Jurnal Sains dan Teknologi
Volume 13 Number 3, Tahun 2024, pp. 517-522
P-ISSN: 2303-3142 E-ISSN: 2548-8570
Open Access: https://doi.org/10.23887/jstundiksha.v13i3.84239

The Investigation of Mercury in an Abandoned Artisanal and Small-Scale Gold Mining (ASGM)

Asep Nurohmat Majalis[1*], Nicko Widiatmoko[2], Yeni Novitasari[3], M Rifat Noor[4], Noviarso Wicaksono[5], R Arif Suryanegara[6]

[1] Research Center for Chemistry, National Research and Innovation Agency, South Tangerang City, Indonesia
[2] Research Center for Limnology and Water Resources, National Research and Innovation Agency, Bogor, Indonesia
[3,4,5,6] Research Center for Mining Technology, National Research and Innovation Agency, South Tangerang City, Indonesia

ARTICLE INFO

Article history:
Received July 21, 2024
Accepted October 04, 2024
Available online October 25, 2024

Kata Kunci:
Merkuri, Ditinggalkan, Polusi, Sedimen, Air Permukaan

Keywords:
Mercury, Abandoned, Pollution, Sediment, Surface Water

ABSTRAK

Merkuri pada pertambangan emas skala kecil dan tradisional (PESK) merupakan masalah lingkungan dan kesehatan yang besar. Karena keberadaan merkuri di lingkungan bersifat persisten, pemetaan dan investigasi merkuri di area PESK yang telah ditinggalkan menjadi sangat penting untuk memitigasi dan meminimalisir pencemaran merkuri. Penelitian ini dilakukan untuk memetakan dan mengeksplorasi keberadaan merkuri di area PESK yang telah ditinggalkan di Desa Kalirejo, Kabupaten Kulon Progo, Yogyakarta. Hasil eksplorasi lapangan menunjukkan bahwa PESK yang ditinggalkan berada di daerah tepi sungai, dekat dengan pemukiman penduduk, dikelilingi oleh lahan pertanian dan perkebunan. Analisis merkuri dengan menggunakan metode dekomposisi termal menunjukkan bahwa empat dari lima sampel sedimen mengandung Hg di atas 0,3 mg/kg, yang mengindikasikan bahwa sedimen di empat titik pengambilan sampel telah terkontaminasi. Analisis merkuri menggunakan spektrometri ICP OES menunjukkan bahwa tiga dari enam sampel air permukaan mengandung Hg di atas 0,005 mg/L, yang mengindikasikan bahwa Hg telah mencemari air permukaan di tiga titik pengambilan sampel. Karena lokasi PESK yang ditinggalkan dekat dengan pemukiman penduduk, tepi sungai, dan dikelilingi oleh lahan pertanian dan perkebunan masyarakat, maka penduduk dapat terpapar merkuri.

ABSTRACT

This paper Mercury in artisanal and small-scale gold mining (ASGM) is a major environmental and health issue. Since mercury in the environment is persistent, mapping and investigating mercury in abandoned ASGM areas is urgent to mitigate and minimize mercury pollution. This research was conducted to map and explore the presence of mercury in abandoned ASGM in Kalirejo Village, Kulon Progo District of Yogyakarta. Field exploration has shown that the abandoned ASGM were in a riverside area, close to settlement, surrounded by farming and plantations. Mercury analysis using the thermal decomposition method showed that four of five sediment samples contained Hg above 0.3 mg/kg, which indicated that the sediments at the four sampling points were contaminated. Mercury analysis using ICP OES spectrometry showed that three of six surface water samples contained Hg above 0.005 mg/L, indicating that Hg contaminated the surface waters at the three sampling points. Because the abandoned ASGM is close to residential areas, the riverside, and surrounded by community farming and plantation areas, residents may be exposed to mercury.

1. INTRODUCTION

Mercury (Hg) is a heavy metal that is highly harmful to human health and the surrounding environment (Kumari et al., 2020; Singh et al., 2023). The presence of mercury in the environment consists of three forms: elemental, inorganic, and organic mercury which all of those can induce toxic effects on mammalian species in unique toxicological profiles and differ in the mechanism of transport and disposition in the body (Yang et al., 2020). Humans are exposed to two major forms of mercury, i.e., mercury vapor and organic mercury (methylmercury and ethyl mercury), and the nervous system, immune system, and kidneys are known to be the primary targets of acute exposure to Hg depending on the exposure route (Yang et al., 2020). Furthermore, the possible adverse effects of mercury on humans, including neurotoxicity, immunotoxicity, genotoxicity, developmental toxicity, cardiovascular toxicity, disrupting endocrine systems, and metabolic effect with mercury exposure, may depend on the doses and the length of exposure, the type of mercury, the age and the sex, and the type of exposure (Guzzi et al., 2021; Yang et al., 2020). Although mercury is highly harmful, people in artisanal and small-scale gold

*Corresponding author.
E-mail addresses: asep039@brin.go.id (Asep Nurohmat Majalis)

mining (ASGM), due to their lack of knowledge about the dangers of mercury, recklessly use mercury to extract gold from the ore. In this technique, known as amalgamation, mercury is added to the slurry, a mixture of milled gold ore and water in a specific composition. The use of mercury during amalgamation is often uncontrolled, causing pollution due to the release and emission of mercury into the environment. The primary issue in ASGM activities is the use of Hg to amalgamate gold ores and thus emits a large amount of Hg into the atmosphere, which affects people who work in ASGM and even who live far away because of long-distance transportation of Hg (Cheng et al., 2023). In addition, amalgamation can release Hg to sediment and water bodies. The non-biodegradable mercury also travels long distances by bio-accumulating in the environment and food chain (Bugmann et al., 2022). The lack of access to knowledge and technology in the Artisanal and Small-Scale Gold Mining (ASGM) sector leads to unsafe practices, including the harmful use of mercury. In areas surrounding ASGM, mercury contamination poses a serious problem that can endanger both the environment and public health. To address this issue, it is necessary to provide socialization and training to the community to reduce mercury use and adopt safer technologies. Although many ASGM sites have been abandoned, there is still a potential risk of residual mercury in the surrounding environment, making it essential to map the distribution of mercury to mitigate further contamination risks (Bugmann et al., 2022).

The characteristics of ASGM is legal or illegal gold extractions conducted by individuals or group with limited capital investment, manual labor, and simple and basic machinery (Cheng et al., 2023; Scammacca et al., 2021). ASGM activities around residential areas are expected to have a more significant detrimental impact on health than if the processing location is in a place far from settlements. At ASGM, gold is generally recovered from ore by an amalgamation process using mercury (Astika et al., 2021; Mambrey et al., 2020; Velásquez-López et al., 2010). The addition of mercury by miners to gold ore at each ASGM location varies depending on the ore's characteristics and the miners' habits (Yoshimura et al., 2021). These habits are derived from experiences and information received from mouth to mouth among miners. On the other hand, researchers have calculated the amount of Hg used in ASGM by multiplying the ASGM production by the Hg: Au ratio, the grams of Hg used (lost to the environment) to produce 1 g of gold (Cheng et al., 2023). Mercury added to the gold ore will eventually undergo a process of emission, release and recovery (Kuang et al., 2022). Mercury will be emitted, released, and recovered respectively when the amalgam melting process occurs, the tailing disposes to the environment, and the squeezing out of amalgam is done (Navrátil et al., 2023; Velásquez-López et al., 2010). In gold ore processing locations that are far from residential areas, the potential frequency of mercury exposure will be lower. In comparison, in residential areas, the possible frequency of exposure will be greater. The potential exposure of mercury to residents around abandoned ASGM areas is also significant because mercury is persistent in the environment (Elwaleed et al., 2024).

Based on the data published by the United Nations Environment Program, the use of Hg for the amalgamation process in ASGM is the highest among other activities, and until 2012 estimated at 1.400 tons of Hg or 24% of total global Hg consumption used in ASGM. Amalgamation is the preferred method used by ASGM to recover free gold from alluvial/colluvial or primary ores (Velásquez-López et al., 2010). The two main methods of Hg are as follows: whole-ore amalgamation (WOA) and concentrate amalgamation (CA), and the amount of Hg used in ASGM is often calculated by multiplying the ASGM production by the Ag: Au ratio (Cheng et al., 2023). 56% of mercury introduced into the amalgamation process is recovered when miners squeeze the excess mercury, around 29% of total mercury is lost when miners burn amalgam, and 15% is lost with the tailings (Velásquez-López et al., 2010). Mitigation efforts to minimize the harmful effects of mercury contamination on the environment and human health in abandoned ASGM areas need to be carried out, with recent research introducing novel approaches such as more focused spatial mapping of mercury distribution and the integration of more effective mercury-free gold processing technologies. The first step for mitigating the impact of Hg release is to map the spreading of mercury in the environment around the abandoned ASGM, especially in sediments, to characterize it and to map land use around the abandoned ASGM. The second step is to socialize and campaign with the local community regarding the mapping results and the necessary preventive actions. The last step is to carry out reclamation to reclaim land function. This research was conducted to map and investigate the presence of mercury in abandoned artisanal and small-scale gold mining (ASGM) sites in Kalirejo Village, located in the Kulon Progo District of Yogyakarta. The study aimed to thoroughly explore the abandoned ASGM area to assess the extent of mercury contamination by examining specific locations associated with previous mining activities. This involved the systematic sampling of both water and sediment from these sites to accurately determine the concentration of mercury present. The findings from this research are anticipated to provide valuable data that can inform policymakers regarding the necessary actions to mitigate and minimize the adverse effects of mercury exposure on both the environment and public health. Furthermore, the results are intended to serve as a foundation for developing effective land restoration strategies for the abandoned ASGM areas, ensuring a sustainable approach to reclaiming these sites while protecting the local ecosystem and community well-being.

2. METHOD

Primary data collection is carried out to determine mining locations, gold processing locations, and sediment and water samples, then plotted on a map of the research area. Determination of location points and geographic positioning is done using a global positioning system (GPS) and a 1:25,000 scale RBI map. Land use in the abandoned ASGM area was processed and analyzed based on the 2019 land use map information. Kalirejo Village, Kokap District, Kulon Progo Regency, Yogyakarta Province has an area of around 1,224.91 ha with land use, i.e., mixed dry land farming, settlements, plantation, and scrub, as presented in Table 1.

Table 1. Kalirejo Village Land use by year 2019

Land uses	Area (Ha)	Percent (%)
Scrub	16.86	1.38
Mixed Dryland Farming	964.43	78.73
Settlement	185.98	15.18
Plantation	57.64	4.71
Total	1,224.91	100

The study has used purposive sampling to select sampling points for sediment and surface water samples. The considerations are the direction of river water flow, the location of abandoned gold processing, and the location of abandoned gold mining. Sampling was done at representative points, i.e., the land around the abandoned gold ore processing site and the river flow near where the tailings flowed. Further, the sampling points are plotted spatially on the map. Sediments and surface water samples were collected in October 2020. The samples were taken sequentially from downstream to upstream. Sediment samples were collected manually using a small soil shovel at predetermined points and indicated to contain mercury at a depth of between 7 to 30 cm. Sediment samples were put into soil sample containers made of aluminum with a diameter of 7.5 cm and a height of 4 cm. Then the sediment samples were closed tightly. The grab sampling was carried out for surface water directly using plastic bottles. The plastic bottles were rinsed three times with the water to be sampled. Furthermore, the water samples are inserted and tightly closed in sample containers with a volume of 500 ml, made of light-tight plastic, which has been given a sample preservative, i.e., nitric acid. Sediment and water samples were put into the cool box until they reached the laboratory for analysis. Mercury concentration in sediment was analyzed using the NIC MA 3000 Mercury Analyzer, and mercury concentration in surface water was analyzed using the ICP OES Prodigy 7. The analysis is conducted at Laboratory of Research Center for Mining Technology, National Research and Innovation Agency.

3. RESULT AND DISCUSSION

Result

Results are Based on the field survey results, the observed abandoned ASGM locations were two ex-mining and four ex-gold ore processing. Those locations are surrounded by residential plantation areas containing consumption crops such as bananas and cassava and production plants such as *Albizia chinensis* and *Tectona grandis*. Those location are also around the river and close to the residential area. The mining locations are in the upstream river, and the ore processing areas are in the downstream of the river. Sediment samples from ASGM are taken around the ex-gold ore processing site and ex-gold ore mining site. Sediment samples (SS-04, SS-05, and SS-06) were taken near the ex-gold ore processing site. Other sediment samples were collected from the river located adjacent to the gold ore mining site, and the river sediment that is part of the tailings from the gold ore processing process, named SS-02 and SS-03, respectively. Meanwhile, the reference (SS-01) of the sediment sample was taken in upstream part of the river. Table 2 indicates that the sediment samples collected around the abandoned gold ore processing site exhibit mercury concentrations ranging from 0.1896 mg/kg to 73.5384 mg/kg (SS-02 – SS-06). The reference soil (SS-01) contains 0.1382 mg/kg of mercury. Our study reveals that the highest mercury concentration is found downstream from the previously active gold ore processing site, which is higer than the global natural/background soil level of 1.1 mg/kg Hg.

Table 2. The Concentration of Mercury in the Sediment

No	Samples ID	Location	Mercury concentration (mg/kg)
1	SS-01	River sediment (upstream)	0.1382
2	SS-02	River Sediment (downstream)	0.1896
3	SS-03	River Sediment as Tailing	0.4145
4	SS-04		0.6598
5	SS-05	River Sediment (downstream)	73.5384
6	SS-06		0.9157

Table 3. The Concentration of Mercury in the Surface Water

No	Samples ID	Coordinate point (UTM Zone 49 S)		Mercury concentration (mg/L)
		X	Y	
1	WS-01	397741.027	9135045.58	0.0219
2	WS-02	397548.770	9134876.98	<0,005
3	WS-03	397031.384	9134255.45	<0,005
3	WS-04	396579.196	9134162.78	0,0087
4	WS-05	396821.252	9133649.97	0,0425
5	WS-06	397036.104	9133071.64	<0,005

The concentration of Hg in surface water at specific points (WS-01, WS-04, and WS 05) was still above 0.005 mg/L (Table 3). Based on the Decree of the State Minister for the Environment of the Republic of Indonesia No. 202 of 2004, an Hg value of 0.05 mg/L is the quality standard for wastewater for gold ore mining activities. This value is also the quality standard for class 4 river water according to the Government Regulation of the Republic of Indonesia No. 22 of 2021. This condition indicates that the river water around the abandoned ASGM is still experiencing mercury pollution even though mining activities have stopped. This condition also indicates that the elemental mercury in the sediment or soil may have undergone speciation and dissolution so that it is carried by water flow up to the river. Although the solubility of elemental mercury is less than other mercury species, except HgS, factors such as pH, turbulence, contact intensity (Tshumah-Mutingwende & Takahashi, 2019), organic ligands or dissolved organic matter and inorganic ligands (hydroxide, chloride, and sulfide) present in water can enhance the dissolution process. The mercury concentration in the surface water that flows from upstream to downstream is not the same because there are influencing factors, including flow rate, the characteristics of sediments, the pH of water, and the organic matter in the river that restrains the river flow rate (Graham et al., 2023; Tang et al., 2024).

Discussion

Mercury contamination remains a significant issue in abandoned artisanal and small-scale gold mining (ASGM) areas, as evidenced by water and sediment sample analysis in Kalirejo Village. While some sampling points now show mercury concentrations below quality standards, many still exceed safe thresholds. Sediment mercury levels range from 0.1896 mg/kg to an alarming 73.5384 mg/kg, far surpassing the global background threshold of 1.1 mg/kg. This indicates that despite years of inactivity, the ASGM area continues to be a source of environmental mercury pollution, with hotspots of severe contamination persisting. The presence of these mercury concentrations poses ongoing risks to environmental and human health. Mercury can persist in ecosystems for decades due to its non-biodegradable nature, spreading through water systems, soil, and air (Radziemska, 2022). In agricultural areas near the ASGM sites, mercury-contaminated soil may transfer the pollutant to crops, potentially entering the human food chain (Addai-Arhin et al., 2022; Saragih et al., 2021). Mercury emissions from these activities could lead to inhalation exposure among workers and residents. Combined, these factors create multiple pathways for mercury to harm local ecosystems and communities.

Given the potential health and environmental hazards, detailed investigations are essential to fully understand the extent and impact of mercury contamination. These should include mapping mercury concentrations at different soil depths, assessing its migration through groundwater, and identifying hotspots for targeted remediation. Understanding the scope of contamination will enable the design of effective land restoration strategies. Interdisciplinary approaches that incorporate public health considerations with environmental science can provide a comprehensive framework for addressing these challenges. Restoration efforts must prioritize safe, cost-effective techniques to rehabilitate contaminated areas while minimizing further risks. Testing pilot projects in affected areas can identify practical methods for reducing mercury levels and restoring land for safe use. At the same time, long-term monitoring of mercury distribution should be conducted to better understand its behaviour over time. Addressing these issues will not only reduce the environmental burden of abandoned ASGM sites, but also protect the health and livelihoods of local communities, and ensure a safer and more sustainable future. This research highlights the significant issue of mercury contamination in abandoned artisanal and small-scale gold mining (ASGM) sites in Kalirejo Village. Findings show that mercury levels in sediment and water remain high, posing risks to both the environment and public health. The contamination affects soil and water, potentially impacting agricultural produce and increasing human exposure through the food chain and air. To mitigate these effects, it is crucial to map and delineate the contaminated areas, engage and educate the local community, and implement targeted land restoration strategies. These efforts can guide policymakers to develop regulations that limit mercury use in mining and promote safer, mercury-free alternatives. By addressing these challenges, we can reduce mercury's harmful impact and support a healthier ecosystem and community.

4. CONCLUSION

The presence of Hg in the abandoned ASGM in Kalirejo Village, Kokap subdistrict, Kulon Progo regency, DIY Province is still being identified. The Hg content in five sediment samples at that location was 0.1896 - 73.5384 mg/kg. Four samples showed a value of Hg content > 0.3 mg/kg. This condition indicates that Hg polluted the land in that area, and restoring the land from Hg is necessary. In six river water samples, three samples contained Hg > 0.005 mg/L, and three others had Hg < 0.005 mg/L. Hg content in water > 0.005 mg/L indicates Hg contamination. Because the abandoned ASGM in Kalirejo Village is located close to residential areas, near a river, and surrounded by community plantation areas, there is a potential danger of mercury exposure to residents. Therefore, to prevent this, it is necessary to carry out land restoration efforts in the abandoned ASGM.

5. ACKNOWLEDGE

The author acknowledges the Agency for the Assessment and Application of Technology /BPPT that has funded this research through the 2020 DIPA about components of engineering and impact management of small-scale gold mining (document number 081.06.3508.003). The author also thanks the Kulon Progo Regency Environmental Service, the Kairejo Village Government, and former miners and residents of Kalirejo Village around the abandoned ASGM.

6. REFERENCES

Addai-Arhin, S., Novirsa, R., Jeong, H., Phan, Q. D., Hirota, N., Ishibashi, Y., Shiratsuchi, H., & Arizono, K. (2022). Mercury waste from artisanal and small-scale gold mining facilities: A risk to farm ecosystems—a case study of Obuasi, Ghana. *Environmental Science and Pollution Research*, *30*(2), 4293–4308. https://doi.org/10.1007/s11356-022-22456-4.

Astika, H., Handayani, S., Damayanti, R., Surono, W., Maryono, S., M., & Octaviano, H. A. (2021). Characterization of potential mercury contamination in the ASGM area of Mandailing Natal, North Sumatra. *IOP Conference Series: Earth and Environmental Science*, *882*(1). https://doi.org/10.1088/1755-1315/882/1/012062

Bugmann, A., Brugger, F., Zongo, T., & Merwe, A. (2022). Doing ASGM without mercury is like trying to make omelets without eggs": Understanding the persistence of mercury use among artisanal gold miners in Burkina Faso. *Environmental Science and Policy*, *133*, 87–97. https://doi.org/10.1016/j.envsci.2022.03.009.

Cheng, Y., Watari, T., Seccatore, J., Nakajima, K., Nansai, K., & Takaoka, M. (2023). A review of gold production, mercury consumption, and emission in artisanal and small-scale gold mining (ASGM. *Resources Policy*, *81*. https://doi.org/10.1016/j.resourpol.2023.103370.

Elwaleed, A., Jeong, H., Abdelbagi, A. H., Quynh, N. T., Nugraha, W. C., Agusa, T., Ishibashi, Y., & Arizono, K. (2024). Assessment of mercury contamination in water and soil from informal artisanal gold mining: Implications for environmental and human health in Darmali Area, Sudan. *Sustainability*, *16*(10), 3931. https://doi.org/10.3390/su16103931.

Graham, A. M., Helten, S., Wadle, A., Mamrak, E., Morsch, J., Lopez, S., & Smith, K. (2023). Mercury transport and methylmercury production in the lower Cedar River (Iowa) floodplain. *Frontiers in Environmental Chemistry*, *4*. https://doi.org/10.3389/fenvc.2023.1242813.

Guzzi, G., Ronchi, A., & Pigatto, P. (2021). Toxic effects of mercury in humans and mammals. In *Chemosphere* (Vol 263). Elsevier Ltd. https://doi.org/10.1016/j.chemosphere.2020.127990.

Kuang, X., Kyaw, W. T., Soe, P. S., Thandar, A. M., Khin, H. E., Zaw, N. M. P., & Sakakibara, M. (2022). A preliminary study on mercury contamination in artisanal and small-scale gold mining area in Mandalay Region, Myanmar by using plant samples. *Journal of Pollutants*. https://doi.org/10.22059/poll.2021.327548.1147.

Kumari, S., Jamwal, R., Mishra, N., & Singh, D. K. (2020). Recent developments in environmental mercury bioremediation and its toxicity: A review. In *Environmental Nanotechnology, Monitoring and Management* (Vol 13). Elsevier B.V. https://doi.org/10.1016/j.enmm.2020.100283.

Mambrey, V., Rakete, S., Tobollik, M., Shoko, D., Moyo, D., Schutzmeier, P., Steckling-Muschack, N., Muteti-Fana, S., & Bose-O'Reilly, S. (2020). Artisanal and small-scale gold mining: A cross-sectional assessment of occupational mercury exposure and exposure risk factors in Kadoma and Shurugwi, Zimbabwe. *Environmental Research*, *184*. https://doi.org/10.1016/j.envres.2020.109379.

Navrátil, T., Rohovec, J., Shanley, J., Matoušková, Š., Nováková, T., Šmejkalová, A. H., & Prokeš, R. (2023). Atmospheric mercury and its deposition during the phasing out of an amalgam electrolysis plant: Temporal, seasonal, and spatial patterns. *Environmental Science and Pollution Research*, *30*(59), 123586–123602. https://doi.org/10.1007/s11356-023-30784-2.

Radziemska, M. (2022). Background level, occurrence, speciation, bioavailability, and management of Hg-contaminated soils. In *Elsevier eBooks* (bll 301–314). https://doi.org/10.1016/b978-0-323-85621-8.00012-1.

Saragih, G., Tapriziah, E., Syofyan, Y., Masitoh, S., Sari, Y., & Pandiangan, H. (2021). Mercury contamination in selected edible plants and soil from artisanal and small-scale gold mining in Sukabumi Regency, Indonesia. *Makara Journal of Science*, *25*(4). https://doi.org/10.7454/mss.v25i4.1280.

Scammacca, O., Gunzburger, Y., & Mehdizadeh, R. (2021). Gold mining in French Guiana: A multi-criteria classification of mining projects for risk assessment at the territorial scale. *Extractive Industries and Society*, *8*(1), 32–43. https://doi.org/10.1016/j.exis.2020.06.020.

Singh, M., Kanaoujiya, R., Meenakshi, & Srivastava, S. (2023). *Mercury impact on wildlife: An analysis of the literature*. Proceedings. https://doi.org/10.1016/j.matpr.2023.05.648.

Tang, Y., Liu, Y., He, Y., Zhang, J., Guo, H., & Liu, W. (2024). Quantifying the impact of anthropogenic emissions and aquatic environmental impacts on sedimentary mercury variations in a typical urban river. *Environmental Pollution*, *355*, 124185. https://doi.org/10.1016/j.envpol.2024.124185.

Tshumah-Mutingwende, R. R. M. S., & Takahashi, F. (2019). Physio-chemical effects of freshwaters on the dissolution of elementary mercury. *Environmental Pollution*, *252*, 627–636. https://doi.org/10.1016/j.envpol.2019.05.130.

Velásquez-López, P. C., Veiga, M. M., & Hall, K. (2010). Mercury balance in amalgamation in artisanal and small-scale gold mining: Identifying strategies for reducing environmental pollution in Portovelo-Zaruma, Ecuador. *Journal of Cleaner Production*, *18*(3), 226–232. https://doi.org/10.1016/j.jclepro.2009.10.010.

Yang, L., Zhang, Y., Wang, F., Luo, Z., Guo, S., & Strähle, U. (2020). Toxicity of mercury: Molecular evidence. In *Chemosphere* (Vol 245). Elsevier Ltd. https://doi.org/10.1016/j.chemosphere.2019.125586.

Yoshimura, A., Suemasu, K., & Veiga, M. M. (2021). Estimation of mercury losses and gold production by artisanal and small-scale gold mining (ASGM. *Journal of Sustainable Metallurgy*, *7*(3), 1045–1059. https://doi.org/10.1007/s40831-021-00394-8.