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Mercury Exposure Impact to The Environment and Community Health from Artisanal and Small-Scale Gold Mining in North Musi Rawas District, South Sumatra Province, Indonesia

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***Abstract*—Mercury is a toxic and hazardous substance used in illegal gold mining activities to extract gold through the amalgamation method, which can contaminate the environment and harm public health. This study aims to determine the mercury levels in the hair of artisanal gold miners and small-scale miners in Suka Menang Village, Karang Jaya District, North Musi Rawas Regency. The research was conducted from August to December 2023 at an unauthorized gold processing site in Suka Menang Village, Karang Jaya District, North Musi Rawas Regency, South Sumatra Province. Data collection used a purposive survey method, combining qualitative methods with a structured questionnaire. Miners were selected based on their involvement in and proximity to small-scale gold mining activities. All miners were directly involved or related to illegal mining activities, although some were only occasionally involved. The study samples included at-risk community members and well water samples. The results show that small-scale gold mining activities in Suka Menang Village have led to mercury contamination in well water, river water, and among the miners. As many as 66.1% of respondents had mercury levels above the threshold set by USEPA, which is 1 µg/g. The study also found that the best strategies to prevent environmental damage and contamination from small-scale gold mining activities are (1) continuing mining activities without using mercury, accompanied by zoning for special mining management in one area, or (2) shutting down or dissolving the activities and facilitating profession shifts.**

***Keywords*—Gold mining; mercury; human hair; strategy.**

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I. INTRODUCTION

Artisanal and small-scale gold mining (ASGM) serves as a vital source of income in rural areas with few economic alternatives [1]. Generally, in remote sectors, these activities are developed simply, without complying with environmental regulations or illegally, for example using Hg in the gold recovery process [2]. As gold demand rises, illegal mining has evolved from a basic activity to a mechanized operation, leading to a surge in the number of people participating in gold mining [3]. Small-scale gold mining is a communal endeavor in regions where the local government has not yet granted permission for mining activities [4], [5].

Small-scale gold mining, or community mining, typically involves extracting gold using mercury. Mercury has been known since the dawn of human civilization and forms various compounds, including inorganic ones like oxide, chloride, and nitrate, as well as organic compounds. Three forms of mercury are toxic to humans: elemental mercury (pure mercury) and ionic mercury salts in the forms of mercury (I) (Hg^{+}) and mercury (II) (Hg^{2+}) [6], [7], [8]. Mercury is dangerous to health if consumed. The impact of mercury on human health mostly occurs in the neuronal system [9], [10], [11]. Mercury contamination can lead to symptoms such as headaches, tremors, tingling sensations particularly in the hands and feet, visual disturbances, mild tremors, and muscle weakness. Over time, mercury exposure can result in nervous system disorders, parkinsonism, speech and hearing impairments, difficulty walking, and memory loss [12].

Mercury, a hazardous heavy metal, poses significant environmental risks. The American Food and Drug Administration (FDA) establishes a threshold level for mercury in the environment, which stands at 0.005 parts per million (ppm). The Republic of Indonesia's government, as outlined in Minister of Health Decree Number 907 of 2002, sets the mercury limit for drinking water consumption at 0.001 mg/l. Hence, if these thresholds are surpassed, community gold mining activities can be categorized as a human-caused contributor to mercury pollution in the environment.

The environmental harm stems from the direct release of mercury into the environment, compounded by the close proximity of mercury waste or tailings disposal sites to residential areas. This proximity is due to the design of the gold extraction machines, commonly referred to as 'Gelundung' or 'Glundung,' which are situated near the workers' living quarters [13]. Generally, tailings containing mercury are immediately thrown into the ground and rivers. As a result, tailings containing mercury flow below the ground surface, making it difficult to observe how far the tailings will flow [14], [15].

North Musi Rawas, the westernmost district in South Sumatra Province, spans an area of 594,416 hectares, predominantly covered by forests. Within this expanse lies the Kerinci Seblat National Park, a vital ecological reserve spanning 168,803 hectares, with forest coverage totaling 153,806 hectares, making it a significant oxygen contributor in the province. Moreover, the district's geography is defined by two major sub-districts: Rawas, stretching approximately 245 kilometers, and Rupit, covering around 93 kilometers, both serving as the headwaters of the Musi River.

Gold has been a longstanding mining prospect in North Musi Rawas since the Dutch colonial era, notably in the Karang Jaya District. Initially, gold extraction was commercially managed with advanced technology by PT. Dwinad Nusa Sejahtera (DNS), which ceased operations in 2018. Following the cessation of commercial mining activities, the concession reverted to state ownership, transforming it into a free area. This transition spurred the emergence of gold mining endeavors conducted by local communities and migrant populations, commonly known as Artisanal and Small-scale Gold Mining (ASGM).

The activity of extracting gold ore (mucking) was carried out in the former concession of PT. DNS, meanwhile the refining process to become gold pellets is carried out in residential areas in Suka Menang Village, where the distance between the former concession of PT. DNS with residential areas is ± 5 km away and in the rock processing process to obtain gold grains, miners use a lot of water and chemicals in the form of Mercury. The waste resulting from the processing is discharged into the water flow (tributary) which empties into the Tiku River and then enters the Rupit River, while the Tiku River and Rupit River play a very big role in their daily lives for the people who live along the river flow, this condition can be proven by their concentration. some residential areas and activities in the river basin, currently these rivers function to support community activities and as a source of drinking water. Based on these problems, this research aims to identify sources of pollution, environmental quality and the level of risk to public health at ASGM locations.

II. Materials and Method

A. Materials

The research was conducted from August to December 2023 at an unlicensed gold processing site in Suka Menang Village, Karang Jaya District, North Musi Rawas Regency, South Sumatra Province (fig. 1). This location was chosen because some of the village residents work as miners or gold ore processors. All gold mining locations are in forest areas, while gold processors are in residential areas, within 1 to 2 km from the mining sites.

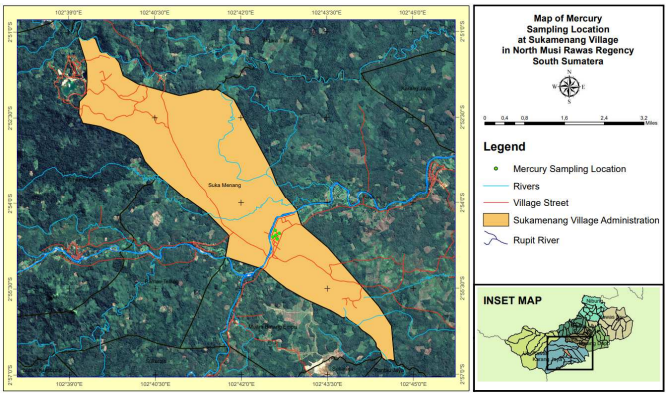

Fig. 1 Research for sampling location

This study employs a purposive survey approach to gather data. Data collection involved a blend of quantitative methods utilizing structured questionnaires and qualitative methods involving in-depth interviews. Respondents were selected based on their engagement in ASGM or ASGM-related activities and their proximity to ASGM sites. All respondents were either directly involved in ASGM or engaged in ASGM-related tasks, with some work on an occasional basis. The study included both miners and non-miners involved in gold ore processing, totaling 50 respondents.

The socio-economic characteristics examined in this survey include length of time as a miner, income level and type of work group in ASGM. Additional questions were asked of miners and processors regarding respondents' knowledge and attitudes towards the use of Hg in gold ore processing and its impact on the environment. Apart from that, this research also assessed miners' perceptions of the role of government, perceptions of environmentally friendly mining and miners' perceptions of the potential for other business opportunities. This research also analyzes mercury levels in well water.

Analysis of mercury levels in well water was carried out at 5 residents' wells which were used to meet daily consumption. Furthermore, analysis of hair mercury levels was carried out on miner and non-miner respondents who were involved in processing gold ore, totaling 50 respondents and communities at risk, totaling 8 respondents. People at risk are people who carry out daily activities in rivers [16]. Total mercury (T-Hg) measurements were carried out on miners' hair samples [17], [18]. Hg analysis was carried out using a Mercury Analyzer NIC MA-3000 and calculated using the combustion system

method contained in International Standard 7473 of the United States Environmental Protection Agency's (USEPA).

B. Method

The gathered data underwent analysis employing both descriptive and statistical methods. Socio-economic backgrounds, as well as miners' knowledge and perceptions, were tabulated and presented descriptively. Mercury exposure was assessed by measuring total mercury (T-Hg) levels in respondents' hair, followed by analysis comparing these values against established human biomonitoring standards, namely the USEPA standards 2005 [19] and water consumption regulations outlined in Minister of Health Regulation No.2 of 2023.

III. Results and Discussion

A. Profile of ASGM

The results of the research show that the majority of ASGM wokers in Suka Menang Village, Karang Jaya District, North Musi Rawas Regency have been mining for 2-4 years, namely 32%, then 30% have been mining for 4-6 years, 20 % have been mining for more than 6 years and 18% have been mining for 1-2 years. Most of the miners in the study (36%) were workers who carried out 3 types of work groups, namely diggers or carvers, rollers/processors and burners and sellers, then 26% were diggers or carvers, 32% were millers/processors and 6% were burners and sellers. Furthermore, 72% of miners' income ranged from IDR 1,500,000 to IDR 5,000,000 and 80% of miners stated that the income they earned met their family needs as seed in Table I.

TABLE I
CHARACTERISTICS OF ASGM WORKERS

Question	Number of people)	Percentage (%)
Long been a Gold Mining		
12 years old	9	18.00
24 years old	16	32.00
4 - 6 years	15	30.00
> 7 years	10	20.00
Type of work group		
Digger or sculptor	13	26.00
Roller/processor	16	32.00
Burners (Burners) and Sellers	3	6.00
All types of work groups	18	36.00
Miner income		
Less than Rp. 1,000,000, -	6	12.00
IDR 1,500,000 to IDR 5,000,000, -	36	72.00
IDR 5,000,000 to IDR 10,000,000, -	4	8.00
Above Rp. 10,000,000, -	4	8.00

The research results show that the average miner is quite aware of the dangers of mining activities and the use of mercury on the environment and health. Furthermore, the average miner also lacks knowledge and does not know mining methods other than those they are used to. The majority of miners stated that currently purchasing mercury is difficult. An average of 0.5 -1 kg of mercury is used in one process. The use of mercury causes environmental pollution. This is shown by miners' statements that well/river water is quite polluted by mercury as depicted in Table II. Figure 2 shows waste disposal and ball mill facilities ASGM in the study area.

TABLE II
KNOWLEDGE OF ASGM WORKERS

Question	Score	Criteria
Dangers of mining activities on the environment and health	2.70	Know enough
The dangers of mercury to the environment and health	2.56	Know enough
Another way to mine gold	1.64	Do not know
Easy of purchasing mercury	1.52	Difficult
The amount of mercury used in one process	3.14	0.5-1 Kg
Mercury pollution in well/river water	2.36	Fairly Polluted

a b

Fig. 2 Gold ball mill in Suka Menang Village, Karang Jaya District, North Musi Rawas Regency. (a) Waste disposal (b) Ball mill facilit

The government's role is an important actor in preventing the negative impacts ASGM on the environment. The research results show that outreach regarding the dangers of mercury is rarely carried out. Furthermore, the average miner also feels that the government pays little attention to efforts to provide business opportunities other than mining and handling ASGM activities. The government's lack of attention to ASGM is also shown by indications that reprimands or warnings to mine workers are still rarely carried out as presented in Table III.

TABLE III
PERCEPTIONS OF ASGM WORKERS REGARDING THE ROLE OF GOVERNMENT

Question	Score	Criteria
Socialization activities about the dangers of mercury (quick water)	2.10	Seldom
The attention of the regional government or central government in providing other employment opportunities	2.40	Less attention
Regional government attention in handling small-scale gold mining activities	2.40	Less attention
Intensity of warnings/warnings/control from the government and other parties	1.82	Seldom

B. Mercury Levels in Mining Workers' Hair and Residents' Well Water

The average of total mercury concentration in the groundwater samples at the villager's five wells is indicated in Table IV. The total concentration of Hg in the well water samples shows that ASGM activities have had an impact on the environment around the processing sites. Residents' well water has been affected by Hg waste discharge as indicated by an average Hg concentration value of 0.55 µg/L. Even

though this value is still below the threshold value of 1 µg/L set by Minister of Health Regulation No.2 of 2023, this shows that ASGM activities have contributed to waste discharge which is percolated into aquifer used by community as clean water sources.

TABLE IV
MERCURY CONCENTRATION IN WELL WATER

Sample Code	Total Hg concentration (µg/L)
Well Water 1	0.54
Well Water 2	0.55
Well Water 3	0.56
Well Water 4	0.55
Well Water 5	0.57
Average	0.55

The research results show that all miner bodies have accumulated heavy metal mercury. The average mercury exposure in miners' hair samples was 2.55 µg /g with the lowest level was 0.27 µg/g and the highest level was 19.00 µg/g (Table V).

TABLE V
DESCRIPTION OF THE TOTAL MERCURY METAL ACCUMULATION OF ASGM WORKERS

Variable	Mean	Median	Elementary school	Min	Max
Accumulation of mercury metal in hair	2.55	1.40	3.27	0.27	19.0

The sensitivity of mercury levels in the body is 1 µg/g [19]. Based on this, it can be seen that 66.1% of mine workers' hair samples have exceeded the threshold that meets the requirements, 52.54% are classified as alert level and 13.56% are classified as high level, while the other 33.9% are still below the threshold (Table 6). On the other hand, it can be seen that mercury levels in at-risk communities located in Lubuk Linggau City are all still below the threshold (Table VII).

TABLE VI
ACCUMULATION OF MERCURY METAL IN MINE WORKERS' HAIR

Mercury levels	Number of people	Percentage (%)	Category
< 1 µg Hg/g hair	20	33,90	Normal
1 - 5 Hg/g hair	31	52,54	Alert Level
≥5 Hg/g hair	8	13,56	High Level

TABEL VII
THE ACCUMULATION OF MERCURY METAL IN PEOPLE'S HAIR IS RISKY

Mercury levels	Number of people	Percentage (%)	Category
< 1 µg Hg/g hair	8	100	Normal

C. Mercury Control Strategy

Conventional mining methods carried out by ASGM miners have been proven to pollute the environment. Therefore, it is necessary to make efforts to switch to other methods that are more environmentally friendly. The research results showed that 96% of workers said they were willing to replace processing methods with more environmentally friendly ones. Furthermore, 88% of workers also stated that a component of environmentally friendly mining methods is processing technology without the use of mercury and cyanide. Furthermore, to make this happen, 46% of miners need investment assistance, 32% of miners need joint processing locations provided by the government, 16% of miners need training and skills, and 6% need regular coaching. As many as 40% of miners each stated that the best option to prevent environmental damage and environmental pollution due to ASGM activities is to continue without applying mercury accompanied with special ASGM management zoning in one place or close or disband and facilitate a change of profession as shown in Table VIII.

TABLE VIII
PERCEPTIONS OF ASGM WORKERS REGARDING ENVIRONMENTALLY FRIENDLY MINING

Question	Number of people)	Percentage (%)
Willingness to replace management methods with more environmentally friendly ones		
Agree	40	80.00
Simply agree	8	16.00
Don't agree	0	0.00
Don't agree	2	4.00
Environmentally friendly mining components		
Do not use mercury	5	10.00
Do not use cyanide	1	2.00
Does not use mercury and cyanide	14	28.00
Using other environmentally friendly technology	30	60.00
Support needed to implement environmentally friendly gold processing		
Training and skills	8	16.00
Capital Assistance	23	46.00
Routine Coaching	3	6.00
Joint processing location provided by the government	16	32.00
The best option to prevent environmental damage and environmental pollution due to ASGM		
Continue by continuing to use mercury	2	4.00
Continued but does not use mercury and is managed in an environmentally friendly manner.	8	16.00
Continued without mercury with special ASGM management zoning in one place.	20	40.00
Closed or disbanded and facilitated change of profession to become a farmer, SME, etc	20	40.00

One effort to prevent environmental degradation due to ASGM is to divert miners' work to other types of work. The results of the research show that actually mining workers have other skills apart from gold mining, namely 58% are farming, 28% are trading, 10% are raising livestock and 4% are others. This is supported by the perception of miners who state that 88% of their area has the potential to develop agricultural businesses. However, 98% of miners have never attended

vocational/skills education. Another thing that supports a change of profession is that 86% of miners stated they were interested in pursuing agribusiness as presented in Table IX.

TABLE IX
PERCEPTIONS OF ASGM WORKERS TOWARDS OTHER BUSINESSES

Question	Number of people)	Percentage (%)
Skills other than Gold Miner		
Farming	29	58.00
Breeding	5	10.00
Trade	14	28.00
Other	2	4.00
Potential land for agriculture		
Potential	21	42.00
Quite Potential	24	48.00
Less Potential	5	10.00
No potential	0	0.00
Participation in vocational/skills education		
Never and often	0	0.00
Never or often	1	2.00
Not completed	0	0.00
Never	49	98.00
Interest in agribusiness and other businesses		
Yes, interested	27	54.00
Quite interested	16	32.00
Not interested	6	12.00
Not interested	1	2.00

D. Discussion

The activity of extracting gold ore (*mucking*) was carried out in the former concession of PT. Dwinad Nusa Sejahtera, meanwhile the refining process to become gold pellets is carried out in Suka Menang Village. Based on the results of interviews, the number of workers involved in gold mining activities ranges from 200-300 people, with an average of 1-7 years of mining, some even more than 7 years. The majority of miners are diggers as well as rollers/processors, burners/burners and sellers with an average income of IDR 1,500,000-IDR 5,000,000. This income is still higher than similar gold miners in Sukabumi Regency, namely around IDR 500,000-IDR 1,000,000 [20].

Miners are actually quite aware of the dangers of mining activities and that the use of mercury is dangerous for the environment and health. However, they still carry out gold mining using mercury. Mining workers continue to use mercury because they do not know of other mining methods without using mercury [21], [22]. This is because the government's role as an important factor in preventing the negative impact of mercury from small-scale gold mining activities on the environment is still low. The research results show that outreach regarding the dangers of mercury is rarely carried out. Moreover, the typical miner perceives that the government allocates limited attention to initiatives aimed at offering alternative business opportunities beyond mining and managing small-scale gold mining operations. Additionally, they feel that reprimands or warnings directed at mining workers are infrequently enforced [23]. Previous findings also report the state's inability to control and supervise mining. Even though there are legal sanctions instruments (administrative and criminal), their implementation has not been effective in eradicating the problem of Hg use and controlling environmental impacts caused by illegal miners [24].

The use of mercury in one production process until it becomes gold ore ranges from 0.5 -1 kg in one process. In 1 production process they need 1 day with 25 working days in 1 month so that the amount of mercury used by workers in 1 month is around 12.5 -25 kg. The total number of coils in Suka Menang Village is 49 units so that in 1 month it is 612.5-1,225 kg/month which will ultimately be released as a by-product into the environment.

The high use of mercury causes environmental pollution. This is shown by miners' statements that well/river water is quite polluted by mercury. This is reinforced by the presence of Hg contamination in residents' well water with an average of 0.55 µg/L. The waste produced in gold processing contains mercury [25], which will then flow along a path from places with high to low hydraulic pressure. The distance between contaminant sources and the slope of the land are also causal factors [26], [27], [28], [29]. In line with the results of previous research which reported that small-scale gold mining activities had caused mercury pollution in wells and river water bodies [30], [31]. In fact, Hg contamination has also been reported to occur in plants and soil [32]. Almost the same results were reported when measuring the Hg concentration of well water in Krueng Sabee with an average of 0.24 µg/L. Resident's wells that receive groundwater supplies suffer from dangerous impacts from water containing Hg if it continues to be consumed for a long time [33], [34].

Hg can be released into the atmosphere through geogenic or anthropogenic sources and enters the natural environment as inorganic Hg and through natural processes is converted into organic Hg, which is the most toxic organic form of methylmercury and dimethylmercury [35], [36], [37], [38]. The greatest risk of exposure to inorganic Hg present in contaminated water bodies for both adults and children is through accidental water consumption [39]. On the other hand, in the work environment, where Hg incorporation is carried out, the main exposure route for humans is by inhaling elemental Hg vapor [40]. In addition, fish consumption has been reported as an important route for the entry of methylmercury into the human body, especially in mining areas [41].

The research results show that all miners have accumulated the heavy metal mercury. The average mercury exposure in miners' hair samples was 2.55 µg /g with the lowest level being 0.27 µg/g and the highest level being 19.00 µg/g. As many as 66.1% of mining workers have passed the threshold according to USEPA [19]. Previous research results also reported that Hg levels in workers' hair exceeded the threshold, including small-scale gold mines in North Gorontalo Regency [42]. Key factors influencing the toxicity of a pollutant to organisms include the route of exposure, the speed of entry and elimination, distribution in tissues, and concentration within them [43]. In this context, people living in contaminated environments have a greater likelihood of adverse health effects, as they are exposed to contaminants through multiple exposure pathways.

Small-scale gold mining activities carried out in Suka Menang Village have caused mercury pollution in the environment and society. Therefore, efforts need to be made to control mercury pollution. In this research, the strategy was

carried out using a questionnaire with questions directed at environmentally friendly gold management and changing livelihoods [44], [45], [46]. In accordance with the results of interviews which show that the best strategy to prevent environmental damage and environmental pollution due to gold mining activities without permits is (1) continued without mercury with special ASGM management zoning in one place, and (2) closed or disbanded and a change of profession facilitated. Both strategies received approval from 40% of the number of mining workers each.

The study findings indicate that nearly all miners' express willingness to adopt more environmentally friendly processing methods. However, they face obstacles due to capital constraints in implementing this change. Another strategy to mitigate environmental degradation from small-scale gold mining is to transition miners to alternative types of work, a proposition supported by 86% of mining workers The research results show that miners have other skills besides mining gold, namely farming, trading and raising livestock. Agricultural activities are the most feasible strategy choice because their area has the potential to develop agricultural businesses. However, job transfer faces the challenge that miners have never attended vocational/skills education.

IV. Conclusion

Small-scale gold mining activities in Suka Menang Village, Karang Jaya District, North Musi Rawas Regency have caused Hg pollution in well and river water as well as mine workers. A total of 66.1 % of respondents were found to contain Hg above the threshold value set by USEPA, namely 1 µg/g. The best strategy to prevent environmental damage and environmental pollution due to gold mining activities without permits is (1) to continue without mercury with special ASGM management zoning in one place, and (2) to close or disband and facilitate a change of profession.

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References

[1] A. A. Meutia, R. Lumowa, and M. Sakakibara, "Indonesian artisanal and small-scale gold mining—A narrative literature review," *Int. J. Environ. Res. Public Health*, vol. 19, no. 7, p. 3955, Apr. 2022, doi:10.3390/ijerph19073955.

[2] A. Abdelaal, M. Sultan, A. Z. Abotalib, M. Bedair, R. V. Krishnamurthy, and M. Elhebiry, "Emerging mercury and methylmercury contamination from new artisanal and small-scale gold mining along the Nile Valley, Egypt," *Environ. Sci. Pollut. Res.*, vol. 30, no. 18, pp. 52514–52534, Apr. 2023, doi: 10.1007/s11356-023-25895-9.

[3] B. Ebus and T. Martinelli, "Venezuela's gold heist: The symbiotic relationship between the state, criminal networks and resource extraction," *Bull. Lat. Am. Res.*, vol. 41, no. 1, pp. 105–122, 2022, doi:10.1111/blar.13246.

[4] S. Sugiarti, B. Yunianto, R. Damayanti, and N. R. Hadijah, "Legalization of illegal small-scale mining, as a policy of business guarantee and environmental management," in *IOP Conf. Ser.: Earth Environ. Sci.*, vol. 882, no. 1, p. 012077, Dec. 2021, doi:10.1088/1755-1315/882/1/012077.

[5] M. Konte and R. C. Vincent, "Mining and quality of public services: The role of local governance and decentralization," *World Dev.*, vol. 140, p. 105350, Apr. 2021, doi: 10.1016/j.worlddev.2020.105350.

[6] A. Kumar, V. Kumar, P. Bakshi, R. D. Parihar, M. Radziemska, and R. Kumar, "Mercury in the natural environment: Biogeochemical cycles and associated health risks," *J. Geochem. Explor.*, vol. 267, p. 107594, Dec. 2024, doi: 10.1016/j.gexplo.2024.107594.

[7] G. Guzzi, A. Ronchi, and P. Pigatto, "Toxic effects of mercury in humans and mammals," *Chemosphere*, vol. 263, p. 127990, Jan. 2021, doi: 10.1016/j.chemosphere.2020.127990.

[8] N. Basu et al., "Our evolved understanding of the human health risks of mercury," *Ambio*, vol. 52, no. 5, pp. 877–896, May 2023, doi:10.1007/s13280-023-01831-6.

[9] S. Keane et al., "Mercury and artisanal and small-scale gold mining: Review of global use estimates and considerations for promoting mercury-free alternatives," *Ambio*, vol. 52, no. 5, pp. 833–852, May 2023, doi: 10.1007/s13280-023-01843-2.

[10] Y. I. Arifin, M. Sakakibara, S. Takakura, M. Jahja, F. Lihawa, and K. Sera, "Artisanal and small-scale gold mining activities and mercury exposure in Gorontalo Utara Regency, Indonesia," *Toxicol. Environ. Chem.*, vol. 102, no. 10, pp. 521–542, Nov. 2020, doi:10.1080/02772248.2020.1839074.

[11] L. Ovadje, B. N. L. Calys-Tagoe, E. Clarke, and N. Basu, "Registration status, mercury exposure biomarkers, and neuropsychological assessment of artisanal and small-scale gold miners (ASGM) from the Western Region of Ghana," *Environ. Res.*, vol. 201, p. 111639, Oct. 2021, doi: 10.1016/j.envres.2021.111639.

[12] K. Taux, T. Kraus, and A. Kaifie, "Mercury exposure and its health effects in workers in the artisanal and small-scale gold mining (ASGM) sector—A systematic review," *Int. J. Environ. Res. Public Health*, vol. 19, no. 4, p. 2081, 2022, doi: 10.3390/ijerph19042081.

[13] C. N. Brunnschweiler, D. Karapetyan, and P. Lujala, "Opportunities and risks of small-scale and artisanal gold mining for local communities: Survey evidence from Ghana," *Extr. Ind. Soc.*, vol. 17, p. 101403, Mar. 2024, doi: 10.1016/j.exis.2024.101403.

[14] M. Mulenga, K. O. Ouma, C. Monde, and S. Syampungani, "Aquatic mercury pollution from artisanal and small-scale gold mining in Sub-Saharan Africa: Status, impacts, and interventions," *Water*, vol. 16, no. 5, p. 756, Mar. 2024, doi: 10.3390/w16050756.

[15] F. Aranoglu, T. Flamand, and S. Duzgun, "Analysis of artisanal and small-scale gold mining in Peru under climate impacts using system dynamics modeling," *Sustainability*, vol. 14, no. 12, p. 7390, Jun. 2022, doi: 10.3390/su14127390.

[16] M. Soprima, H. Kusnoputranto, and I. Inswiasri, "Kajian risiko kesehatan masyarakat akibat pajanan merkuri pada pertambangan emas rakyat di Kabupaten Lebak, Banten," *J. Ekol. Kesehat.*, vol. 14, no. 4, pp. 296–308, 2016, doi: 10.22435/jek.v14i4.4708.296-308.

[17] F. Koenigsmark et al., "Efficacy of hair total mercury content as a biomarker of methylmercury exposure to communities in the area of artisanal and small-scale gold mining in Madre de Dios, Peru," *Int. J. Environ. Res. Public Health*, vol. 18, no. 24, p. 13350, Dec. 2021, doi:10.3390/ijerph182413350.

[18] M. A. Ondayo, M. J. Watts, C. J. Mitchell, D. C. P. King, and O. Osano, "Review: Artisanal gold mining in Africa—Environmental pollution and human health implications," *Expo. Health*, vol. 16, no. 4, pp. 1067–1095, Aug. 2024, doi: 10.1007/s12403-023-00611-7.

[19] USEPA, "Water quality criterion for the protection of human health: Methylmercury," 2005. [Online]. Available: http://www.epa.gov/waterscience/criteria/methylmercury/document.

[20] A. H. Harianja et al., "Mercury exposure in artisanal and small-scale gold mining communities in Sukabumi, Indonesia," *J. Health Pollut.*, vol. 10, no. 28, pp. 1–11, 2020, doi: 10.5696/2156-9614-10.28.201209.

[21] T. C. S. Bello et al., "Mercury exposure in women of reproductive age in Rondônia State, Amazon region, Brazil," *Int. J. Environ. Res. Public Health*, vol. 20, no. 6, p. 5225, Mar. 2023, doi:10.3390/ijerph20065225.

[22] I. Martoredjo et al., "Trends in mercury contamination distribution among human and animal populations in the Amazon region," *Toxics*, vol. 12, no. 3, p. 204, Mar. 2024, doi: 10.3390/toxics12030204.

[23] C. Mestanza-Ramón et al., "Gold mining in the Amazon region of Ecuador: History and a review of its socio-environmental impacts," *Land*, vol. 11, no. 2, pp. 1–22, 2022, doi:10.3390/land11020221.

[24] M. V. Capparelli et al., "An integrative approach to assess the environmental impacts of gold mining contamination in the

Amazon," *Toxics*, vol. 9, no. 7, p. 149, Jul. 2021, doi:10.3390/toxics9070149.

[25] A. K. Donkor, H. Ghoveisi, and J.-C. J. Bonzongo, "Use of metallic mercury in artisanal gold mining by amalgamation: A review of temporal and spatial trends and environmental pollution," *Minerals*, vol. 14, no. 6, p. 555, May 2024, doi: 10.3390/min14060555.

[26] L. L. Tampushi, J. M. Onyari, and N. J. Muthama, "Environmental distribution and risk of exposure of heavy metal pollutants from Lolgorian artisanal gold mining in Kenya," *Bull. Environ. Contam. Toxicol.*, vol. 109, no. 2, pp. 310–316, Aug. 2022, doi:10.1007/s00128-022-03575-7.

[27] M. Mulenga, K. O. Ouma, C. Monde, and S. Syampungani, "Aquatic mercury pollution from artisanal and small-scale gold mining in Sub-Saharan Africa: Status, impacts, and interventions," *Water*, vol. 16, no. 5, p. 756, Mar. 2024, doi: 10.3390/w16050756.

[28] A. J. Clark, A. L. Labaj, J. P. Smol, L. M. Campbell, and J. Kurek, "Arsenic and mercury contamination and complex aquatic bioindicator responses to historical gold mining and modern watershed stressors in urban Nova Scotia, Canada," *Sci. Total Environ.*, vol. 787, p. 147374, Sep. 2021, doi: 10.1016/j.scitotenv.2021.147374.

[29] Z. Diarra, D. Dieme, and M. Bouchard, "Biomonitoring of exposure to metals and metalloids using toenail and fingernail sampling in individuals from artisanal gold mining areas in Mali," *Environ. Adv.*, vol. 17, p. 100589, Oct. 2024, doi: 10.1016/j.envadv.2024.100589.

[30] C. Mestanza-Ramón et al., "Human health risk assessment due to mercury use in gold mining areas in the Ecuadorian Andean region," *Chemosphere*, vol. 344, p. 140351, Dec. 2023, doi:10.1016/j.chemosphere.2023.140351.

[31] I. Passarelli et al., "Hg pollution in groundwater of Andean region of Ecuador and human health risk assessment," *Resources*, vol. 13, no. 6, p. 84, Jun. 2024, doi: 10.3390/resources13060084.

[32] G. S. Saragih, E. R. Tapriziah, Y. Syofyan, S. Masitoh, Y. S. H. Pandiangan, and Andriantoro, "Mercury contamination in selected edible plants and soil from artisanal and small-scale gold mining in Sukabumi Regency, Indonesia," *Makara J. Sci.*, vol. 25, no. 4, pp. 222–228, 2021, doi: 10.7454/mss.v25i4.1280.

[33] A. Elwaleed et al., "Assessment of mercury contamination in water and soil from informal artisanal gold mining: Implications for environmental and human health in Darmali area, Sudan," *Sustainability*, vol. 16, no. 10, p. 3931, May 2024, doi:10.3390/su16103931.

[34] A. R. Aldous, T. Tear, and L. E. Fernandez, "The global challenge of reducing mercury contamination from artisanal and small-scale gold mining (ASGM): Evaluating solutions using generic theories of change," *Ecotoxicology*, Jul. 2024, doi: 10.1007/s10646-024-02741-3.

[35] M. M. Al-Sulaiti, M. A. Al-Ghouti, G. A. Ramadan, and L. Soubra, "Health risk assessment of methyl mercury from fish consumption in a sample of adult Qatari residents," *Environ. Monit. Assess.*, vol. 195, no. 5, May 2023, doi: 10.1007/s10661-023-11194-w.

[36] P. Basta et al., "Risk assessment of mercury-contaminated fish consumption in the Brazilian Amazon: An ecological study," *Toxics*, vol. 11, no. 9, p. 800, Sep. 2023, doi: 10.3390/toxics11090800.

[37] P. Lin, P.-I. Lee, and M.-P. Ling, "Probabilistic benefit-risk analysis of fish: Nutritional benefit versus methylmercury-contaminated risk," *Mar. Pollut. Bull.*, vol. 193, p. 115179, Aug. 2023, doi:10.1016/j.marpolbul.2023.115179.

[38] E. Vasco, M. G. Dias, and L. Oliveira, "Mercury exposure assessment from the first harmonised total diet study in Portugal," *Expo. Health*, Aug. 2024, doi: 10.1007/s12403-024-00649-1.

[39] S. Jiménez-Oyola et al., "Human health risk assessment for exposure to potentially toxic elements in polluted rivers in the Ecuadorian Amazon," *Water*, vol. 13, no. 5, p. 613, 2021, doi:10.3390/w13050613.

[40] Q. Liu, Y. Cheng, and C. Fan, "Pollution characteristics and health exposure risks of heavy metals in river water affected by human activities," *Sustainability*, vol. 15, no. 10, p. 8389, 2023, doi:10.3390/su15108389.

[41] G. Caicedo-Rivas, M. Salas-Moreno, and J. Marrugo-Negrete, "Health risk assessment for human exposure to heavy metals via food consumption in inhabitants of middle basin of the Atrato River in the Colombian Pacific," *Int. J. Environ. Res. Public Health*, vol. 20, no. 1, p. 435, 2023, doi: 10.3390/ijerph20010435.

[42] Y. I. Arifin, M. Sakakibara, S. Takakura, M. Jahja, F. Lihawa, and K. Sera, "Artisanal and small-scale gold mining activities and mercury exposure in Gorontalo Utara Regency, Indonesia," *Toxicol. Environ. Chem.*, vol. 102, no. 10, pp. 521–542, 2020, doi:10.1080/02772248.2020.1839074.

[43] S. Das, K. W. Sultana, A. R. Ndhlala, M. Mondal, and I. Chandra, "Heavy metal pollution in the environment and its impact on health: Exploring green technology for remediation," *Environ. Health Insights*, vol. 17, 2023, doi: 10.1177/11786302231201259.

[44] L. Dongwei et al., "Differentiated emission control strategy based on comprehensive evaluation of multi-media pollution: Case of mercury emission control," *J. Environ. Sci.*, vol. 123, pp. 222–234, Jan. 2023, doi: 10.1016/j.jes.2022.03.028.

[45] D. Xie, X. Ge, L. Duan, and J. Mulder, "Effects of acid deposition control in China: A review based on responses of subtropical forests," *Front. Environ. Sci. Eng.*, vol. 18, no. 6, p. 77, Jun. 2024, doi:10.1007/s11783-024-1837-4.

[46] T. Zhang et al., "Characteristics and risk assessments of mercury pollution in a county region undergoing industrialization in northeastern China: A case study in Gongzhuling," *Front. Environ. Sci.*, vol. 12, Sep. 2024, doi: 10.3389/fenvs.2024.1440426.