Justicia Islamica: Jurnal Kajian Hukum dan Sosial
Vol 23 No 1, June 2026

Aligning Mercury Governance With Livelihoods, Legal Frameworks, and Religious Norms: Evidence from Indonesia's ASGM

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DOI: https://doi.org/10.21154/justicia.v23i1.12274
Received: Nov 11, 2025 | *Revised*: Jan 8, 2026 | *Accepted*: Feb 2, 2026

Abstract: This study aims to examine the health impacts of mercury exposure on miners and communities, analyse patterns of regulatory compliance in the context of largely informal mining, and evaluate the effectiveness of policies and legal instruments designed to reduce mercury use and mitigate environmental impacts. This study synthesises toxicological and biomonitoring evidence, community-based qualitative studies on practices and risk perceptions, and regulatory analysis in relation to international obligations. Results show that mercury biomarkers remain persistently high and there are neurological impacts on exposed populations, while informality limits oversight and weakens compliance. Interventions focused on enforcement often trigger displacement of activities (mining), rather than changes to more sustainable extraction practices. Policy effectiveness increases when regulations are combined with livelihood-sensitive supporting factors, including cooperative-based formalisation, access to financing and training, and technological transition through integrated governance. The study proposes a governance-livelihood-Islamic norm model and a compliance architecture aligned with *maqasid al-sharia*.
Keywords: Artisanal and small-scale gold mining; mercury exposure; policy effectiveness; Minamata Convention.

Abstrak: Studi ini bertujuan untuk mengkaji dampak kesehatan akibat paparan merkuri pada penambang dan masyarakat, menganalisis pola kepatuhan regulasi dalam konteks pertambangan yang sebagian besar bersifat informal, dan mengevaluasi efektivitas kebijakan, serta instrumen hukum yang dirancang untuk mengurangi penggunaan merkuri dan menekan dampak lingkungan. Studi ini mensitensis bukti toksiologis dan biomonitoring, studi kualitatif berbasis komunitas tentang praktik dan persepsi risiko, serta analisis regulasi dalam kaitannya dengan kewajiban internasional. Hasil menunjukkan bahwa biomaker merkuri tetap tinggi secara persisten dan terdapat dampak neurologis pada

populasi yang tertpapar, sementara informalitas membatasi pengawasan dan melemahkan kepatuhan. Intervensi yang berfokus pada penegakan serung memicu perpindahan aktivitas (tambang), bukan perubahan praktik ekstraksi yang lebih berkelanjutan. Efektivitas kebijakan meningkat ketika regulasi dipadukan dengan faktor pendukung yang peka terhadap mata pencaharian, termasuk formalisasi berbasis koperasi, akses terhadap pembiayaan dan pelatihan, serta transisi teknologi melalui tata kelola terintegrasi. Studi mengusulkan model tata kelola-mata pencaharian-normal Islam dan arsitektur kepatuhan yang selaras dengan *maqasid al-syariah.*
Kata Kunci: pertambangan emas skala kecil dan tradisional; paparan merkuri; efektivitas kebijakan; konvensi minamata.

Introduction

Mercury pollution remains a major global environmental and public health concern, with ASGM recognised as a significant source of exposure in low-regulated settings. Of particular concern is methylmercury (MeHg), formed through aquatic biotransformation, which is the most bioavailable and neurotoxic form of mercury.[1] Dietary exposure, most notably through contaminated rice and fish, extends health risks beyond miners to surrounding communities, effectively integrating contamination within rural food systems.[2] Across the ASGM context, mercury-dependent extraction. Therefore, it generates multi-layered harms through both occupational contact and wider environmental dispersion, with impacts consistently reported on neurological,

[1] G. C. Compeau and R. Bartha, "Sulfate-Reducing Bacteria: Principal Methylators of Mercury in Anoxic Estuarine Sediment," *Applied and Environmental Microbiology* 50, no. 2 (August 1985): 498–502, https://doi.org/10.1128/aem.50.2.498-502.1985; François M. M. Morel, Anne M. L. Kraepiel, and Marc Amyot, "THE CHEMICAL CYCLE AND BIOACCUMULATION OF MERCURY," *Annual Review of Ecology and Systematics* 29, no. 1 (November 1998): 543–66, https://doi.org/10.1146/annurev.ecolsys.29.1.543; Memet Varol, Gökhan Karakaya, and Muhammet Raşit Sünbül, "Spatiotemporal Variations, Health Risks, Pollution Status and Possible Sources of Dissolved Trace Metal(Loid)s in the Karasu River, Turkey," *Environmental Research* 202 (November 2021): 111733, https://doi.org/10.1016/j.envres.2021.111733.

[2] Tia Agustiani et al., "Mercury Contamination and Human Health Risk by Artisanal Small-Scale Gold Mining (ASGM) Activity in Gunung Pongkor, West Java, Indonesia," *Earth* 6, no. 3 (July 2025): 67, https://doi.org/10.3390/earth6030067; Stephan Bose-O'Reilly et al., "A Preliminary Study on Health Effects in Villagers Exposed to Mercury in a Small-Scale Artisanal Gold Mining Area in Indonesia," *Environmental Research* 149 (August 2016): 274–81, https://doi.org/10.1016/j.envres.2016.04.007; Milena Horvat et al., "Total Mercury, Methylmercury and Selenium in Mercury Polluted Areas in the Province Guizhou, China," *Science of The Total Environment* 304, nos. 1–3 (March 2003): 231–56, https://doi.org/10.1016/S0048-9697(02)00572-7.

renal, and developmental outcomes alongside contamination of soil and aquatic systems. Evidence from Indonesia similarly documents not only the acute manifestation of exposure, but also the retention of methylmercury in human tissues, including neural structures.[3] These risks are not evenly distributed, as children and pregnant women remain disproportionately vulnerable due to heightened sensitivity to developmental neurotoxicity.[4]

Beyond its environmental and health costs, ASGM continues to operate as a livelihood-based economic sector in rural Indonesia, supporting millions of households and serving as a de facto safety net under conditions of structural poverty and limited formal employment opportunities.[5] Escalating global gold prices further incentivise participation, reinforcing the sector's embeddedness within rural economies.[6] Yet the continued reliance on mercury amalgamation generates a fundamental policy paradox: the same activity that secures immediate income simultaneously reproduces health harms, ecological degradation, and recurring regulatory conflict.[7] This tension translates into urgent governance dilemmas situated at the intersection of environmental justice, public health protection, and sustainable development.

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[3] Lars Friberg and N. Karle Mottet, "Accumulation of Methylmercury and Inorganic Mercury in the Brain," *Biological Trace Element Research* 21, no. 1 (July 1989): 201–6, https://doi.org/10.1007/BF02917253.

[4] Pyae S. Soe et al., "Mercury Pollution From Artisanal and Small-Scale Gold Mining in Myanmar and Other Southeast Asian Countries," *International Journal of Environmental Research and Public Health* 19, no. 10 (2022): 6290, https://doi.org/10.3390/ijerph19106290; Marco Tamburini et al., "Bioaccumulation of Mercury and Other Trace Elements in the Edible Holothurian Holothuria (Halodeima) Atra in Relation to Gold Mining Activities in North Sulawesi, Indonesia," *Frontiers in Marine Science* 9 (2022), https://doi.org/10.3389/fmars.2022.863629.

[5] Amanda Adelina Harun et al., "Indonesian Mining Regulations Shift as a Potential Sector in Developing the Economy," *Jurnal Pamator : Jurnal Ilmiah Universitas Trunojoyo* 16, no. 2 (June 2023): 419–34, https://doi.org/10.21107/pamator.v16i2.20114; Win T. Kyaw and Masayuki Sakakibara, "Transdisciplinary Communities of Practice to Resolve Health Problems in Southeast Asian Artisanal and Small-Scale Gold Mining Communities," *International Journal of Environmental Research and Public Health* 19, no. 9 (2022): 5422, https://doi.org/10.3390/ijerph19095422.

[6] Satoru Komatsu et al., "Examining Preference Heterogeneity in Best-Worst Scaling: Case of Preferences for Job Opportunities in Artisanal Small-Scale Gold Mining (ASGM) Communities in Indonesia," *International Journal of Environmental Research and Public Health* 19, no. 1 (2021): 306, https://doi.org/10.3390/ijerph19010306.

[7] C D. Nuryanty et al., "Predictive Modelling of Mercury Pollution in Indonesian ASGM Areas and Evaluation of the Main Factors Using Machine Learning Algorithm," *Iop Conference Series Earth and Environmental Science* 1109, no. 1 (2022): 012046, https://doi.org/10.1088/1755-1315/1109/1/012046; Kira Taux, Thomas Kraus, and Andrea Kaifie, "Mercury Exposure and Its Health Effects in Workers in the Artisanal and Small-Scale Gold Mining (ASGM) Sector—A Systematic Review," *International Journal of Environmental Research and Public Health* 19, no. 4 (2022): 2081, https://doi.org/10.3390/ijerph19042081.

At the international level, the Minamata Convention on Mercury operates as the principal normative basis for mercury control. Following its adoption in 2013 and Indonesia's ratification in 2017, the Convention has required states to eliminate or, at a minimum, substantially reduce mercury use in ASGM through National Action Plans and related instruments.[8] In response, Indonesia issued Presidential Regulation No. 21 of 2019 to formalise a mercury phase-out agenda. However, implementation has remained constrained by entrenched informality, fragmented enforcement capacity, and the continued presence of domestic cinnabar mining that sustains illicit mercury supply chains.[9] This persistent divergence between international commitments and operational realities points to a substantive governance gap, where formal legal mandates have yet to translate into durable shifts in extraction practices.

Regulatory compliance within the ASGM sector largely mirrors these structural constraints. Empirical studies suggest that approximately 70–80% of ASGM miners continue operate outside of formal licensing, thereby limiting regulatory visibility, weakening routine oversight, and complicating enforcement efforts.[10] Crackdowns often result in geographic displacement of operations rather than behavioural change, reinforcing a cycle of illegality and limiting state visibility.[11] This dynamic underscores the limited efficacy of

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[8] Mochammad Farisi, Akbar K. Putra, and Novianti Novianti, "Penggunaan Merkuri Pada Tambang Emas Ilegal: Diaturkah Dalam Minamata Convention?," *Uti Possidetis Journal of International Law* 3, no. 3 (2022): 320–44, https://doi.org/10.22437/up.v3i3.19281; Ali A. Sari et al., "National Action Plan for the Reduction and Abolishment of Mercury Use: Regulation Implementation in 2019-2020," *Iop Conference Series Earth and Environmental Science* 789, no. 1 (2021): 012040, https://doi.org/10.1088/1755-1315/789/1/012040.

[9] Susan E. Keane et al., "Mercury and Artisanal and Small-Scale Gold Mining: Review of Global Use Estimates and Considerations for Promoting Mercury-Free Alternatives," *Ambio* 52, no. 5 (2023): 833–52, https://doi.org/10.1007/s13280-023-01843-2; Juan S. L. Rodríguez and Morgane M. Fritz, "How Does Eliminating Mercury From Artisanal and Small-scale Gold Mining Lead to Achieving Sustainable Development Goals?," *Natural Resources Forum* 47, no. 2 (2023): 214–28, https://doi.org/10.1111/1477-8947.12279.

[10] Satomi Kimijima, Masayuki Sakakibara, and Masahiko Nagai, "Investigation of Long-Term Roving Artisanal and Small-Scale Gold Mining Activities Using Time-Series Sentinel-1 and Global Surface Water Datasets," *International Journal of Environmental Research and Public Health* 19, no. 9 (2022): 5530, https://doi.org/10.3390/ijerph19095530; Ami A. Meutia, Royke Lumowa, and Masayuki Sakakibara, "Indonesian Artisanal and Small-Scale Gold Mining—A Narrative Literature Review," *International Journal of Environmental Research and Public Health* 19, no. 7 (2022): 3955, https://doi.org/10.3390/ijerph19073955.

[11] Fenty U. Puluhulawa, Amanda A. Harun, and Karlin Z. Mamu, "Formalization of ASGM in the Frame of Economic and Environmental Sustainability," *E3s Web of Conferences* 440 (2023): 04001, https://doi.org/10.1051/e3sconf/202344004001.

punitive-only approaches, as they frequently drive miners further into informality. Instead, literature emphasises the need for regulatory frameworks that couple formalisation with socio-economic support, thereby aligning compliance with the lived realities of miners.[12]

Alternative strategies identified in the literature focus on both technological and socio-economic solutions. Mercury-free processing options—including gravity concentration and controlled cyanidation cyanidation-have shown technical viability in laboratory settings and are widely advanced as practical alternatives to amalgamation.[13] Beyond technological substitutions, community-based governance approaches highlight that inclusive participation and sustained stakeholder engagement are critical to achieving durable transitions.[14] Comparative evidence from countries such as Peru, Ghana, and Tanzania further suggests that participatory strategies supported through community education, livelihood diversification, and cooperative mining arrangements tend to deliver more sustained reductions in mercury use over time.[15]

These cross-national experiences help clarify the enabling conditions under which reforms generate measurable outcomes. In Ecuador and Ghana, regulatory strategies that incorporate community perspectives, expand access to microfinance, and introduce supply-chain incentives have been associated with meaningful reductions in mercury use, whereas stand-alone prohibitions

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[12] Samuel J. Spiegel and Marcello M. Veiga, "International Guidelines on Mercury Management in Small-Scale Gold Mining," *Journal of Cleaner Production* 18, no. 4 (March 2010): 375–85, https://doi.org/10.1016/j.jclepro.2009.10.020.

[13] Louisa J. Esdaile and Justin M. Chalker, "The Mercury Problem in Artisanal and Small-Scale Gold Mining," *Chemistry – A European Journal* 24, no. 27 (May 2018): 6905–16, https://doi.org/10.1002/chem.201704840; Keane et al., "Mercury and Artisanal and Small-Scale Gold Mining: Review of Global Use Estimates and Considerations for Promoting Mercury-Free Alternatives."

[14] Rodríguez and Fritz, "How Does Eliminating Mercury From Artisanal and Small-scale Gold Mining Lead to Achieving Sustainable Development Goals?"; Samuel Spiegel et al., "The Minamata Convention on Mercury: Time to Seek Solutions with Artisanal Mining Communities," *Environmental Health Perspectives* 122, no. 8 (August 2014), https://doi.org/10.1289/ehp.1408514.

[15] Rolando Q. Aquino, Fredy F. G. Zúñiga, and Aaron Malone, "Soil and Urine Mercury Levels in Secocha: A Case Study of Artisanal and Small-Scale Gold Mining in Peru," *Mining* 4, no. 2 (2024): 389–400, https://doi.org/10.3390/mining4020022; Angella N. G. Puspita et al., "Socio-Economic Baseline, Economic Feasibility Study and Processing Activities ASGM in Obi Island, South Halmahera District, North Maluku Province, Indonesia," *Journal of Degraded and Mining Lands Management* 10, no. 4 (2023): 4611, https://doi.org/10.15243/jdmlm.2023.104.4611; Allan Rocha De Souza, Luca Schirru, and Miguel Bastos Alvarenga, "Text and Data Mining in Health Research: Reflections on Copyright," *Cadernos de Saúde Pública* 40, no. 5 (2024): e00169023, https://doi.org/10.1590/0102-311xen169023.

have generally shown limited effect.[16] At the same time, the literature cautions that such progress is often uneven, with successful adoption frequently confined to pilot interventions that remain difficult to scale across wider informal mining settings. This underscores the ongoing challenge of bridging the gap between technical feasibility and socio-political acceptability.

Despite extensive research on mercury toxicology, regulatory deficits, and technology alternatives, existing scholarship remains fragmented across disciplines and rarely integrates health evidence with compliance dynamics under informality. Accordingly, policy debates have yet to develop a coherent conceptual account of how poverty-driven informality, continued mercury dependence, and enforcement limitations interact to shape regulatory outcomes in Indonesia. Existing scholarship often treats toxicological evidence and legal responses as separate domains, thereby overlooking the structural interdependence between socio-economic vulnerability, health risks, and the design of regulatory instruments.[17] In addition, miners' perspectives remain insufficiently represented in both academic and policy discussions, which constrains contextual understanding and sustains misalignments between regulatory ambition and on-the-ground feasibility.[18] This analytical gap underscores the need for interdisciplinary frameworks that more explicitly integrate health, law, and socio-economic dynamics.

Within the Islamic worldview, the stewardship of natural resources (*khilafah fi al-arḍ*)[19] is framed as a moral responsibility that aligns ecological

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[16] Carlos Mestanza-Ramón et al., "Artisanal and Small-Scale Gold Mining (ASGM): Management and Socioenvironmental Impacts in the Northern Amazon of Ecuador," *Sustainability* 14, no. 11 (2022): 6854, https://doi.org/10.3390/su14116854; Taux, Kraus, and Kaifie, "Mercury Exposure and Its Health Effects in Workers in the Artisanal and Small-Scale Gold Mining (ASGM) Sector—A Systematic Review."

[17] Juliana Siqueira-Gay and Luis E. Sánchez, "The Outbreak of Illegal Gold Mining in the Brazilian Amazon Boosts Deforestation," *Regional Environmental Change* 21, no. 2 (June 2021): 28, https://doi.org/10.1007/s10113-021-01761-7; Leonard L. Tampushi, John M. Onyari, and Nzioka J. Muthama, "A Review of Mining Regulations and Environmental Sustainability of Artisanal Gold Mining Sector," *Asian Journal of Environment & Ecology*, 2021, 1–16, https://doi.org/10.9734/ajee/2021/v16i430253.

[18] Sabine Luning and Robert J. Pijpers, "Governing Access to Gold in Ghana: In-Depth Geopolitics on Mining Concessions," *Africa* 87, no. 4 (November 2017): 758–79, https://doi.org/10.1017/S0001972017000353; Puluhulawa, Harun, and Mamu, "Formalization of ASGM in the Frame of Economic and Environmental Sustainability."

[19] Anisa Madani Nasution et al., "Pengelolaan Sumber Daya Alam Dan Pelestarian Lingkungan Hidup Dalam Perspektif Islam : Tinjauan Ayat-Ayat Alqur'an," *Jurnal Ekonomi Bisnis Dan Akuntansi* 5, no. 2 (July 2025): 502–11, https://doi.org/10.55606/jebaku.v5i2.5435.

balance (*mizan*)[20] with broader commitments to social justice. The Qur'an repeatedly condemns corruption and destruction on Earth (*fasad fi al-arḍ*)[21] as violations of divine trust (Q.S. Al-A'raf [7]:56; Ar-Rum [30]:41). In the context of artisanal mining, excessive mercury use and its resultant harm to human health and ecosystems contradict the *maqaṣid al-sharia* principles of *ḥifẓ al-nafs* (protection of life) and *ḥifẓ al-bi'ah* (preservation of the environment).[22] Accordingly, sustainable ASGM governance may be viewed not merely as a legal or policy imperative but as a form of *'ibadah*—a moral obligation to protect creation and ensure justice for affected communities.

This study advances an integrative perspective to explain the persistence of mercury use in Indonesia's ASGM despite recognised health risks and formal regulatory commitments. It synthesises evidence on mercury-related health impacts, compliance constraints under pervasive informality, and the effectiveness of policies and legal instruments. International ASGM cases are employed as analytical reference points rather than as a systematic cross-national comparison. The review is therefore delimited to scholarship that clarifies how informality, enforcement constraints, and livelihood dependence jointly shape compliance trajectories, culminating in a conceptual framework to inform pathways toward mercury-free transitions. On this basis, the study is structured around three guiding questions: (1) how do documented health-risk pathways reinforce the urgency of mercury reduction; (2) through what mechanisms do informality and governance constraints sustain weak compliance and continued mercury dependence; and (3) under what conditions do policy and legal instruments become more effective when coupled with livelihood-sensitive enablers, including cooperative

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[20] Ismail and Mokhamad Sukron, "Qur'anic Critique of Exploitative Anthropocentrism: Exegesis of Verses on Land and Nature in the Context of Raja Ampat Mining," *International Journal of Social Science and Religion (IJSSR)*, July 31, 2025, 209–20, https://doi.org/10.53639/ijssr.v6i2.337.

[21] Nia Kurniati and Hisan Mursalin, "Pandangan Islam Terhadap Upaya Pelestarian Lingkungan," *Mauriduna: Journal of Islamic Studies* 4, no. 2 (November 2023): 212–20, https://doi.org/10.37274/mauriduna.v4i2.842.

[22] Suud Sarim Karimullah, "Humanitarian Ecology in Islamic Law: Balancing Human Needs and Environmental Preservation in Islamic Law," *Asy-Syari'ah* 26, no. 2 (December 2024): 113–36, https://doi.org/10.15575/as.v26i2.38177; Abdurrohman Kasdi, "Actualizations of Maqashid Al-Shariah in Modern Life: Maqashid al-Shariah Theory As a Method of the Development of Islamic Laws and Shariah Economics," *Justicia Islamica* 16, no. 2 (November 2019): 247–68, https://doi.org/10.21154/justicia.v16i2.1666.

formalization, access to finance and training, and support for technology transition?

Methodologically, this article is a conceptual and integrative literature review rather than a field-based investigation. It does not cover all ASGM regions in Indonesia, and relies on secondary sources, which may introduce regional bias. Accordingly, the findings are not intended for empirical generalisation, but they support theory-building through the synthesis of public health, legal, and governance literatures.

Persistence of Mercury use in ASGM

This conceptual review explains the persistence of mercury use in Indonesia's ASGM through a governance-livelihood-capacity framework that links informality, enforcement capacity, knowledge and technical capacity, livelihood dependency, and compliance outcomes. The analysis shows that informality limits oversight and enforcement credibility, while punitive crackdowns often produce displacement rather than sustained behavioural or technological change, with livelihood dependency mediating miners' capacity to comply. Therefore, compliance is more likely to improve when legal instruments are paired with enabling supports[23] such as cooperative-based formalisation, training, finance, and accessible technology, shifting governance from a coercion-centred approach to incentive aligned.

Mercury exposure continues to be recognised as one of the most serious global environmental and public health challenges, particularly within artisanal and small-scale gold mining (ASGM) communities. From a regulatory compliance standpoint, the continued use of mercury cannot be attributed to toxicological risk alone; it is also shaped by the interaction between enforcement credibility, perceived regulatory legitimacy, and practical availability of feasible alternatives.[24] Mercury (Hg), the only metal that remains liquid at room temperature, exhibits both chemical persistence and high

[23] Hari Prasad Josyula, "The Impact of New Regulatory Initiatives on Payments," *Journal of Payments Strategy & Systems* 19, no. 3 (September 2025): 203, https://doi.org/10.69554/XISS7425.

[24] Allison Aldous, Tim Tear, and Luis 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* 33, nos. 4–5 (2024): 506–17, https://doi.org/10.1007/s10646-024-02741-3.

toxicological potency, which together render it uniquely hazardous.[25] Once released into the environment, mercury is not degradable and instead accumulates in soils, aquatic systems, and biota, thereby amplifying exposure risk over time.[26] In this sense, Indonesia provided a particularly consequential analytical case, because mercury dependence is sustained under conditions where informality is structurally embedded in livelihood systems and where governance interventions have struggled to achieve durable compliance outcomes.

Literature identifies informality as a defining feature of ASGM in Indonesia, with an estimated 70–80% operations remaining unlicensed due to structural barriers in the permitting system.[27] Licensing requirements are often prohibitively complex and costly, aligning with the political economy of informality, which keeps miners outside formal regimes when compliance costs exceed expected benefits.[28]Particularly in areas of poverty and limited employment alternatives. Enforcement through raids and crackdowns has typically produced spatial displacement rather than sustained behavioural change, as miners relocate to remote areas while continuing mercury-based extraction.[29] These dynamics often deepen distrust between mining communities and state authorities, thereby constraining cooperative governance, sustaining mercury dependence despite deterrence-oriented interventions.

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[25] L. Crespo-López et al., "Use of Recycled Carbon Fibre as an Additive in the Manufacture of Porous Bricks More Durable against Salt Crystallization," *Ceramics International* 50, no. 6 (2024): 9682–96, Scopus, https://doi.org/10.1016/j.ceramint.2023.12.287; Hansell Gonzalez-Raymat et al., "Elemental Mercury: Its Unique Properties Affect Its Behavior and Fate in the Environment," *Environmental Pollution* 229 (October 2017): 69–86, https://doi.org/10.1016/j.envpol.2017.04.101.

[26] L. Lizárraga-Mendiola et al., "Geochemical Behavior of Heavy Metals in a Zn–Pb–Cu Mining Area in the State of Mexico (Central Mexico)," *Environmental Monitoring and Assessment* 155, nos. 1–4 (August 2009): 355–72, https://doi.org/10.1007/s10661-008-0440-1.

[27] Satomi Kimijima, Masayuki Sakakibara, and Masahiko Nagai, "Detection of Artisanal and Small-Scale Gold Mining Activities and Their Transformation Using Earth Observation, Nighttime Light, and Precipitation Data," *International Journal of Environmental Research and Public Health* 18, no. 20 (2021): 10954, https://doi.org/10.3390/ijerph182010954; Meutia, Lumowa, and Sakakibara, "Indonesian Artisanal and Small-Scale Gold Mining—A Narrative Literature Review."

[28] Sergej Ljubownikow and Jo Crotty, "Achieving Regulatory Legitimacy in Volatile Institutional Contexts: The Case of Russian Non-Profits," *Socio-Economic Review* 21, no. 2 (June 2023): 1197–216, https://doi.org/10.1093/ser/mwac006.

[29] Ndeye Marame Ngom et al., "Recent Expansion of Artisanal Gold Mining along the Bandama River (Côte d'Ivoire)," *International Journal of Applied Earth Observation and Geoinformation* 112 (August 2022): 102873, https://doi.org/10.1016/j.jag.2022.102873; Puluhulawa, Harun, and MAMU, "Formalization of ASGM in the Frame of Economic and Environmental Sustainability."

Beyond financial limitations, the effectiveness of legal instruments is further weakened by persistent knowledge gaps within ASGM communities. Many miners remain insufficiently informed about the long-term health consequences of mercury exposure and, at the same time, lack awareness of the environmental and economic advantages associated with mercury-free extraction methods.[30] While education initiatives and technical trainings have been introduced in some settings, they are commonly sporadic, under-resourced, and geographically limited, particularly in remote rural settlements. The absence of systematic outreach means that miners rarely receive the continuous support required to adopt and institutionalise safer practices.[31] As a result, policy shortcomings stem less from inadequate legal design than from weak institutional mechanisms for translating regulatory goals into actionable community-level capacity. This pattern aligns with the compliance literature's emphasis on "capacity to comply": even where rules are formally clear, compliance remains unlikely when targeted communities lack sustained training, trusted information channels, and feasible technological pathways.[32] Without coordinated education and capacity-building, regulatory frameworks are therefore unlikely to shift entrenched behaviours durably.

The dynamics of compliance within ASGM cannot be fully explained through legal frameworks alone; instead, they must be situated within broader socio-economic contexts. Factors such as chronic poverty, scarcity of employment opportunities, and elevated international gold prices create compelling incentives for miners to persist in mercury use, even in the face of formal prohibitions.[33] For miners operating under daily income insecurity, regulatory restrictions are frequently viewed as impractical, particularly where safer technological alternatives remain financially unaffordable or logistically

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30 Puspita et al., "Socio-Economic Baseline, Economic Feasibility Study and Processing Activities ASGM in Obi Island, South Halmahera District, North Maluku Province, Indonesia."

31 Meutia, Lumowa, and Sakakibara, "Indonesian Artisanal and Small-Scale Gold Mining—A Narrative Literature Review."

32 René Véron et al., "Environmental Governance in Small Cities: Decentralization, Municipal Capacity and Autonomy in Gujarat and West Bengal," *Journal of South Asian Development* 19, no. 3 (December 2024): 325–44, https://doi.org/10.1177/09731741241228359.

33 Archippe N. Manzila, Thandazile Moyo, and Jochen Petersen, "A Study on the Applicability of Agitated Cyanide Leaching and Thiosulphate Leaching for Gold Extraction in Artisanal and Small-Scale Gold Mining," *Minerals* 12, no. 10 (2022): 1291, https://doi.org/10.3390/min12101291; Mestanza-Ramón et al., "Artisanal and Small-Scale Gold Mining (ASGM): Management and Socioenvironmental Impacts in the Northern Amazon of Ecuador."

inaccessible. Scholarship consistently indicates that livelihood imperatives mediate how miners interpret and respond to regulatory frameworks. From a governance and incentives standpoint, livelihood dependency functions as a key linkage between regulation and behaviour, where survival pressures dominate, miners tend to prioritise immediate earnings over formal compliance, especially in the absence of viable alternatives.[34] Compliance outcomes improve more sustainably when regulatory initiatives are complemented by socio-economic enabling measures, including microfinance access, livelihood diversification, and the diffusion of mercury-free technologies.[35] Comparative lessons from Peru, Ghana, and Tanzania further support this pattern, suggesting that compliance becomes more durable when legal reforms are tied to economic incentives and participatory governance arrangements.[36] Collectively, these findings underscore that effective compliance strategies must be embedded within the broader socio-economic realities of ASGM communities, where survival considerations often outweigh abstract regulatory obligations.

Cross-national scholarship shows that compliance with ASGM regulations varies across contexts, yet outcomes are consistently shaped by structural barriers. The analytical value of cross-national comparison lies in distinguishing mechanisms that may be transferable, including cooperative-based formalisation that reduces licensing transaction costs and improves state visibility, sustained education and capacity building to support mercury-free adoption, and incentive-aligned program linking finance, training, and market access to compliance requirements. However, transferability is constrained where contextual conditions differ, including domestic mercury supply chains, enforcement credibility and legitimacy, administrative fragmentation, and levels of community trust. Evidence from Peru indicates that cooperative-based arrangements, when it is paired with sustained

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[34] Stefan Rakete et al., "Biomonitoring of Arsenic, Cadmium and Lead in Two Artisanal and Small-Scale Gold Mining Areas in Zimbabwe," *Environmental Science and Pollution Research* 29, no. 3 (2021): 4762–68, https://doi.org/10.1007/s11356-021-15940-w.

[35] Spiegel and Veiga, "International Guidelines on Mercury Management in Small-Scale Gold Mining."

[36] Aquino, Zúñiga, and Malone, "Soil and Urine Mercury Levels in Secocha: A Case Study of Artisanal and Small-Scale Gold Mining in Peru"; Puspita et al., "Socio-Economic Baseline, Economic Feasibility Study and Processing Activities ASGM in Obi Island, South Halmahera District, North Maluku Province, Indonesia"; Souza, Schirru, and Alvarenga, "Text and Data Mining in Health Research."

capacity building and financial support, can facilitate more durable transitions toward mercury-free mining practice.[37] For Indonesia, these suggest that legal reform in isolation is unlikely to produce long-term compliance unless it is reinforced by parallel socio-economic measures and governance improvements that make compliance both feasible and credible.

Medical Impacts of Mercury Exposure

Mercury (Hg) is the only metal that remains liquid at room temperature, a property that contributes to its environmental mobility and persistence.[38] Because it cannot be degraded, mercury accumulates in soils and sediments over long periods.[39] Despite its established toxicity, it remains widely used in ASGM. Of particular concern is methylmercury (MeHg), the most hazardous organic form, produced in aquatic systems through bacterial methylation.[40] Methylmercury has been detected in water, soils, fish, and staple crops such as rice and cassava cultivated near mining areas, creating multiple exposure pathways.[41] Human exposure primarily occurs through the consumption of contaminated fish and rice, while inhalation of mercury vapour during amalgamation often exceeds the exposure limits set by the World Health Organisation (WHO) of 1 $\mu g/m^3$.[42] Once absorbed, mercury distributes systematically, accumulates in renal and neural tissues, and can cross the blood-brain barrier, where inorganic species may persist for years.[43] A case

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[37] Rodríguez and Fritz, "How Does Eliminating Mercury From Artisanal and Small-scale Gold Mining Lead to Achieving Sustainable Development Goals?"; Aquino, Zúñiga, and Malone, "Soil and Urine Mercury Levels in Secocha: A Case Study of Artisanal and Small-Scale Gold Mining in Peru."

[38] Crespo-López et al., "Use of Recycled Carbon Fibre as an Additive in the Manufacture of Porous Bricks More Durable against Salt Crystallization"; Gonzalez-Raymat et al., "Elemental Mercury."

[39] Lizárraga-Mendiola et al., "Geochemical Behavior of Heavy Metals in a Zn–Pb–Cu Mining Area in the State of Mexico (Central Mexico)."

[40] Compeau and Bartha, "Sulfate-Reducing Bacteria"; Morel, Kraepiel, and Amyot, "The Chemical Cycle And Bioaccumulation Of Mercury."

[41] Bose-O'Reilly et al., "A Preliminary Study on Health Effects in Villagers Exposed to Mercury in a Small-Scale Artisanal Gold Mining Area in Indonesia"; Agustiani et al., "Mercury Contamination and Human Health Risk by Artisanal Small-Scale Gold Mining (ASGM) Activity in Gunung Pongkor, West Java, Indonesia."

[42] Horvat et al., "Total Mercury, Methylmercury and Selenium in Mercury Polluted Areas in the Province Guizhou, China"; UNEP (United Nations Environment Programme), *Reducing Mercury Use in Artisanal and Small-Scale Gold Mining: A Practical Guide*, no. 2012 (UNEP (United Nations Environment Programme), n.d.), accessed September 19, 2025, https://www.unep.org/resources/report/

[43] Angelika Edyta Charkiewicz et al., "Mercury Exposure and Health Effects: What Do We Really Know?," *International Journal of Molecular Sciences* 26, no. 5 (March 2025): 2326, https://doi.org/10.3390/ijms26052326; Thomas W. Clarkson, "The Toxicology of Mercury," *Critical*

study conducted in Cisitu, West Java, reported mercury intoxication symptoms among 83%R of residents near ASGM sites, accompanied by elevated mercury levels in urine and hair, with estimated intakes 8-86 times above safe thresholds.[44] Toxicological evidence further indicates that methylmercury induces oxidative stress and disrupts neurodevelopmental processes critical to central nervous system function.[45]

Biomonitoring in mining regions has consistently revealed elevated mercury levels in human biological samples. Blood analysis conducted in Lebaksitu revealed average mercury concentrations of 26.94 μg/L, significantly above the established adult reference of <10 μg/L, and correlated with the length of residence near mining areas.[46] Urine and hair samples have also been utilised to measure mercury exposure. The WHO (1991) indicated that urinary mercury levels exceeding 100 μg/g creatinine are highly predictive of neurological symptoms, while concentrations between 30–100 μg/g creatinine are associated with subclinical toxic effects. Field studies in Kalimantan and Sulawesi reported mean urinary mercury levels of 69.35 μg/g creatinine and 31.89 μg/g creatinine, respectively, with maximum recorded levels far surpassing international safety thresholds.[47] Similarly, research in West Sumatra revealed a dose–response relationship between years of occupational exposure and blood mercury concentrations, with a miner of 20 years presenting a significantly higher mercury burden compared to

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Reviews in Clinical Laboratory Sciences 34, no. 4 (January 1997): 369–403, https://doi.org/10.3109/10408369708998098.

44 Bose-O'Reilly et al., "A Preliminary Study on Health Effects in Villagers Exposed to Mercury in a Small-Scale Artisanal Gold Mining Area in Indonesia."

45 Márcia C. Carvalho et al., "Effects of 2,3-Dimercapto-1-Propanesulfonic Acid (DMPS) on Methylmercury-Induced Locomotor Deficits and Cerebellar Toxicity in Mice," *Toxicology* 239, no. 3 (October 2007): 195–203, https://doi.org/10.1016/j.tox.2007.07.009; Takuji Kishimoto, Tetsuhisa Oguri, and Manabu Tada, "Effect of Methylmercury (CH3HgCl) Injury on Nitric Oxide Synthase (NOS) Activity in Cultured Human Umbilical Vascular Endothelial Cells," *Toxicology* 103, no. 1 (November 1995): 1–7, https://doi.org/10.1016/0300-483X(95)99370-R; R.A. Ponce et al., "Effects of Methyl Mercury on the Cell Cycle of Primary Rat CNS Cells in Vitro," *Toxicology and Applied Pharmacology* 127, no. 1 (July 1994): 83–90, https://doi.org/10.1006/taap.1994.1142; P.R. Sager, M. Aschner, and P.M. Rodier, "Persistent, Differential Alterations in Developing Cerebellar Cortex of Male and Female Mice after Methylmercury Exposure," *Developmental Brain Research* 12, no. 1 (January 1984): 1–11, https://doi.org/10.1016/0165-3806(84)90170-6.

46 Yuli Kristianingsih, "Bahaya Merkuri Pada Masyarakat Dipertambangan Emas Skala Kecil (PESK) Lebaksitu," *Jurnal Ilmiah Kesehatan* 10, no. 1 (September 2019): 32–38, https://doi.org/10.37012/jik.v10i1.12.

47 Bose-O'Reilly et al., "A Preliminary Study on Health Effects in Villagers Exposed to Mercury in a Small-Scale Artisanal Gold Mining Area in Indonesia."

colleagues with shorter employment durations.[48] Mercury exhibits both acute and chronic toxicity, as inorganic forms can remain sequestered in the body for prolonged durations. Although the biological half-life of methylmercury is estimated at 40–80 days, residues can be detected in brain tissue even two decades post-exposure.[49] These findings collectively illustrate the severe and enduring health burden experienced by ASGM workers and their surrounding communities.

Table 1. Effects of mercury exposure on different organ systems in Indonesia

Organ System	Symptoms and Signs	Study Location (s)
Nervous system	Ataxia, tremors, impaired balance, dysdiadochokinesia, sleep disorders, nystagmus, dysarthria[50]	Cisitu, West Java; Bolaang Mongondow, North Sulawesi
Renal system	Proteinuria[51]	West Lombok, West Nusa Tenggara
Hematological system	Decreased haemoglobin and increased hematocrit[52]	West Lombok, West Nusa Tenggara
Endocrine system	Thyroid dysfunction is characterised by elevated FT4 and TSH[53]	West Lombok, West Nusa Tenggara

[48] Herix Sonata Ms, Merry Thressia, and Dewi Yudiana Shinta, "Toksisitas Merkuri (Hg) Pada Penambang Emas Di Nagari Koto Tuo Sijunjung Sumbar," *Sehati: Jurnal Kesehatan* 1, no. 1 (February 2021): 33–38, https://doi.org/10.52364/sehati.v1i1.1.

[49] Friberg and Mottet, "Accumulation of Methylmercury and Inorganic Mercury in the Brain"; Esther Ogundipe and Emmanuel Obeng-Gyasi, "Joint Effects of Lifestyle Habits and Heavy Metals Exposure on Chronic Stress Among U.S. Adults: Insights from NHANES 2017–2018," *Journal of Xenobiotics* 15, no. 1 (January 2025): 7, https://doi.org/10.3390/jox15010007; Kevin M. Rice et al., "Environmental Mercury and Its Toxic Effects," *Journal of Preventive Medicine & Public Health* 47, no. 2 (March 2014): 74–83, https://doi.org/10.3961/jpmph.2014.47.2.74.

[50] Bose-O'Reilly et al., "A Preliminary Study on Health Effects in Villagers Exposed to Mercury in a Small-Scale Artisanal Gold Mining Area in Indonesia"; Yayu Indriati Arifin et al., "Mercury Exposure from Small Scale Gold Mining Activities and Neurological Symptoms on Inhabitants and Miners: A Case Study in Bolaang Mongondow, North Sulawesi Province, Indonesia," *IOP Conference Series: Earth and Environmental Science* 589, no. 1 (November 2020): 012013, https://doi.org/10.1088/1755-1315/589/1/012013.

[51] Ardiana Ekawanti and Baiq Dewi Krisnayanti, "Effect of Mercury Exposure on Renal Function and Hematological Parameters among Artisanal and Small-Scale Gold Miners at Sekotong, West Lombok, Indonesia," *Journal of Health and Pollution* 5, no. 9 (December 2015): 25–32, https://doi.org/10.5696/2156-9614-5-9.25.

[52] Ekawanti and Krisnayanti.

[53] Izza Hananingtyas, Suhartono Suhartono, and Nurjazuli Nurjazuli, "Hubungan Paparan Merkuri (Hg) Dengan Gangguan Fungsi Tiroid Pada Penambang Emas Tradisional Di Desa Jendi Kecamatan Selogiri Kabupaten Wonogiri," *Jurnal Kesehatan Lingkungan Indonesia* 2013, no. December (n.d.), https://doi.org/10.14710/jkli.12.1.58%20-%2063.

Patterns of Legal Compliance among ASGM Actors with National and International Regulations

Patterns of legal compliance among ASGM actors in Indonesia are shaped less by deliberate than by structural constraints that limit miners' capacity to comply. For individuals and communities whose economic survival depends on ASGM, these barriers constitute an insurmountable challenge. The absence of formal permits not only limits regulatory visibility and routine oversight but also consolidates hazardous practices for both miners and surrounding ecosystems, including continued reliance on mercury-based amalgamation. Informal mining persists largely because it is embedded in the socio-economic conditions of marginalised rural areas, where ASGM often represents one of the few viable livelihood options. In this context, the gap between statutory requirements and miners' lived realities reflects structural barriers to formal integration, indicating that informality should be understood less as a voluntary preference than as an outcome of systemic exclusion from accessible governance pathways.[54]

Table 2. Policy Matrix for Mercury Elimination in Indonesia

Level	Instrument	Key Actors	Implementation
International	Minamata Convention on mercury (ratified by Indonesia, 2017)	National government; relevant ministries; enforcement authorities	Supply-chain enforcement gap; the continued availability of mercury through illicit supply routes, including domestic cinnabar-linked distribution networks, weakens the credibility and effectiveness of phase-out commitments.
National	Presidential regulation (Perpres) No. 21/2019 on the National Action Plan	Coordinating agencies: Ministry of Environment and Forestry (KLHK); Ministry of	Fragmented agency mandates: although the policy architecture is formally established, implementation remains constrained by overlapping institutional roles

[54] Amidu Kalokoh and Lada V. Kochtcheeva, "Governing the Artisanal Gold Mining Sector in the Mano River Union: A Comparative Study of Liberia and Sierra Leone," *Journal of International Development* 34, no. 7 (October 2022): 1398–413, https://doi.org/10.1002/jid.3643.

	for Mercury Reduction and Elimination	Energy and Mineral Resources (ESDM); inter-ministerial stakeholders	and weak interagency coordination, which limits translation into workable local compliance mechanisms.
Sub-national	Provincial and district licensing/ administrative regimes (permit and oversight mechanisms)	Provincial governments; district governments; licensing offices; local enforcement units	High transaction costs: licensing regimes that are administratively complex and financially burdensome sustain informality, reduce state visibility, and restrict routine oversight, thereby reinforcing non-compliance.
Informal/ community practice	Customary mining practices and entrenched mercury amalgamation routines	Mining communities, local brokers, and informal operators	Cultural resistance and feasibility constraints: mercury use endures as a socially embedded and operationally convenient technique where safer alternatives remain inaccessible, unaffordable, or unsupported by sustained capacity-building efforts.

Source: Authors, 2026

The matrix in **Table 2** indicates that Indonesia's mercury phase-out regime operates across multiple governance layers, ranging from international commitments and national policy instruments to subnational licensing systems and deeply embedded informal practices-yet implementation gaps remain persistent at each level. Internationally, mercury reduction obligations are weakened by persistent deficiencies in supply chain enforcement. At the national level, Perpres No. 21 of 2019 establishes a formal policy roadmap, but fragmented institutional mandates limit coherent implementation. Sub-nationally, costly and administratively complex licensing requirements sustain informality and reduce state visibility, thereby constraining routine oversight. At the informal level, customary mining practices persist where viable alternatives remain inaccessible. These gaps fall into three interacting

compliance mechanisms: licensing barriers that reproduce informality, weak enforcement credibility that produces displacement rather than behavioural change, and feasibility constraints that sustain mercury dependence. Policy effectiveness is more likely when legal controls are complemented by enabling supports that expand access to finance skills development and pathways for adopting mercury-free technologies.

Enforcement efforts in Indonesia's ASGM sector are frequently inconsistent and episodic, and therefore tend to fall short of addressing the structural drivers of non-compliance. At the local level, compliance outcomes are largely shaped by enforcement credibility and administrative capacity: sporadic raids and punitive crackdowns often trigger spatial displacement rather than durable behavioural change, as miners relocate to less accessible areas where monitoring becomes increasingly difficult.[55] These challenges are compounded by institutional fragmentations, including overlapping ministers' mandates and weak interagency coordination, which together limit the state's ability to enforce mining regulations systematically. As a result, international commitments, particularly under the Minamata Convention, remain difficult to operationalise through concrete compliance mechanisms on the ground.

Indonesia's ratification of the Minamata Convention in 2017 signalled a formal commitment to mercury phase-out, later institutionalised through the National Action Plan as a policy roadmap for sectoral reform.[56] Nevertheless, mercury-based practices remain pervasive, sustained in part by illegal supply chains supported by domestic cinnabar-linked production and distribution networks.[57] This persistence illustrates the limits of translating treaty obligations into effective local interventions under conditions of informality and livelihood vulnerability. Scholars have cautioned that international

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[55] Aly Badara Toure et al., "Knowledge, Attitudes, and Practices of People Living in Artisanal Mining Areas on Water Pollution in Siguiri, Guinea, 2023," *Frontiers in Public Health* 13 (April 2025): 1482032, https://doi.org/10.3389/fpubh.2025.1482032; Kalokoh and Kochtcheeva, "Governing the Artisanal Gold Mining Sector in the Mano River Union."

[56] Farisi, Putra, and Novianti, "Penggunaan Merkuri Pada Tambang Emas Ilegal: Diaturkah Dalam Minamata Convention?"; Sari et al., "National Action Plan for the Reduction and Abolishment of Mercury Use: Regulation Implementation in 2019-2020."

[57] Rodríguez and Fritz, "How Does Eliminating Mercury From Artisanal and Small-scale Gold Mining Lead to Achieving Sustainable Development Goals?"; Andrew Leland Waack et al., "Letter to the Editor Regarding 'Clear-Cell Renal Cell Carcinoma and Glioblastoma Multiforme Coexistence: Double Primary Malignancy, Does It Have a Causal Relationship?,'" *Surgical Neurology International* 14 (April 2023): 134, https://doi.org/10.25259/SNI_151_2023.

compliance risks become largely symbolic when socio-economic realities are not incorporated into regulatory design. For miners, facing poverty and income insecurity, treaty-based obligations carry limited practical salience when weighed against immediate survival imperatives.[58] This reinforces the need for regulatory strategies that combine legal controls with livelihood-sensitive incentives and feasible alternatives to support meaningful behavioural change within ASGM.

To operationalise the gap between international norms and domestic practice, there are three interrelated compliance mechanisms. First, high licensing transaction costs and complex administrative requirements sustain informality and reduce state visibility, limiting routine oversight.[59] Second, weak enforcement credibility, characterised by sporadic monitoring, inconsistent sanctions, and limited follow-up, encourages avoidance strategies and geographic displacement rather than compliance.[60] Third, feasibility constraints, including continued limited access to mercury technologies, reinforce mercury dependence even under formal prohibition. Taken together, these mechanisms explain why implementation gaps persist despite strong formal commitments and why policy success depends on aligning regulatory expectations with local feasibility conditions.

Within this governance context, Islamic legal reasoning may be treated as an analytical ethical lens that can strengthen compliance by enhancing perceived legitimacy and community engagement, rather than functioning as a purely normative add-on. In Islamic legal thought, the state's duty to prevent environmental harm is consistent with the doctrine of *siyāsah shar'iyyah*, which legitimises public policy interventions aimed at protecting collective

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[58] Aldous, Tear, and Fernandez, "The Global Challenge of Reducing Mercury Contamination From Artisanal and Small-Scale Gold Mining (ASGM): Evaluating Solutions Using Generic Theories of Change"; Keane et al., "Mercury and Artisanal and Small-Scale Gold Mining: Review of Global Use Estimates and Considerations for Promoting Mercury-Free Alternatives."

[59] Elida Rahajeng Puspitasari and Mohammad Hazyar Arumbinang, "Climate Justice and Legal Frameworks in Indonesia: Ensuring Equity for Marginalized Communities in Green Policy Implementation," *IOP Conference Series: Earth and Environmental Science* 1566, no. 1 (December 2025): 012029, https://doi.org/10.1088/1755-1315/1566/1/012029.

[60] Rebecca J. Welch et al., "The Role of Acoustic Telemetry in Assessing Fish Connectivity within Marine Seascapes: A Global Review," *Journal of Fish Biology* 106, no. 5 (May 2025): 1285–304, https://doi.org/10.1111/jfb.16011.

welfare.[61] From this perspective, mercury phase-out measures are not only administrative instruments of regulation, but also reflect moral accountability grounded in justice (*'adl*) and trusteeship (*amanah*). Moreover, within *fiqh al-bi'ah* (Islamic environmental jurisprudence), safeguarding ecological integrity is positioned as a core dimension of governance and public responsibility.[62] The concept of *khalifah* (stewardship/replacement) further frames human communities as stewards of the Earth, obligated to preserve balance (*mizan*) between economic activity and environmental protection.[63] Accordingly, mercury elimination policies may be interpreted as governance commitments that integrate legal compliance with ethical obligations to prevent harm and sustain environmental well-being. The principles of *'adl* (justice) and *amanah* (trusteeship) further shape contemporary interpretations of environmental governance, advocating for equitable resource management and ethical responsibility toward natural assets.[64] Moreover, the Qur'anic prohibition of *fasad* (corruption or destruction) reinforces the alignment of environmental policy with communal welfare, fostering sustainable practices that reflect Islamic ethical standards.[65]

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[61] Dwi Wijayanti, Samsul Munir, and Nurul Syalafiyah, "Tinjauan Hukum Siyasah Terhadap Kebijakan Publik Dalam Penanganan Lingkungan Hidup," *Islamic Law: Jurnal Siyasah* 9, no. 2 (December 2024): 132–43, https://doi.org/10.53429/iljs.v9i2.598.

[62] Fahmi Hamdi et al., "Integrating Maqashid Al-Sharia, Fiqh al-Bi'ah, and Islamic Ethics for Sustainable Water Management: A Case Study of Indonesia," *Al-Ahkam: Jurnal Ilmu Syari'ah Dan Hukum* 10, no. 1 (June 2025): 1–19, https://doi.org/10.22515/alahkam.v10i1.11277.

[63] Muhammad Sholihin, Catur Sugiyanto, and Akhmad A. Susamto, "Environmental Protection Versus Economic Growth in the Views of Muslims: A Large Sample of Empirical Evidence," *International Journal of Energy Sector Management* 18, no. 6 (2023): 1592–609, https://doi.org/10.1108/ijesm-08-2023-0030; Idris Idris et al., "The Principles of Islamic Law in Preserving Ecological Balance: An Analysis of Natural Resource Management Policies," *Jomn* 2, no. 3 (2025): 174–86, https://doi.org/10.62568/jomn.v2i3.472; Sri D. R. Ningsih et al., "≪b>Safeguarding Maritime Sovereignty: Comparative Law Enforcement Against Illegal Fishing in Positive and Contemporary Islamic Law</B>," *Milrev Metro Islamic Law Review* 4, no. 2 (2025): 1028–50, https://doi.org/10.32332/milrev.v4i2.11303.

[64] Fahmi Hamdi et al., "Integrating Maqashid Al-Sharia, Fiqh Al-Bi'ah, and Islamic Ethics for Sustainable Water Management," *Al-Ahkam Jurnal Ilmu Syari'ah Dan Hukum* 10, no. 1 (2025): 1–19, https://doi.org/10.22515/alahkam.v10i1.11277; Mohammed A. M. Alasmari and Ali Abduh m Osaime Hakami, "The Principle of Islah (Consideration of Public Interest) and Its Impact on the Sustainability of Vegetation Cover the Kingdom of Saudi Arabia," *International Journal of Religion* 5, no. 2 (2024): 401–5, https://doi.org/10.61707/yxkf3j47.

[65] Munib Munib et al., "Conservation Environmental Sustainability in the Perspective of Islamic Legal Philosophy," *Samarah Jurnal Hukum Keluarga Dan Hukum Islam* 6, no. 2 (2022): 556, https://doi.org/10.22373/sjhk.v6i2.12411; Hamzah Hamzah et al., "Sustainable Development of

Islamic ecological ethics conceptualises humans as *khalifah*-trusteed, responsible for maintaining and preserving the earth.[66] This worldview offers an ethical and spiritual approach to sustainability by stressing the interconnectedness of living systems and framing environmental protection as a moral obligation.[67] It therefore supports a holistic model of development in which economic and social advancement is integrated with ethical responsibility.[68] Taken together, these principles provide a normative foundation that aligns Islamic teachings with broader sustainability agendas, guiding human – environment relations through justice, balance, and accountable governance.[69]

The accumulated evidence (in the literature) indicates that patterns in Indonesia's ASGM sector are shaped less by intentional resistance to regulation than by persistent structural constraints that limit miners' practical capacity to comply. The entrenched nature of informality reflects systemic barriers that prevent miners from entering formal regulatory frameworks, while pressing livelihood imperatives drive continued dependence on mercury-based extraction practices despite their recognised hazards. These realities imply that punitive enforcement strategies, when applied in isolation, risk exacerbating informality by forcing miners deeper into unregulated practices and distancing them from regulatory oversight. Scholarly consensus, therefore, advocates for multi-sectoral strategies that integrate legal reform with complementary initiatives such as livelihood diversification, community

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Mangrove Ecosystem Policy in South Sulawesi From the Perspectives of Siyāsah and Fiqh Al-Bi'ah," *Juris (Jurnal Ilmiah Syariah)* 22, no. 2 (2023): 367, https://doi.org/10.31958/juris.v22i2.10559.

66 Muhamed Ali and Muaz Agushi, "Eco-Islam: Integrating Islamic Ethics into Environmental Policy for Sustainable Living," *International Journal of Religion* 5, no. 9 (June 2024): 949–57, https://doi.org/10.61707/gq0we205.

67 Heba Hasan, "Islam and Ecological Sustainability: An Exploration into Prophet's Perspective on Environment," *Social Science Journal for Advanced Research* 2, no. 6 (November 2022): 15–21, https://doi.org/10.54741/ssjar.2.6.4; Heba Ahmed Aboukhousa, Mohamed Abdelgalil Hassan, and Mohamed Abouelfadl Badran, "Empowering Environmental Sustainability: Islamic Values and Their Synergy with the SDGs," *Journal of Infrastructure, Policy and Development* 8, no. 15 (December 2024): 10407, https://doi.org/10.24294/jipd10407.

68 Aboukhousa, Hassan, and Badran, "Empowering Environmental Sustainability."

69 Zainab Amin, "Sharīʿah and Climate Justice: Exploring Islamic Legal Foundations for Environmental Protection in Pakistan," *Muslim World Journal of Human Rights*, ahead of print, 2025, https://doi.org/10.1515/mwjhr-2025-0014; Abdu S. Sholihin, "Menelisik Urgensitas Fikih Ekologi Terhadap Pelestarian Lingkungan Hidup," *Iqtishaduna Jurnal Ilmiah Mahasiswa Hukum Ekonomi Syari Ah*, 2025, 637–46, https://doi.org/10.24252/iqtishaduna.vi.54558.

health monitoring, and the dissemination of mercury-free technologies.[70] Future policy design should therefore emphasise incentive-aligned and participatory governance that lowers formalisation barriers while widening access to training, finance, and feasible technological alternatives. Integrating socio-economic support into regulatory interventions would better enable Indonesia to reconcile its Minamata Convention commitments with the lived realities of ASGM communities. Such an approach is likely to strengthen compliance while advancing long-term public health and environmental protection through the intersection of legal design, health risks, and livelihood structures, underscoring the need for holistic and context-responsive strategies to support a sustainable mercury phase-out.

Effectiveness of Policies and Legal Instruments in Reducing Mercury Use and Mitigating Environmental Impacts

A key constraint limiting the effectiveness of mercury-reduction policies is the severe financial pressure experienced by ASGM miners. Although both national and international frameworks promote mercury-free alternatives, such as controlled cyanidation or borax-based methods, implementation often falters when miners lack the capital required for technological transition. Mercury remains the preferred option because it is inexpensive, widely available, and technically simple, enabling miners to maintain production without substantial upfront investment.[71] Studies further indicate that the costs of adopting safer technologies are widely perceived as unaffordable, particularly in remote areas where access to formal credit and institutional support remains limited.[72] Consequently, legal mandates to eliminate mercury frequently generate weak compliance when they are not accompanied by economic instruments that reduce transition costs. This gap between regulatory ambition and miners' economic feasibility highlights the need to embed subsidies, microfinance mechanisms, and accessible funding pathways within the mercury phase-out.

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70 Spiegel and Veiga, "International Guidelines on Mercury Management in Small-Scale Gold Mining."

71 Nuryanty et al., "Predictive Modelling of Mercury Pollution in Indonesian ASGM Areas and Evaluation of the Main Factors Using Machine Learning Algorithm."

72 Keane et al., "Mercury and Artisanal and Small-Scale Gold Mining: Review of Global Use Estimates and Considerations for Promoting Mercury-Free Alternatives."

1. Regulatory and Enforcement Challenges

Although formal legal frameworks have been introduced to regulate ASGM and reduce mercury dependence, their effectiveness is persistently constrained by structural weaknesses in enforcement capacity. A substantial share of ASGMN operations remains unlicensed, limiting state visibility and weakening accountability under national law.[73] In practice, existing legal instruments often fail to translate into compliance because institutional coordination is fragmented and field-level enforcement presence is limited.[74] Empirical evidence further indicates that enforcement actions-commonly carried out through raids or short-term crackdowns- tend to displace mining activities into more remote areas rather than generating sustained behavioural change.[75] These patterns suggest that the central challenge lies less in the formal design of regulation than in institutional capacity deficits, governance fragmentation, and entrenched informality.

In parallel, socio-cultural factors continue to blunt regulatory effectiveness. In many mining communities, mercury use is embedded not only as a production technique but also as inherited knowledge tied to local identity and intergenerational practice.[76] Where regulatory interventions fail to engage these social meanings, they are often perceived as externally imposed constraints, thereby reinforcing resistance and weakening adherence. Policies are therefore more likely to gain traction when they incorporate culturally sensitive strategies that respect local practices while progressively demonstrating the practical and economic advantages of safer alternatives.

Another structural constraint that weakens the effectiveness of mercury-reduction policy frameworks is the sustained domestic and global demand for gold. The sector's high profitability encourages miners to prioritise immediate income from mercury-based extraction over longer-term health and

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[73] Meutia, Lumowa, and Sakakibara, "Indonesian Artisanal and Small-Scale Gold Mining—A Narrative Literature Review."

[74] Nuryanty et al., "Predictive Modelling of Mercury Pollution in Indonesian ASGM Areas and Evaluation of the Main Factors Using Machine Learning Algorithm."

[75] Rodríguez and Fritz, "How Does Eliminating Mercury From Artisanal and Small-scale Gold Mining Lead to Achieving Sustainable Development Goals?"

[76] Enoch Adranyi, Lindsay C. Stringer, and Henrice Altink, "Joined-Up Governance for More Complementary Interactions Between Expanding Artisanal Small-Scale Gold Mining and Agriculture: Insights From Ghana," *Plos One* 19, no. 4 (2024): e0298392, https://doi.org/10.1371/journal.pone.0298392.

environmental considerations embedded in regulation.[77] Volatility in the international gold process further intensifies these pressures, reinforcing the limited impact of policies that operate independently of market dynamics.

Despite these obstacles, cooperative-based and community-driven formalisation efforts have demonstrated promising outcomes. Organising miners into cooperatives has been shown to improve compliance with environmental regulations, as collective responsibility enhances accountability and fosters peer-driven.[78] Alternative livelihood programs likewise strengthen mercury-reduction strategies by reducing dependence on ASGM as the sole source of household income.[79] Diversified income streams relieve the economic pressure to prioritise short-term gold extraction, thereby enabling miners to comply more readily with environmental and health-oriented regulations.[80]

2. Integrated Governance and Cross-Sector Collaboration

Integrated governance frameworks that align environmental, health, and economic objectives have shown relatively stronger policy performance. These approaches institutionalise collaboration among government agencies, mining communities, and non-governmental organisations, enabling more coordinated design and implementation.[81] In ASGMN settings, conceptual site models help operationalise interventions by connecting pollution sources, exposure pathways, and affected populations. NGO-led partnerships are also critical in closing state capacity gaps through education, resource support, and

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[77] Jonathan George et al., "Informal Gold Miners With Mercury Toxicity: Novel Asymmetrical Neurological Presentations," *South African Medical Journal* 113, no. 12 (2023): 20, https://doi.org/10.7196/samj.2023.v113i12.1127.

[78] Josephine Singo et al., "Health and Safety Risk Mitigation Among Artisanal and Small-Scale Gold Miners in Zimbabwe," *International Journal of Environmental Research and Public Health* 19, no. 21 (2022): 14352, https://doi.org/10.3390/ijerph192114352.

[79] G P. Yoga et al., "Mercury Contamination on Aquatic Organisms in Related to Artisanal Small-Scale Gold Mining Activity in Indonesia: A Mini Review," *Iop Conference Series Earth and Environmental Science* 1062, no. 1 (2022): 012023, https://doi.org/10.1088/1755-1315/1062/1/012023.

[80] Mestanza-Ramón et al., "Artisanal and Small-Scale Gold Mining (ASGM): Management and Socioenvironmental Impacts in the Northern Amazon of Ecuador."

[81] Edmond N. Kohio et al., "Environmental Cyanide Pollution From Artisanal Gold Mining in Burkina Faso: Human Exposure Risk Analysis Based on a Conceptual Site Model," *International Journal of Environmental Research and Public Health* 22, no. 7 (2025): 1125, https://doi.org/10.3390/ijerph22071125.

community advocacy.[82] By embedding participation and multi-actor accountability, integrated governance can expand policy effectiveness beyond the limited reach of legal prohibition alone.

Policy evaluations are also shaped by the debate between coercive and incentive-based instruments. Enforcement-centred measures, such as bans and police crackdowns, often displace activities rather than eliminate mercury use, exposing the limits of deterrence.[83] By contrast, incentive-based strategies, including microfinance and subsidies for mercury-free technologies, more consistently support voluntary compliance and longer-term transitions.[84] When the miners perceive tangible benefits and practical support, adoption of safer practices becomes more feasible, suggesting that hybrid policy mixes outperform punitive approaches applied in isolation.

Islamic legal principles may be used as an analytical lens to evaluate the legitimacy and feasibility of mercury-reduction policies in ASGM governance. Within *fiqh al-biah*, *maqasid al-sharia* provides a normative framework that connects environmental regulation to public welfare. The objective of *hifz al-nafs* (p*rotection* of life) strengthens the case for harm-reduction responses to mercury neurotoxicity and its documented neurological and developmental impacts.[85] In parallel, *hifz al-mal* (protection of livelihood) indicates that compliance is unlikely when regulatory interventions threaten basic income security in mining-dependent communities.[86] *Hifz al-bi'ah* (environmental

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[82] Lao-Tzu Allan-Blitz, Charlotte Goldfine, and Timothy B. Erickson, "Environmental and Health Risks Posed to Children by Artisanal Gold Mining: A Systematic Review," *Sage Open Medicine* 10 (2022), https://doi.org/10.1177/20503121221076934.

[83] Puluhulawa, Harun, and MAMU, "Formalization of ASGM in the Frame of Economic and Environmental Sustainability."

[84] Spiegel and Veiga, "International Guidelines on Mercury Management in Small-Scale Gold Mining."

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[86] Ian Clark et al., "Persistently Non-Compliant Employment Practice in the Informal Economy: Permissive Visibility in a Multiple Regulator Setting," *Cambridge Journal of Economics* 47, no. 3 (June 2023): 611–32, https://doi.org/10.1093/cje/bead007.

preservation) further positions mercury pollution as a governance issue due to its contribution to ecosystem degradation and food-system contamination.[87]

From a governance perspective, *siyāsah sharīʿiyyah* legitimises a state directed toward *maslahah* (public interests),[88] as reflected in the doctrine of *taṣarruf al-imām 'alā al-ra'iyyah manūṭun bi al-maṣlaḥah* (a leader's policies toward the people must be based on the common good). The Quranic prohibition of *fasad fi al-ard* reinforces mercury pollution as a legally relevant harm warranting regulation.[89] Importantly, the principle of *tadarruj* (gradual transformation) provides a jurisprudential basis for policy-mix approaches that combine enforcement with enabling supports, rather than abrupt crackdowns that risk displacement and deeper informality.[90] In this way, Islamic legal reasoning strengthens the case for compliance strategies that are ethically grounded, socio-economically feasible, and institutionally credible.

Despite encouraging examples, significant limitations continue to undermine the overall impact of current frameworks. Weak enforcement, insufficient financial support, inadequate educational outreach, and limited cultural integration remain the pressing challenges. Comparative evidence indicates that cooperative-based and incentive-driven programs tend to deliver more durable outcomes, yet their scalability across Indonesia's geographically dispersed and socially diverse ASGM communities remains uncertain.[91] Policy transformation is further constrained by weak interagency coordination and continuing mismatch between international commitments and local implementation realities. These persistent gaps suggest that, without

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87 Hasan Al Banna and Umi Rosyidah, "The Construction of Ecological Fiqh from the Perspective of Yusuf Al-Qardhawi," *Ma'mal: Jurnal Laboratorium Syariah Dan Hukum* 7, no. 2 (April 2025): 214–33, https://doi.org/10.15642/mal.v7i2.468.

88 Maimun Maimun and Dani Amran Hakim, "Siyāsah Syar'iyyah and Its Application to Constitutional Issues in Indonesia," *As-Siyasi: Journal of Constitutional Law* 3, no. 1 (June 2023): 111–30, https://doi.org/10.24042/as-siyasi.v3i1.15710.

89 Mohammad Hashim Kamali, "*Maqasid* and Protection of the Environment (*Hifz al-Bi'ah*)," in *Goals and Purposes of Shariah*, 1st ed., by Mohammad Hashim Kamali (Oxford University PressNew York, NY, 2025), 260–81, https://doi.org/10.1093/9780197786390.003.0028.

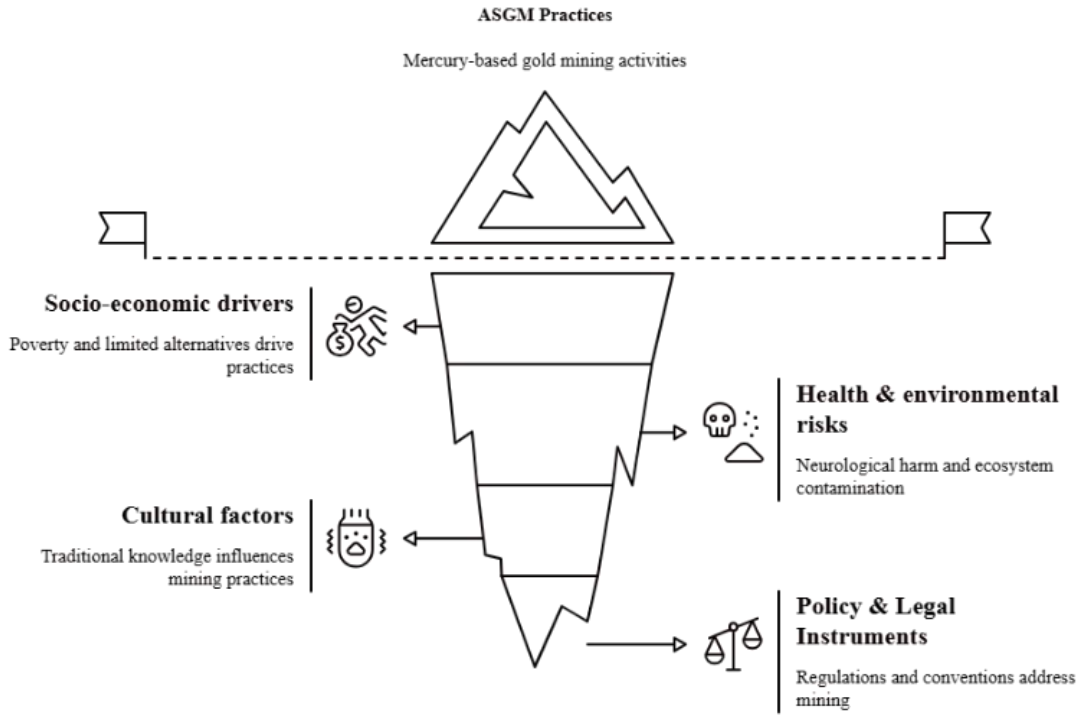
90 Muhyar Fanani and Florian Pohl, "Fiqh-Based Social Transformation in Farmer Empowerment: A Participatory Action Research Approach," *Al-Jami'ah: Journal of Islamic Studies* 62, no. 2 (December 2024): 305–35, https://doi.org/10.14421/ajis.2024.622.305-335.

91 Aquino, Zúñiga, and Malone, "Soil and Urine Mercury Levels in Secocha: A Case Study of Artisanal and Small-Scale Gold Mining in Peru"; Rodríguez and Fritz, "How Does Eliminating Mercury From Artisanal and Small-scale Gold Mining Lead to Achieving Sustainable Development Goals?"

deeper integration of socio-economic and cultural conditions, mercury-reduction policies will likely remain partial in effect.

Overall, the literature underscores that policy effectiveness depends on whether legal instruments can be operationalised in ways that reflect economic constraints, community capacities, and socio-cultural practices. Prohibition-centred approaches that overlook financial, educational, and cultural barriers are therefore unlikely to achieve comprehensive mercury elimination. More viable pathways require multi-sectoral policy mixes that connect international obligations with local feasibility, including cooperative formalisation, incentive structures, livelihood diversification, and sustained capacity-building. Such strategies can strengthen compliance while advancing public health protection, environmental sustainability, and community commitments.

Figure 1: Conceptual framework of ASGM in Indonesia



Source: Authors, 2026.

To frame the analysis of policy effectiveness, **Figure 1** presents a conceptual framework that positions ASGM at the core, surrounded by socio-economic and health risks, with regulatory and governance responses forming the outer layer. The arrows represent feedback loops, demonstrating how

poverty, informality, and cultural traditions reinforce mercury dependence, while weak enforcement and policy gaps maintain cycles of exposure and non-compliance. This model serves as the analytical lens for evaluating the effectiveness of existing legal instruments in reducing mercury use.

Conclusion

This study argues that the continued use of mercury in Indonesia's ASGM is most convincingly understood as a governance-livelihood-capacity challenge, rather than as a straightforward outcome of weak regulation or limited awareness of health risks. Patterns of non-compliance emerge from interacting constraints: pervasive informality reduces state visibility and routine oversight; inconsistent enforcement credibility incentivises avoidance and geographic relocation; and feasibility barriers-particularly limited access to affordable mercury-free processing options- reinforce continued dependence on amalgamation. In this respect, the persistent gap between Indonesia's obligations under the Minamata Convention and field-level practices is not merely legal or administrative but shaped by misaligned incentives and uneven practical capacity to comply.

Building on this diagnosis, the article advances a compliance architecture that moves beyond enforcement-dominated strategies toward a sequenced policy mix combining credible monitoring with livelihood-sensitive enabling measures. For Indonesia, sustained mercury reduction requires lowering formalisation barriers through cooperative-based licensing pathways, strengthening interagency coordination and supply-chain control beyond episodic crackdowns, and improving feasibility through integrated packages of training, finance, and technology transition tied to measurable compliance milestones. While positive law supplies the institutional instruments for licensing, supervision, and sanctions, its impact remains limited where legitimacy is contested, and compliance is structurally unrealistic within informal livelihood systems. Here, Islamic legal reasoning may reinforce regulatory design by framing mercury reduction as a public welfare obligation grounded in *maqasid al-sharia* and legitimising gradual transformation (*tadarruj*) rather than abrupt coercion. Ultimately, this study demonstrated that mercury phase-out depends not only on regulatory principles but also on the ability to operate as a form of social license that enhances policy

acceptance and supports longer-term mercury-free transitions beyond short-term displacement.

Acknowledgement

The Author(s) gratefully acknowledge the financial support from the Kementerian Pendidikan Tinggi, Sains dan Teknologi, melalui Direktorat Jenderal Riset dan Pengembangan, through The Reputable Journal Publication Assistance Program of 2025, Contract No: 038/SPK/C3/DT.05.00/BP/2025. This support was provided specifically to facilitate the publication process of this manuscript. The Author(s) also recognise the collaborative contribution of all co-authors in developing the research rationale, conducting the analysis, and refining the manuscript through internal review and revision. The use of generative Artificial Intelligence (e.g. OpenAI ChatGPT) was strictly limited to language refinement and structural editing only, and generating empirical data was not used in the substantive arguments or analytical interpretations. Conceptual ideas and analyses remain the responsibility of the author(s).

Disclosure Statement

First author, Amanda Adelina Harun, led the study conceptualisation, drafting of the manuscript, and contributed to the mining law and regulatory analysis. Second author, Vanessa Veronica, contributed to the medical impacts of mercury exposure section and related to the evidence synthesis. The third author, Fenty U Puluhulawa, contributed to the analysis of policy and legal instrument effectiveness in reducing mercury use and mitigating environmental impacts. All authors reviewed and approved the final manuscript.

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