individuals in rural parts of Indonesia are also impacted by artisanal and small-scale gold mining [6].

The government ratified the worldwide treaty on mercury in the Minamata Conventions [12] as Law of the Republic of Indonesia No. 11 of 2017 [13]. The government attempted to decrease mercury consumption by regulating mercury trading and prohibiting mercury imports. As a result, mercury became prohibitively costly, and miners moved to methods other than amalgamation. The discovery of mercury deposits (cinnabar) mined locally produced mercury illegally trafficked to supply ASGM miners in Indonesia [14]. Mercury mined from a local mine is relatively inexpensive. As a result, government attempts to decrease mercury consumption are ineffective, and amalgamation remains the preferred method for gold extraction among miners. Recent government action has resulted in the signing of Presidential Decree No. 21 of 2019 on National Action Plan for Mercury Reduction and Elimination (RAN-PPM) [15] and the issuance of several mercury-banning derivative ordinances. By regulating mercury-containing ASGM procedures and attempting to develop mercury-free gold processing technologies, it is claimed that this rule may lower mercury use by up to 10.45 tons [2].

Mercury use has been reduced, but maximum efforts have not been made to address the environmental damage associated with mercury contamination. Environmental problems attributable to mercury contamination need to be further addressed, including a vigilant search for the most appropriate remediation technique tailored to the socioeconomic conditions of ASGM operators. This study examined mercury contamination at Indonesian ASGM mining sites, tailings waste as the main source, and remediation strategy.

2. Artisanal gold mining mercury contamination

Mercury contamination in artisanal gold mining is primarily a result of the gold amalgamation procedure. Elevated mercury concentrations have been reported found in soil [16, 17, 18, 19, 20], river water and sediments [18, 21, 22, 23, 24, 25], and even in the air [26].

Mercury contamination may expose the population in ASGM sites, miners, and other residents, to direct and indirect chemical hazards. During neurological examinations, some common symptoms of mercury poisoning were observed in ASGM miners and residents [27]. More detailed information on the health effects of mercury exposure can be found in Table 1 [7]. Mercury enters the body indirectly via the food chain, whereas ASGM miners also receive direct exposure to mercury vapor or liquid mercury [27].

2.1 Mercury in amalgamation

Gold amalgamation involves alloying gold particles with metallic mercury to make amalgam, then heating in retorts until the mercury evaporates to separate the gold from it [28]. Mercury pollution at ASGM mining sites is primarily caused by the amalgamation process, which produces various mercury wastes, including mine tailings and mercury vapor from heating and melting the amalgam (Figure 1) [3, 9]. Mercury vapor is more dangerous since it directly exposes humans to mercury, but mine tailings are more significant mercury contamination sources because they are deposited in soil and water and persist longer. Long-rotating amalgamation barrels with numerous iron balls might "flour" and lose mercury to the tailings [4, 14].

Table 1. Chemical hazard due to mercury exposure in ASGM mining site (modified from [7])

Hazard type	Source of exposure	Health outcome
Mercury (elemental)	Mercury emitted during gold amalgamation and mercury burning off.	Erethism (excitability), Irritability Excessive shyness Insomnia Severe salivation Gingivitis Tremors Kidney disease Acute gastrointestinal effect Pneumonitis and pulmonary oedema (from direct inhalation)
Methyl mercury	Mercury bioaccumulated in the environment and food chain	Visual disturbance Ataxia Paresthesias Hearing loss Dysarthria Mental deterioration Muscle tremor Movement disorders Paralysis and death (severe exposure) Fetal toxicity, cognitive and motoric delays and impairment (prenatal exposure)

2.2 Tailing waste management

The Indonesian government issued Minister of Environment Regulation No. 23 of 2008 concerning technical guidelines for preventing pollution and/or environmental damage from small-scale gold mining [29] to avoid the environmental impact of small-scale gold mining. The violation of this requirement by ASGM practices in Indonesia will be examined in Section 3.2. In most cases, tailings are inappropriately discharged into the environment, potentially contaminating the surrounding soil and water.

Indonesian Government Regulation No. 101 of 2014 on the Management of Toxic and Hazardous Wastes [30] suggests that the quality standard of these wastes before landfilling is TCLP ≤ 0.05 mg/L or a total concentration ≤ 75 mg/kg. According to this regulation, anyone is prohibited from disposing toxic and hazardous wastes directly into the Environment without a permit. The contaminant content must be neutralized or reduced prior to disposal. As part of environmental remediation, the contaminated soil and degraded land should be remediated. Referring to the environmentally sound management of mercury and mercury waste in Indonesia, it is stated that mixed waste containing Hg < 260 mg/kg must be treated with a stabilization/encapsulation process before being disposed of in a B3 waste landfill [31]. However, wastes with mercury levels above 260 mg/kg are unacceptable for treatment and disposal at these sites and must be shipped to other countries with better mercury remediation capacities and technologies.

Mercury is either converted to elemental mercury and emited into the air or attaches to particles in the water and is rapidly deposited/buried in sediments [6]. Substantial quantities of mercury may be lost in amalgamation wastes as microscopic mercury droplets scattered throughout the residues (mercury flour). It may be readily washed away and carried far away from the mine site (Figure 1) [4]. Mercury's fate in the ASGM mercury cycle is critical, particularly in aquatic systems, since inorganic mercury is transformed to methylmercury, which is toxic and bioaccumulates [32].

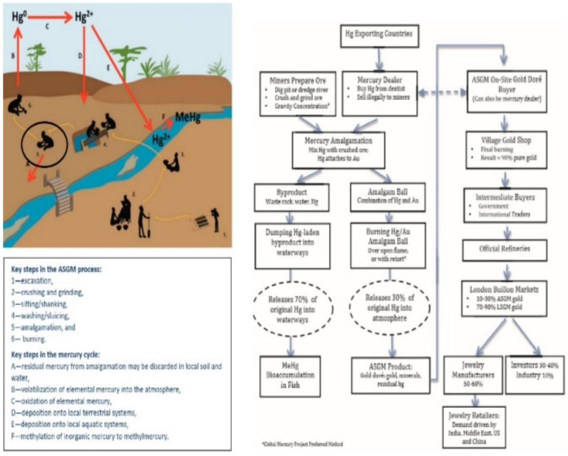

Figure 1. Mercury cycle and mercury release in amalgamation process in artisanal gold mining (ASGM) (modified from [3, 32])

3. Site assessments (case study) of mercury contamination in Indonesian ASGM mining sites

3.1 Site assessment

The majority of the mercury contamination in Indonesia's soil derives from the country's widespread practice of mercury amalgamation gold refinement and indiscriminate dumping of tailing waste [33]. The evaluation of several ASGM mining locations in Indonesia is shown in Table 2 [19, 22, 25, 34, 35, 36, 37, 38]. Mercury pollution in Indonesia is often caused by activities commonly practiced by ASGM, including: (a) excessive mercury use in amalgamation, (b) long-rotating amalgamation barrels, (c) manual amalgamation of the concentrate in a pond, (d) traditional panning of amalgam, (e) recycling amalgam waste for processing in a cyanide plant, and (f) discharging a portion of the residues from amalgamation and cyanide plants into streams, rivers, or the ocean or dumping on land.

Table 2. Mercury concentration in tailing waste and waste management of several ASGM sites in Indonesia (from various sources).

No.	Site location	Hg in tailing waste (mg/kg)	Waste management

1.	Banyumas (Java)[25]	7.49 – 92.00	The gray hue of the stream water shows that ore processing and mining wastes are dumped directly into the river since mining activities are concentrated near the channels.
2.	Galangan (Kalimantan) and Talawaan (Sulawesi) [34]	Up to 1250 with an average of 317	Release of amalgamation tailing to the river
3.	Lombok and Sumbawa (West Nusa Tenggara) [35]	Amalgam tailing 741 – 7874 Cyanide tailing 103 – 6615	The final residue of cyanide tailings are dumped into unlined tailings ponds or flushed into waterways.
4.	Lebak, Banten (Java)[36]	630 – 77910	Direct river discharge of mercury processing wastewater
5.	Buru (Maluku)[19, 22, 37]	166.1 – 825	Released of the waste to trommel waste ponds, drained downstream to the marsh and river, kept on neighboring farmland and grounds without treatment.
6.	Kulon Progo (Java)[38]	164.19 – 383.21	The gold processing tailings flooded the existing containment facilities and spilled out into the environment. In some mine sites, tailings from a heap are without further processing.

3.2 Tailing wastes, mercury speciation, and waste management

The result showed that wastes from ASGM sites still contain mercury at high concentrations of up to one thousand mg/kg. Mercury speciation is dominated by F5 (mercury sulphide), F2 (soluble in human gastric acid), and F4 (elemental Hg) [22]. Other mercury species occur at lower concentrations than the dominant species (< 15mg/kg). The highest mercury concentration is found in the waste from the first gold extraction trommel. The results of various environmental tests show that the ASGM wastes are mainly dumped into the surrounding soils and waters without proper treatment (Table 2).

3.3 Remediation technology

Mercury cannot disintegrate in the environment, thus removal or immobilization is required for cleanup. Thermal desorption, electrokinetic, and soil flushing/washing remove insoluble Hg species, whereas containment, solidification/stabilization (S/S), and vitrification immobilize it by converting it to less soluble forms. Alternative soil remediation methods include phytoremediation and nanotechnology [39]. Remediation of mercury contamination from point sources depends on feasibility. Treatments such as physical separation, hydrometallurgical and thermal methods can be applied. Otherwise, they can be secured by the method of containment and capping. Bioremediation, containment, and solidification/stabilization are the commonly recommended remediation methods for mercury contamination in Indonesia [35, 38, 40, 41, 42] (Table 3). The combination of containment and bioremediation (bioextraction/biomining) is recommended for higher mercury concentrations, especially if the waste still contains gold at significant concentrations [35]. Another method is solidification/stabilization (S/S) with Portland cement [38].

Instead of conventional remediation measures such as phytoremediation and Portland cement-based consolidation/stabilization, green and sustainable remediation (GSR) could be a promising remediation strategy to implement in ASGM operational areas. The concept of GSR has emerged in this decade from the merging of the concepts of green remediation (USA) and sustainable remediation (Europe) [43]. This concept considers several aspects, i.e., 1). secondary impacts (going beyond boundaries), 2). future impacts (looking beyond the current time horizon), 3). social and economic impacts (social and economic sustainability), 4). resilience to environmental, social, and economic changes (promoting resilience to change), and 5). adoption of nature-based solutions (incorporating nature-based solutions). According to Wang et al. (2020), mercury remediation using the stabilization and containment method is more cost-effective than other methods [44].

Table 3. Proposed soil remediation techniques for mercury contamination in Indonesia

No.	Remediation technology	Reason
1.	Phytoextraction, in addition to containment [35]	Owing to the lack of regulations governing tailings management, it is unlikely that an artisanal miner will invest in a waste containment system if there is no potential for profit.
2.	Stabilization and solidification using Portland cement [38]	S/S technology has the advantages of being inexpensive, ecologically benign, and simple to implement for the treatment of hazardous waste.
3.	Phytoremediation [40, 41]	Phytoremediation is an inexpensive and ecologically acceptable substitute for traditional soil heating, removal, and washing methods.
4.	In situ bioremediation using indigenous bacteria [42]	This removal procedure is less harmful to the environment and less expensive than physical techniques..
5.	Stabilization using local geomaterial (clay, zeolite, diatomite)[43]	Green and sustainable remediation, low cost, and the effectivity can be improved by using a thermal and chemical treatment

One component of the GSC is stabilization with green materials. Several materials have been proposed as green materials; one of them is natural minerals [43]. Natural minerals such as clay and zeolite are inexpensive and environmentally friendly. These geomaterials potentially improve the stability of mercury in waste [45]. Although the raw minerals have weak adsorption capacity for mercury, chemically altered minerals were found to have excellent adsorption capacity. In a recent study on mercury waste remediation, it was investigated and found that a more economical S/S process can be achieved by using chemically bonded phosphate ceramics (CBPC) with natural zeolites (NZ) and thiol functional zeolites (TFZ) as additives [46]. The CBPC process is more effective than conventional cement processes. At the same time, TFZ as an additive is more efficient than NZ in stabilizing mercury. The use of other green materials such as biochar, industrial waste materials, metal oxides, and nanomaterials produced by green synthesis methods has several drawbacks. The use of biochar to immobilize mercury has not been sufficient to reduce total Hg, and the mechanism of Hg immobilization is not fully understood. Industrial wastes can release significant amounts of toxic metals and organic pollutants into the Environment, the application of metal oxides can promote soil acidification, and the application of nanomaterials is relatively expensive. They can harm soil microorganisms, plants, and humans [43, 44].

Clay and zeolite are inexpensive geomaterials, and the deposits can be found in many places in Indonesia. Moreover, their effectiveness in stabilizing mercury can be enhanced by thermal and chemical activation. The use of local geomaterials for mercury remediation can provide a relatively low-cost and simple remediation strategy for ASGM mining sites.

4. Conclusions

Artisanal gold mining during the gold rush in Indonesia potentially contributes to soil and water quality degradation due to mercury contamination and the adverse health effects of mercury poisoning. This chemical hazard results from the excessive use of mercury in amalgamation, poor waste disposal, and lack of enforcement of environmental regulations related to mercury in artisanal gold mining. Improper waste disposal through the discharge of tailings into the river can expand the contaminated area downstream and treat living organisms with methylmercury. Remediation methods through containment, consolidation/stabilization, and phytoremediation are some alternative methods that are relatively inexpensive, simple, and potentially applicable to ASGM mining sites. Given the socioeconomic characteristics of ASGM mining, there is potential for future research on the application of local natural minerals/geomaterials to mercury remediation to provide a cost-effective and simple remediation technology for use at ASGM mining sites.

5. Credit authorship contribution statement

Anita Yuliyanti (Master of Arts in Earth Science, researcher) and Aminuddin (Master of Engineering in Environmental Geology, researcher) completed the literature review and were in charge of manuscript writing.

6. Author's note

The authors declare that there is no conflict of interest in the publishing of this article and confirms that the material is plagiarism-free.

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