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ILLEGAL GOLD MINING: A SYSTEMATIC LITERATURE REVIEW FROM AN ENVIRONMENTAL POLICY PERSPECTIVE

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ABSTRACT

This systematic literature review analyzes the complexity of illegal gold mining (ASGM) from an environmental policy perspective through a review of 53 selected scientific publications (2000-2025). This review yielded three key findings. First, ASGM is consistently identified as the world's largest source of anthropogenic mercury emissions, accounting for approximately 37% globally, with significant ecological and public health implications. The literature emphasises the persistence of bioaccumulation and biomagnification mechanisms, which increase the risk of long-term exposure to vulnerable communities and critical ecosystems. Second, although Indonesia has adopted various regulatory frameworks—including the Minerba Law, the Environmental Protection and Management Law (PPLH), the National Action Plan for Mercury Reduction and Elimination (RAN PPM), and ratification of the Minamata Convention—studies indicate recurring implementation gaps. Weak law enforcement, structural corruption, overlapping institutional mandates, and limited technical capacity are repeatedly cited as obstacles that undermine policy effectiveness. Third, the persistence of ASGM is rooted in systemic governance deficits where command-and-control strategies are inadequate in addressing the socio-economic realities of communities dependent on mining. The literature indicates that ASGM operates as a subsistence economy, rendering repressive approaches counterproductive without viable alternatives. Overall, these findings underscore the need for a paradigm shift towards inclusive environmental governance that combines targeted formalisation, community-driven economic diversification, and supply chain interventions to disrupt illegal mercury flows. Such an integrative approach offers a more sustainable pathway to reducing environmental risks while supporting community resilience.

Keywords: Illegal Gold Mining, Environmental Policy, Mercury, Systematic Literature Review

INTRODUCTION

Artisanal and Small-Scale Gold Mining (ASGM) is one of the most common mineral extraction activities in developing countries and a major contributor to global mercury emissions. According to the United Nations Environment Programme (UNEP, 2019), the ASGM sector contributes approximately 37% of total global anthropogenic mercury emissions, making it the largest source of mercury pollution in the atmosphere and aquatic environments. Small-scale and artisanal gold mining (ASGM) is the largest source of anthropogenic mercury emissions. Approximately 200 metric tons of elemental mercury are commercialized annually for ASGM purposes; this amount accounts for >30% of the total mercury used in industrial applications (UNEP, 2019; Gallo Corredor et al., 2021; Yoshimura et al., 2021). This practice generally uses mercury to bind gold in the amalgamation process because it is low cost and the technology is simple. Because the gold extraction techniques used in ASGM are still rudimentary, most of the mercury used in ASGM ends up being disseminated into the environment (Gutiérrez-Mosquera, et al., 2021). The uncontrolled use of mercury in ASGM has led to the spread of mercury in local

waters (Casso-Hartmann et al., 2022). Furthermore, due to the recent increase in global gold prices, ASGM is expected to increase (Yoshimura et al., 2021).

Mercury is a pollutant of global concern due to its high potential to form complexes with organic matter found in the environmental matrix. The formation of complexes can lead to the formation of persistent and highly dangerous compounds such as methylmercury. Organic mercury (e.g., ethylmercury and methylmercury) is the most toxic form of heavy metal to human health. Once released into the environment, mercury can accumulate and be magnified throughout the food chain, increasing the risk to terrestrial and aquatic ecosystems (Gallo Corredor et al., 2021; Gutiérrez-Mosquera et al., 2021).

Indonesia is one of the countries with the largest ASGM activities in the world, with thousands of mining sites scattered across various regions such as Kalimantan, Sumatra, Sulawesi, and Papua. Many of them operate without official permits and are known as Unlicensed Gold Mining (PETI). According to (Meutia et al., 2022), more than two thousand active gold mining sites are currently registered in Indonesia, with most still using mercury-based amalgamation methods. Uncontrolled PETI activities have caused serious environmental degradation and created social, economic, and legal dilemmas.

The environmental impact of mercury use in the Artisanal and Small-Scale Gold Mining (ASGM) sector has been widely reported, including water, soil, and sediment contamination, as well as mercury bioaccumulation in the food chain, which poses a risk to human health. A field study in Mount Pongkor, West Java, showed that gold amalgamation activities caused a significant increase in mercury levels, with Hg concentrations in river water reaching 4.49 μg/L and in soil reaching 144 mg/kg dw, exceeding safe environmental thresholds (Agustiani et al., 2025). Similar research occurred in Simpenan, Sukabumi Regency, where small-scale gold mining activities caused an increase in mercury concentrations in sediments and river water to above 3 mg/L, indicating a high ecological risk to aquatic biota (Nuryanty et al., 2024).

In addition to Java, the impact of mercury from ASGM activities has also been found in Riau and South Sumatra. A study in Kebunlado Village, Riau, revealed that small-scale gold mining activities caused significant changes in the physical and chemical properties of post-mining soil and increased mercury levels that exceeded environmental quality thresholds (Amri et al., 2020). Meanwhile, research in North Musi Rawas, South Sumatra, showed that mercury levels in the water and soil around the mining site reached toxicity levels that could endanger the health of the local community (Amallia et al., 2024). The effects of chronic mercury exposure, as described by the World Health Organization (2021), include neurological disorders, cognitive impairment, kidney damage, and teratogenic effects on fetuses. In addition to ecological and health impacts, illegal mining activities also cause social conflicts between local communities, miners, and government officials, often due to weak law enforcement, economic inequality, and limited alternative livelihoods (Meutia et al., 2022).

Regulatory-wise, Indonesia has various legal instruments and policies to control the environmental impact of Artisanal and Small-Scale Gold Mining (ASGM) and illegal gold mining (PETI). The main legal basis for the mining sector is regulated through Law Number 4 of 2009 concerning Mineral and Coal Mining (Minerba Law), which regulates

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sustainable mining governance and prohibits illegal mining practices (Government of the Republic of Indonesia, 2009a). In addition, aspects of environmental protection and management are regulated in Law No. 32 of 2009 concerning Environmental Protection and Management (PPLH Law), which is the legal basis for prevention and law enforcement efforts against mercury pollution (Government of the Republic of Indonesia, 2009b).

As a form of commitment to international agreements, Indonesia has ratified the Minamata Convention on Mercury through Law No. 11 of 2017, which requires state parties to phase out the use of mercury in small-scale gold mining activities (Government of the Republic of Indonesia, 2017). The implementation of this commitment is outlined in Presidential Regulation No. 21 of 2019 concerning the National Action Plan for Mercury Reduction and Elimination (RAN PPM), which sets a target for the total elimination of mercury use in the ASGM sector by 2030 (Regulation of the Republic of Indonesia, 2019).

Furthermore, the Ministry of Environment and Forestry (KLHK) is actively strengthening the monitoring of mercury circulation and use through inter-agency coordination and national programs for mercury control in the energy, manufacturing, and small-scale mining sectors (Ministry of Environment and Forestry, 2024). These measures demonstrate that Indonesia is not only legally committed, but also institutionally committed to achieving sustainable and mercury-free mining management in accordance with the mandate of the Minamata Convention.

However, various studies show that there is an implementation gap between policy and reality in the field. Although the legal and regulatory framework is in place, law enforcement remains weak, inter-agency coordination is not yet optimal, and community involvement in environmental monitoring is still limited (Sinding, 2025; Nurul et al., 2024). In addition, mercury-free alternative technologies have not been fully implemented due to cost factors, lack of technical training, and social resistance among traditional miners (Keane et al., 2023).

Thus, a systematic literature review is needed to identify patterns of mercury use in small-scale gold mining, its ecological and health impacts, and to assess the extent to which public policy and environmental law have been effective in controlling the problem. This review is expected to provide strategic recommendations for the formulation of more sustainable, equitable, and evidence-based policies.

The research gap identified in this review is the limited integration of environmental policy analysis with socio-economic and governance perspectives in explaining why formal regulations repeatedly fail to curb small-scale gold mining (ASGM). The existing literature tends to examine mercury pollution, legal frameworks, or socio-economic drivers in isolation, leaving a gap in policy-oriented holistic synthesis.

The novelty of this review lies in its formulation of an integrated governance model that bridges environmental regulation, community livelihood strategies, and supply chain disruption mechanisms, offering a comprehensive framework for designing more inclusive and effective ASGM mitigation policies.

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MATERIALS AND METHODS

2.1 Research Object

The research object in this study is illegal gold mining in the context of environmental pollution, the impact of mercury uses in the amalgamation process, and the successes and weaknesses of environmental policy. The reasons for choosing illegal gold mining as the research object are:

a. High international relevance
b. Critical to health and ecosystems – mercury has the potential to cause acute and chronic poisoning.
c. The gap between regulation and implementation remains a major problem in environmental management
d. Lack of policy literature synthesis – most research is still technical or laboratory-based.

2.2 Research Question

Research Questions are formulated based on the needs of the selected topic. The following are the research questions in this study:

RQ1. What are the trends in research on illegal gold mining over the past 25 years?
RQ2. How have countries around the world developed in terms of research on illegal gold mining based on the 10 most cited references each year (2000-2025)?
RQ3. How does the literature explain the environmental impact of illegal gold mining activities?
RQ4. How effective are environmental policies and legal instruments in controlling illegal gold mining?

2.3 Search Process

The search process is used to obtain relevant sources to answer the Research Question (RQ) and other related references. The search process was conducted using the Publish or Perish 8 application with the keywords: illegal gold mining, mercury, and environmental policy with a range of 2000-2025 and a search for journal papers on Google Scholar (https://scholar.google.com/).

2.4 Inclusion and Exclusion Criteria

Articles were selected based on predetermined inclusion and exclusion criteria to ensure that each selected study was relevant and supported the research objectives. The selection process included reviewing titles, abstracts, and keywords, as well as examining the suitability of the topics with the research focus on illegal gold mining and environmental policy. To ensure that the review results were relevant and of high quality, the following inclusion and exclusion criteria were applied:

Table 1 Inclusion and Exclusion Criteria

Inclusion	Exclusion
Studies focusing on small-scale gold mining (ASGM) or illegal gold mining (PETI)	Articles not related to ASGM, PETI, or the use of mercury in the context of mining
Studies assessing policy implementation, regulatory	Non-scientific publications (e.g.,

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effectiveness, or mercury control strategies, including the National Action Plan on Mercury Pollution (RAN PPM) and the Minamata Convention	media reports, internal documents without peer review, or opinions).
Articles written in English or Indonesian, published in the last 25 years (2000–2025).	Articles that are more than 25 years old or not in English/Indonesian.

2.5 Quality Assesment

In SLR research, the data found will be evaluated based on the following quality assessment criteria questions:

QA1. Was the journal paper published between 2000 and 2025?

QA2. Does the journal paper mention the country where illegal gold mining took place?

QA3. Does the journal article explicitly discuss illegal gold mining activities?

QA4. Does the journal article describe the policies used to address illegal gold mining?

Each paper will be given a score for each of the above questions.

1. Y (Yes): if the article meets the criteria
2. T (No): if the article does not meet the criteria

2.6 Data Collection

Data collection is an important stage in SLR research to obtain all scientific publications relevant to the topics of illegal gold mining, mercury use, and environmental policy in Indonesia. This stage is carried out through a systematic procedure that ensures that all data sources are accountable, replicable, and meet scientific standards.

Data collection was conducted using Publish or Perish 8 software with the keywords: illegal gold mining and environmental policy, and direct searches via Google Scholar (https://scholar.google.com/). The publication years used were 2000–2025, in line with developments in environmental regulations and the dynamics of illegal mining issues.

1. Open the Publish or Perish 8 application.

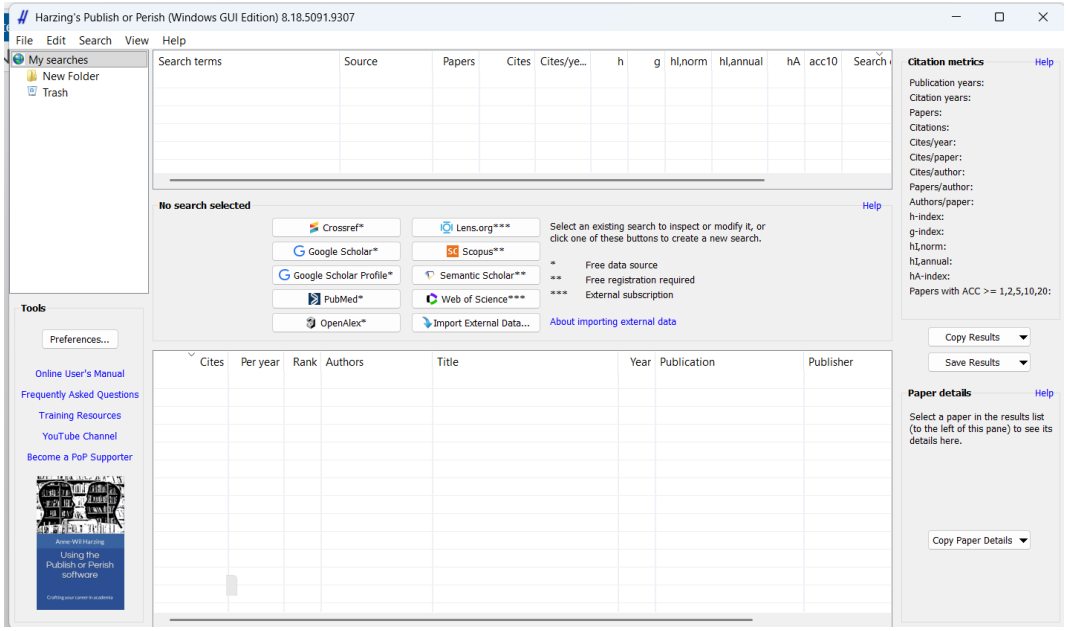

Fig.1 Publish or Perish 8 Application Display

2. Enter the keywords: illegal gold mining and environmental policy in the search form and set the search on Scopus to the range 2000-2025. This step can be seen in Figure 2.

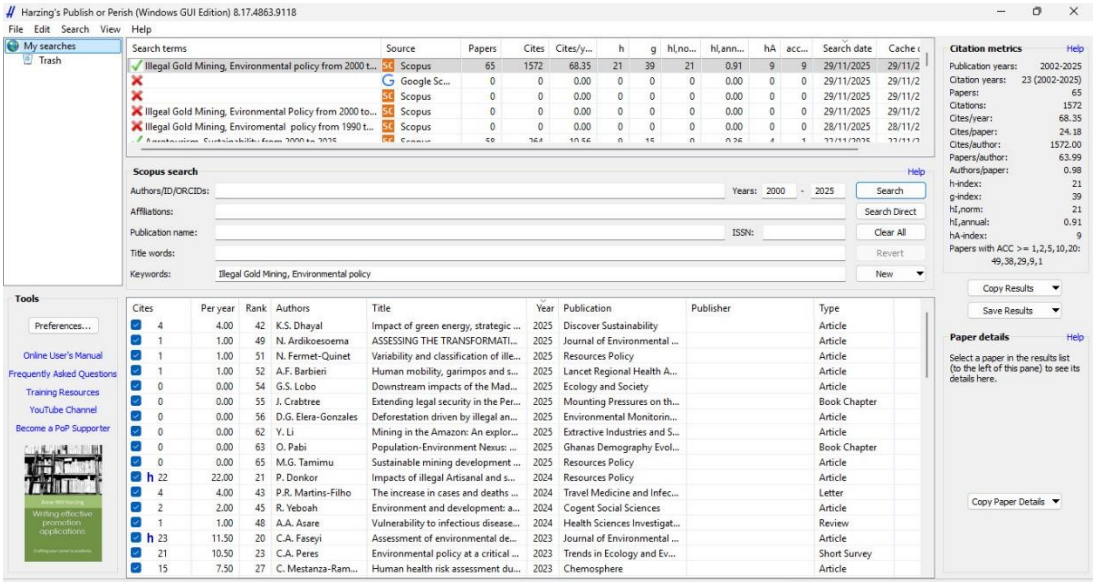

Fig.2 Search Results for Keywords Illegal Gold Mining and Environmental Policy

3. Transfer the data obtained in the application to Excel by reviewing the copy result menu and selecting result for Excel with header, then opening the Excel menu.
4. It will appear in the Excel menu as shown in Figure 3

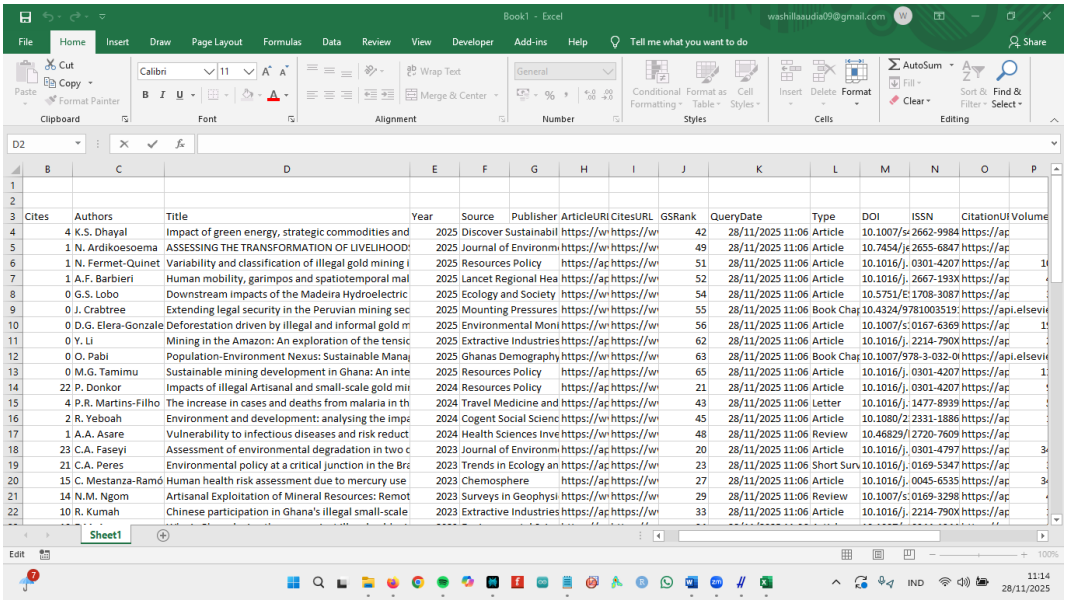

Fig.3 Excel Menu Display

5. Filter Excel by sorting the most citations each year. This step can be seen in Figure 4.

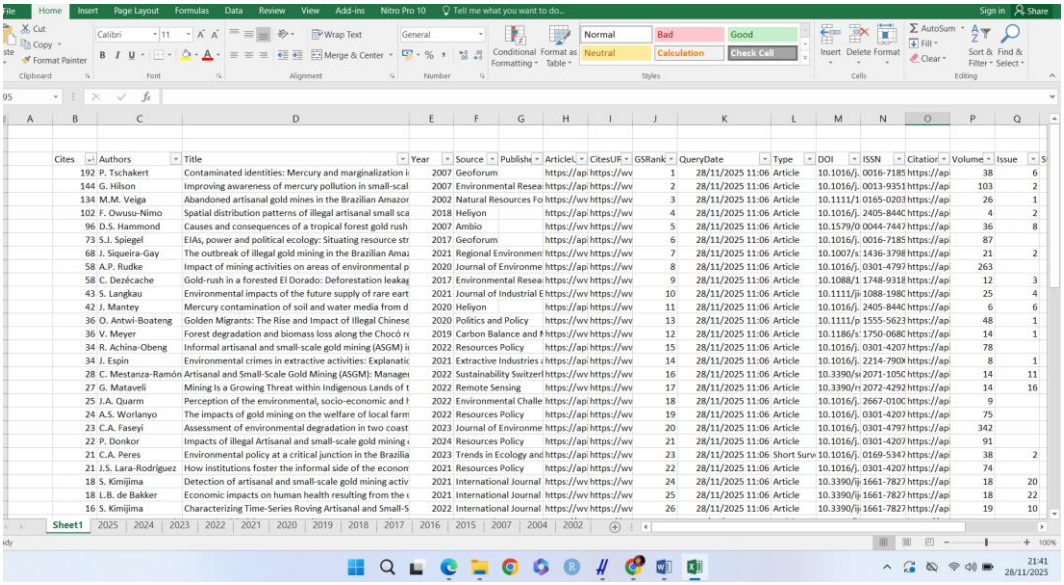

Fig.4 Excel Filter Results Based on Most Citations

6. Collect data annually with the 10 most cited references.

This Systematic Literature Review (SLR) follows the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) 2020 guidelines to ensure transparency and quality reporting.

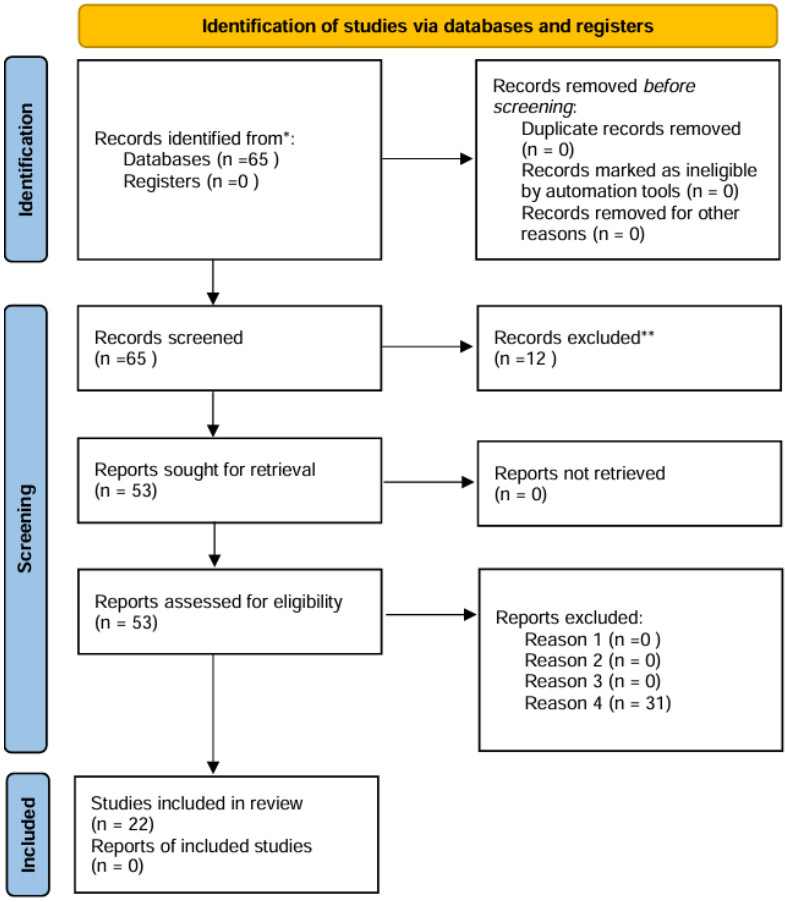

Fig.5 Result of finding articles using PRISMA

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This PRISMA diagram summarises the study selection process in this literature review. Of the 65 records obtained through database searches, 12 records were eliminated at the initial screening stage. All 53 remaining reports were accessed and reviewed for eligibility. At the eligibility stage, 31 reports were excluded because they did not meet the established criteria. Thus, 22 studies were deemed eligible and included in the final analysis. This diagram shows a transparent and systematic selection process in accordance with PRISMA standards.

RESULT

3.1 Search Process Results

Search and process obtained from the Publish or Perish 8 application with keywords: illegal gold mining and environmental policy with a range of 2000-2025 with 65 Scopus-indexed journal articles. The search results in Table 1 are grouped based on the 10 most cited articles in each year to facilitate the analysis of data through the search process.

Table 2 Grouping of Journal Articles Based On The 10 Most Cited Articles Each Year

No	Year	Citation	Title
1	2025	4	Impact of green energy, strategic commodities and economic policy uncertainty towards environmental sustainability for Sub-Saharan Africa
2	2025	1	Assessing The Transformation of Livelihoods in Illegal Gold Mining Communities
3	2025	1	Variability and classification of illegal gold mining in French Guiana for impact-based territorial planning
4	2025	1	Human mobility, garimpos and spatiotemporal malaria transmission in the Yanomami Indigenous Territory: a retrospective observational study
5	2024	22	Impacts of illegal Artisanal and small-scale gold mining on livelihoods in cocoa farming communities: A case of Amansie West District, Ghana
6	2024	4	The increase in cases and deaths from malaria in the Brazilian Yanomami territory is associated with the spread of illegal gold mining in the region: A 20-year ecological study
7	2024	2	Environment and development: analysing the impact of diplomatic relations and governance challenges in countering Chinese Involvement in Illegal gold mining in Ghana
8	2024	1	Vulnerability to infectious diseases and risk reduction measures among galamsey gold mining communities in Ghana: A narrative review
9	2023	23	Assessment of environmental degradation in two coastal communities of Ghana using Driver Pressure State Impact Response (DPSIR) framework
10	2023	21	Environmental policy at a critical junction in the Brazilian Amazon

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No	Year	Citation	Title
11	2023	15	Human health risk assessment due to mercury use in gold mining areas in the Ecuadorian Andean region
12	2023	14	Artisanal Exploitation of Mineral Resources: Remote Sensing Observations of Environmental Consequences, Social and Ethical Aspects
13	2023	10	Chinese participation in Ghana's illegal small-scale gold mining: Linking local pull factors to distributional inequities
14	2023	10	Why is Ghana losing the war against illegal gold mining (Galamsey)? An artificial neural network-based investigations
15	2023	10	Operation mercury: Impacts of national-level armed forces intervention and anticorruption strategy on artisanal gold mining and water quality in the Peruvian Amazon
16	2023	2	Changing the degradation footprint of mining on Indigenous Lands
17	2023	1	Illegal Gold Mining and Sustainable Human Security In Osun State, Nigeria
18	2022	34	Informal artisanal and small-scale gold mining (ASGM) in Ghana: Assessing environmental impacts, reasons for engagement, and mitigation strategies
19	2022	28	Artisanal and Small-Scale Gold Mining (ASGM): Management and Socioenvironmental Impacts in the Northern Amazon of Ecuador
20	2022	27	Mining Is a Growing Threat within Indigenous Lands of the Brazilian Amazon
21	2022	25	Perception of the environmental, socio-economic and health impacts of artisanal gold mining in the Amansie West District, Ghana
22	2022	24	The impacts of gold mining on the welfare of local farmers in Asutifi-North District in Ghana: A quantitative and multi-dimensional approach
23	2022	16	Characterizing Time-Series Roving Artisanal and Small-Scale Gold Mining Activities in Indonesia Using Sentinel-1 Data
24	2022	11	Investigation of Long-Term Roving Artisanal and Small-Scale Gold Mining Activities Using Time-Series Sentinel-1 and Global Surface Water Datasets
25	2022	9	Framing illegal artisanal and small-scale gold mining in the Ghanaian media during the #StopGalamsey campaign
26	2022	1	Actual Problems of Illegal Mining In Peru: Prospects And Challenges
27	2021	68	The outbreak of illegal gold mining in the Brazilian Amazon boosts deforestation
28	2021	43	Environmental impacts of the future supply of rare earths for magnet applications

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No	Year	Citation	Title
29	2021	34	Environmental crimes in extractive activities: Explanations for low enforcement effectiveness in the case of illegal gold mining in Madre de Dios, Peru
30	2021	21	How institutions foster the informal side of the economy: Gold and platinum mining in Chocó, Colombia
31	2021	18	Detection of artisanal and small-scale gold mining activities and their transformation using earth observation, nighttime light, and precipitation data
32	2021	18	Economic impacts on human health resulting from the use of mercury in the illegal gold mining in the brazilian amazon: A methodological assessment
33	2021	7	Legalization of illegal small-scale mining, as a policy of business guarantee and environmental management
34	2020	58	Impact of mining activities on areas of environmental protection in the southwest of the Amazon: A GIS- and remote sensing-based assessment
35	2020	42	Mercury contamination of soil and water media from different illegal artisanal small-scale gold mining operations (galamsey)
36	2020	36	Golden Migrants: The Rise and Impact of Illegal Chinese Small-Scale Mining in Ghana
37	2020	13	The New Eldorado: Organized Crime, Informal Mining, and the Global Scarcity of Metals andMinerals
38	2020	9	Re-imagining environmental governance: Gold dredge mining vs Territorial Health in the Colombian Amazon
39	2020	7	Between Informality and Organized Crime: Criminalization of Small-Scale Mining in the Peruvian Rainforest
40	2020	6	When Gold Speaks, Every Tongue Is Silent: The Thin Line Between Legal, Illegal, and Informal in Peru's Gold Supply Chain
41	2020	3	Establishing a science-policy-society interface for biodiversity conservation and human well-being in the Amazon: The case of Madre de Dios, Peru
42	2019	36	Forest degradation and biomass loss along the Chocó region of Colombia
43	2019	15	Sino-Ghana bilateral relations and Chinese migrants' illegal gold mining in Ghana
44	2018	102	Spatial distribution patterns of illegal artisanal small scale gold mining (Galamsey) operations in Ghana: A focus on the Western Region
45	2017	73	EIAs, power and political ecology: Situating resource struggles and the techno-politics of small-scale mining
46	2017	58	Gold-rush in a forested El Dorado: Deforestation leakages and the need for regional cooperation
47	2017	9	Estimating the "forgone" ESVs for small-scale gold mining using historical image data

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No	Year	Citation	Title
48	2016	11	The new kid on the old block: Coltan, conflict-prone minerals, and post-war reconstruction in Sierra Leone
49	2015	2	Political ecology of the small-scale gold mining in Cagayan de Oro city, Philippines
50	2007	192	Contaminated identities: Mercury and marginalization in Ghana's artisanal mining sector
51	2007	144	Improving awareness of mercury pollution in small-scale gold mining communities: Challenges and ways forward in rural Ghana
52	2007	96	Causes and consequences of a tropical forest gold rush in the Guiana Shield, South America
53	2002	134	Abandoned artisanal gold mines in the Brazilian Amazon: A legacy of mercury pollution

3.2 Selection Results: Inclusion and Exclusion Criteria

The search process yielded 65 journals selected based on the criteria of the 10 most cited articles each year and selected based on the issues (inclusion and exclusion criteria). This process left 53 journal articles after data scanning. Table 2 shows the quality assessment results to indicate whether the data was used in this study or not.

3.3 Quality Assessment Results

Table 3 Quality Assessment

No	Year	Citation	Title	QA1	QA2	QA3	QA4	Result
1	2025	4	Impact of green energy, strategic commodities and economic policy uncertainty towards environmental sustainability for Sub-Saharan Africa	**Y**	**T**	**Y**	**Y**	**X**
2	2025	1	Assessing The Transformation of Livelihoods in Illegal Gold Mining Communities	**Y**	**Y**	**Y**	**T**	**X**
3	2025	1	Variability and classification of illegal gold mining in French Guiana for impact-based territorial planning	**Y**	**Y**	**Y**	**T**	**X**
4	2025	1	Human mobility, garimpos and spatiotemporal malaria transmission in the Yanomami Indigenous Territory: a retrospective observational study	**Y**	**Y**	**Y**	**T**	**X**
5	2024	22	Impacts of illegal Artisanal and small-scale gold mining on livelihoods in cocoa farming communities: A case of Amansie West District, Ghana	**Y**	**Y**	**Y**	**T**	**X**

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No	Year	Citation	Title	QA1	QA2	QA3	QA4	Result
6	2024	4	The increase in cases and deaths from malaria in the Brazilian Yanomami territory is associated with the spread of illegal gold mining in the region: A 20-year ecological study	**Y**	**Y**	**Y**	**T**	**X**
7	2024	2	Environment and development: analysing the impact of diplomatic relations and governance challenges in countering Chinese Involvement in Illegal gold mining in Ghana	**Y**	**Y**	**Y**	**Y**	✓
8	2024	1	Vulnerability to infectious diseases and risk reduction measures among galamsey gold mining communities in Ghana: A narrative review	**Y**	**Y**	**Y**	**T**	**X**
9	2023	23	Assessment of environmental degradation in two coastal communities of Ghana using Driver Pressure State Impact Response (DPSIR) framework	**Y**	**T**	**Y**	**Y**	**X**
10	2023	21	Environmental policy at a critical junction in the Brazilian Amazon	**Y**	**T**	**Y**	**Y**	**X**
11	2023	15	Human health risk assessment due to mercury use in gold mining areas in the Ecuadorian Andean region	**Y**	**Y**	**Y**	**T**	**X**
12	2023	14	Artisanal Exploitation of Mineral Resources: Remote Sensing Observations of Environmental Consequences, Social and Ethical Aspects	**Y**	**T**	**Y**	**T**	**X**
13	2023	10	Chinese participation in Ghana's illegal small-scale gold mining: Linking local pull factors to distributional inequities	**Y**	**Y**	**Y**	**Y**	✓
14	2023	10	Why is Ghana losing the war against illegal gold mining (Galamsey)? An artificial neural network-based investigations	**Y**	**Y**	**Y**	**Y**	✓
15	2023	10	Operation mercury: Impacts of national-level armed forces intervention and anticorruption strategy on artisanal gold mining and water quality in the Peruvian Amazon	**Y**	**Y**	**Y**	**Y**	✓
16	2023	2	Changing the degradation footprint of mining on Indigenous Lands	**Y**	**T**	**Y**	**T**	**X**

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No	Year	Citation	Title	QA1	QA2	QA3	QA4	Result
17	2023	1	Illegal Gold Mining and Sustainable Human Security In Osun State, Nigeria	Y	Y	Y	Y	✓
18	2022	34	Informal artisanal and small-scale gold mining (ASGM) in Ghana: Assessing environmental impacts, reasons for engagement, and mitigation strategies	Y	Y	Y	Y	✓
19	2022	28	Artisanal and Small-Scale Gold Mining (ASGM): Management and Socioenvironmental Impacts in the Northern Amazon of Ecuador	Y	Y	Y	Y	✓
20	2022	27	Mining Is a Growing Threat within Indigenous Lands of the Brazilian Amazon	Y	Y	Y	T	X
21	2022	25	Perception of the environmental, socio-economic and health impacts of artisanal gold mining in the Amansie West District, Ghana	Y	Y	Y	T	X
22	2022	24	The impacts of gold mining on the welfare of local farmers in Asutifi-North District in Ghana: A quantitative and multi-dimensional approach	Y	Y	Y	T	X
23	2022	16	Characterizing Time-Series Roving Artisanal and Small-Scale Gold Mining Activities in Indonesia Using Sentinel-1 Data	Y	Y	Y	T	X
24	2022	11	Investigation of Long-Term Roving Artisanal and Small-Scale Gold Mining Activities Using Time-Series Sentinel-1 and Global Surface Water Datasets	Y	Y	Y	T	X
25	2022	9	Framing illegal artisanal and small-scale gold mining in the Ghanaian media during the #StopGalamsey campaign	Y	Y	T	Y	X
26	2022	1	Actual Problems of Illegal Mining In Peru: Prospects And Challenges	Y	Y	Y	Y	✓
27	2021	68	The outbreak of illegal gold mining in the Brazilian Amazon boosts deforestation	Y	Y	Y	T	X
28	2021	43	Environmental impacts of the future supply of rare earths for magnet applications	Y	T	Y	T	X

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No	Year	Citation	Title	QA1	QA2	QA3	QA4	Result
29	2021	34	Environmental crimes in extractive activities: Explanations for low enforcement effectiveness in the case of illegal gold mining in Madre de Dios, Peru	**Y**	**Y**	**Y**	**Y**	✓
30	2021	21	How institutions foster the informal side of the economy: Gold and platinum mining in Chocó, Colombia	**Y**	**Y**	**T**	**Y**	**X**
31	2021	18	Detection of artisanal and small-scale gold mining activities and their transformation using earth observation, nighttime light, and precipitation data	**Y**	**Y**	**Y**	**T**	**X**
32	2021	18	Economic impacts on human health resulting from the use of mercury in the illegal gold mining in the brazilian amazon: A methodological assessment	**Y**	**Y**	**Y**	**T**	**X**
33	2021	7	Legalization of illegal small-scale mining, as a policy of business guarantee and environmental management	**Y**	**Y**	**Y**	**Y**	✓
34	2020	58	Impact of mining activities on areas of environmental protection in the southwest of the Amazon: A GIS- and remote sensing-based assessment	**Y**	**T**	**Y**	**Y**	**X**
35	2020	42	Mercury contamination of soil and water media from different illegal artisanal small-scale gold mining operations (galamsey)	**Y**	**Y**	**Y**	**T**	**X**
36	2020	36	Golden Migrants: The Rise and Impact of Illegal Chinese Small-Scale Mining in Ghana	**Y**	**Y**	**Y**	**Y**	✓
37	2020	13	The New Eldorado: Organized Crime, Informal Mining, and the Global Scarcity of Metals andMinerals	**Y**	**Y**	**T**	**Y**	**X**
38	2020	9	Re-imagining environmental governance: Gold dredge mining vs Territorial Health in the Colombian Amazon	**Y**	**Y**	**Y**	**Y**	✓
39	2020	7	Between Informality and Organized Crime: Criminalization of Small-Scale Mining in the Peruvian Rainforest	**Y**	**Y**	**Y**	**Y**	✓

No	Year	Citation	Title	QA1	QA2	QA3	QA4	Result
40	2020	6	When Gold Speaks, Every Tongue Is Silent: The Thin Line Between Legal, Illegal, and Informal in Peru's Gold Supply Chain	**Y**	**Y**	**Y**	**Y**	✓
41	2020	3	Establishing a science-policy-society interface for biodiversity conservation and human well-being in the Amazon: The case of Madre de Dios, Peru	**Y**	**T**	**Y**	**Y**	**X**
42	2019	36	Forest degradation and biomass loss along the Chocó region of Colombia	**Y**	**T**	**Y**	**T**	**X**
43	2019	15	Sino-Ghana bilateral relations and Chinese migrants' illegal gold mining in Ghana	**Y**	**Y**	**Y**	**Y**	✓
44	2018	102	Spatial distribution patterns of illegal artisanal small scale gold mining (Galamsey) operations in Ghana: A focus on the Western Region	**Y**	**Y**	**Y**	**T**	**X**
45	2017	73	EIAs, power and political ecology: Situating resource struggles and the techno-politics of small-scale mining	**Y**	**Y**	**Y**	**Y**	✓
46	2017	58	Gold-rush in a forested El Dorado: Deforestation leakages and the need for regional cooperation	**Y**	**Y**	**Y**	**T**	**X**
47	2017	9	Estimating the "forgone" ESVs for small-scale gold mining using historical image data	**Y**	**Y**	**Y**	**T**	**X**
48	2016	11	The new kid on the old block: Coltan, conflict-prone minerals, and post-war reconstruction in Sierra Leone	**Y**	**T**	**Y**	**T**	**X**
49	2015	2	Political ecology of the small-scale gold mining in Cagayan de Oro city, Philippines	**Y**	**Y**	**Y**	**Y**	✓
50	2007	192	Contaminated identities: Mercury and marginalization in Ghana's artisanal mining sector	**T**	**Y**	**Y**	**T**	**X**
51	2007	144	Improving awareness of mercury pollution in small-scale gold mining communities: Challenges and ways forward in rural Ghana	**T**	**Y**	**Y**	**T**	**X**
52	2007	96	Causes and consequences of a tropical forest gold rush in the Guiana Shield, South America	**T**	**Y**	**Y**	**T**	**X**

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No	Year	Citation	Title	QA1	QA2	QA3	QA4	Result
53	2002	134	Abandoned artisanal gold mines in the Brazilian Amazon: A legacy of mercury pollution	T	Y	Y	T	X

Symbol Explanation:
✓: for journals or data used in the research. the data was selected because it discusses illegal gold mining, environmental and state policies written in journal papers between 2000 and 2025 and provides sufficient information for data selection.
X: for journals or data not used in the research because the data does not provide sufficient information for data selection.

3.4 Data Analysis

This stage answers questions from the research question (RQ) and discusses the results of research developments on illegal gold mining, environmental policies, and countries conducting research, which are produced in research from the 10 most cited articles each year from 2000 to 2025 in international journals.

DISCUSSION

RQ1. What are the trends in research on illegal gold mining around the world over the past 25 years?

Early 2000s research was dominated by field-based, site-level studies documenting mercury contamination and its health/ecosystem impacts in hotspots (Amazon, Ghana, Guianas). Over time the literature broadened from toxicology and geochemistry into social, economic, governance and biodiversity dimensions.

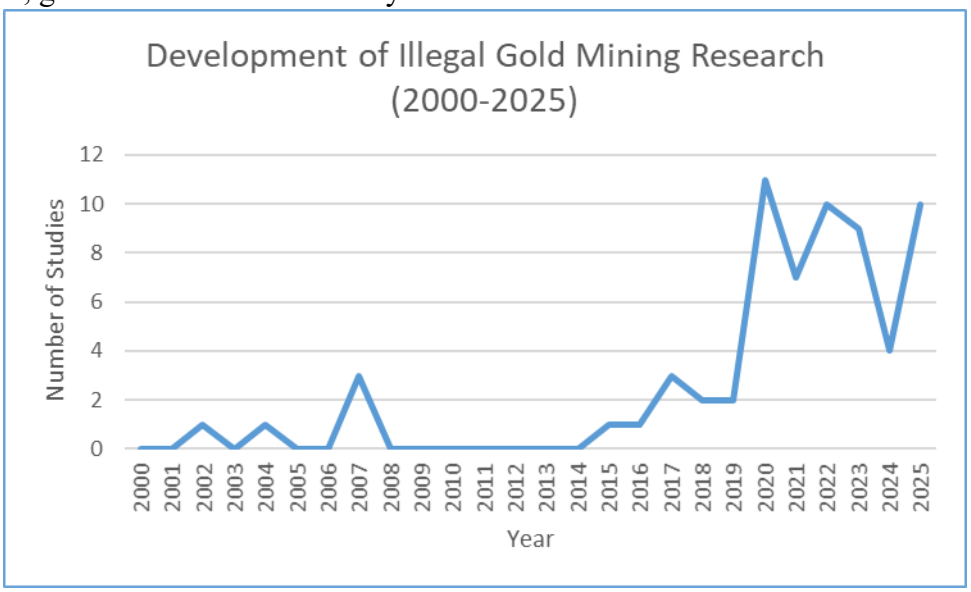

Fig.5 Graph of Illegal Gold Mining Research Development From 2000 to 2025

The graph showing the distribution of articles per year indicates a significant increase in research on illegal gold mining, mercury, and environmental issues over the past two decades, with the sharpest increase occurring between 2018 and 2025. At the

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beginning of the period from 2002 to 2007, the number of articles published was still small and focused only on mercury pollution and local environmental impacts. From 2015 to 2018, research began to increase due to global attention to political ecology and the use of spatial technology to map illegal gold mining activities. The research trend peaked between 2021 and 2025, driven by growing concerns about deforestation in the Amazon, mercury pollution, health risks, crime in mining, and the need for improved policy and governance. This increase shows that the issue of illegal gold mining has become a major focus in global environmental research and is driving the development of multidisciplinary research approaches.

RQ2. How have countries around the world progressed in research on illegal gold mining based on the 10 most cited studies each year (2000-2025)?

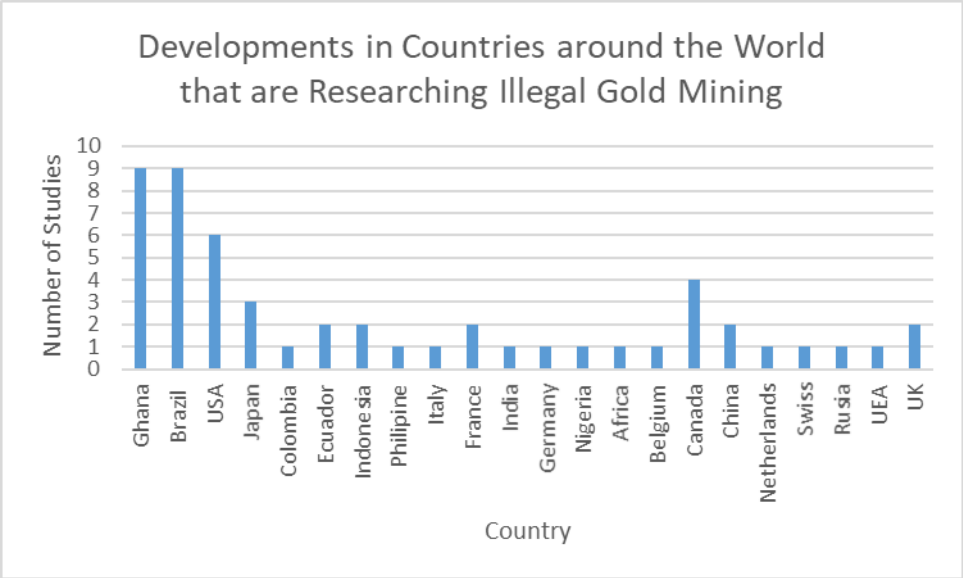

Fig.6 Global Developments in Illegal Gold Mining Research

The distribution of publications shows that Ghana and Brazil rank first as the countries that have conducted the most research on this issue, with nine studies each. They are followed by the United States, which has six studies, as a country that is active in producing scientific knowledge. The dominance of Ghana and Brazil is due to two main factors: first, the existence of very intense small-scale gold mining activities in both countries, which has driven the need to study its impact on the environment, society, and health; second, the existence of strong academic capabilities and research networks in the fields of environment and mining. The United States, despite not being a center of illegal gold mining activity, still contributes significantly due to the strength of its research institutions in the fields of toxicology, geochemistry, and monitoring methods. Countries such as Canada, Japan, France, China, and the United Kingdom produced fewer studies but still made important contributions through sophisticated analytical approaches and comprehensive regulatory frameworks. Overall, this pattern shows that countries with close ties to the issue, strong research capacity, and global academic interest tend to produce more research on this topic.

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RQ3: Comprehensive Analysis of the Environmental Impact of Small-Scale, Traditional, and Artisanal Gold Mining (ASGM) Activities in a Literature Review

A systematic literature review reveals that the environmental impact of ASGM is not a simple phenomenon, but rather a complex syndrome that encompasses ecological, health, and socio-economic dimensions. At the heart of this problem lies the use of mercury (Hg) in the extraction process, which triggers a chain of non-linear and protracted impacts. This analysis will describe this complexity through a multidisciplinary approach.

1. Mercury Pollution Pathways and Mechanisms: From Air Emissions to Cellular Poisoning

a. Air pollution: Mercury evaporates and is released into the atmosphere at high temperatures. In traditional gold extraction processes (such as amalgamation techniques), gold and mercury are separated through heating, causing significant mercury volatilization into the air. This forms a source of pollution in regional and even global atmospheric circulation. Research shows that Artisanal and Small-Scale Gold Mining (ASGM), including PETI, contributes 37% of global mercury emissions, making it a major anthropogenic source of mercury (Trench et al., 2024)(Wei Chen et al., 2018).

b. Water Contamination: Mercury is easily soluble in water and binds to sediments, settling at the bottom of rivers or lakes and threatening the health of aquatic ecosystems. For example, in some regions of Indonesia and Brazil, mercury concentrations in river water exceed permissible standards, seriously impacting aquatic life.

c. Bioaccumulation and Biomagnification: Amplification of Hazards in the Food Chain

This concept is key to understanding why low concentrations in water can lead to severe poisoning in humans.

Bioaccumulation: Low-level aquatic organisms (such as plankton and algae) absorb methylmercury from the water. This compound accumulates in their body tissues because the rate of absorption is higher than the rate of excretion.

Biomagnification: At each trophic level in the food chain (e.g., from plankton → herbivorous fish → carnivorous fish → humans), the concentration of methylmercury increases exponentially. Large predatory fish (such as sharks, tuna, or stingrays in freshwater ecosystems) can have methylmercury concentrations hundreds of thousands to millions of times higher than the surrounding water. This explains why communities that consume fish from polluted rivers, even those far from mining sites, remain at high risk.

2. Multidimensional Impacts: Ecosystem Degradation and Public Health Crises

Aquatic and Terrestrial Ecosystem Degradation: Studies in large gold mining areas such as Java, Sumatra, Kalimantan, and Papua have documented significant ecological damage. For example, ecological research in the Simpenan area shows that mercury compounds cause a decline in fish spawning capacity and a drastic reduction in biodiversity.

Public health hazards: Prolonged exposure to mercury can cause neurological and kidney disorders, increase the risk of cancer, ovarian abnormalities, or fetal malformations

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(Mestanza-ram et al., 2021). The impacts are cumulative and synergistic, creating a vicious cycle of degradation.

a. Irreversible Ecosystem Degradation. Ecological damage goes beyond chemical pollution. ASGM activities often involve deforestation, land clearing, and massive river sedimentation. This causes, Hydrological Changes (River siltation alters flow patterns, increases the risk of flooding, and damages aquatic habitats); Biodiversity Loss (In addition to declining fish populations due to mercury toxicity e.g., reproductive failure, nervous system damage, the loss of terrestrial habitat also drives local extinctions of flora and fauna). Studies in Simpenan and other areas show a shift in biological communities from sensitive species to pollution-tolerant species, signaling an overall decline in ecosystem health.

b. Public Health Crisis and Environmental Justice. Human exposure to methylmercury is a serious public health threat, with the most severe impacts on vulnerable groups, Neurotoxicity (Methylmercury easily crosses the blood-brain barrier and placenta. In fetuses and children, this causes permanent brain damage, characterized by decreased Intelligence Quotient (IQ), memory impairment, and cognitive delays); Teratogenic Effects (Exposure in pregnant women can cause cerebral palsy, microcephaly, and other congenital abnormalities); Systemic Toxicity (In adults, chronic exposure is associated with kidney, cardiovascular, and immune system disorders). Of particular note is environmental injustice. Often, local communities that are not directly involved in ASGM but depend on rivers for water and protein bear the heaviest health burden.

3. Global Perspective and Socio-Economic Traps

Countries with active ASGM operations globally (e.g., Indonesia, Ghana, Brazil) consistently show that illegal gold mining not only causes substantial ecological impacts, but is also accompanied by significant socio-economic inequality and conflict. This imbalance exacerbates local communities' neglect of resource and environmental protection issues (Mestanza-ram et al., 2021; Xing Zhou et al., 2024). Cases in Indonesia, Ghana, Brazil, and other countries show a consistent pattern: PETI is a symptom of deeper structural problems.

a. Subsistence Economy and the Poverty Cycle: For many miners, PETI is the only affordable source of livelihood in conditions of economic hardship. This creates an “environmental-poverty paradox”: environmentally destructive activities are driven by the need to escape poverty, but ultimately worsen long-term conditions by poisoning the resources on which they depend (land and water).

b. Conflict and Weak Governance: PETI operations often intersect with jurisdictional overlaps, corruption, and weak law enforcement. This fuels agrarian conflicts, resource grabs, and in some cases, links to organized crime. The state's inability to provide viable economic alternatives and consistently enforce the law reinforces this cycle.

c. Complexity in Solutions: A total ban without alternative solutions often fails because it ignores the root economic problems. A more holistic approach is needed, such as formalizing the PETI sector, introducing mercury-free gold extraction technologies (e.g.,

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closed-loop cyanide or gravity techniques), and sustainable alternative economic development programs.

The environmental impact of ASGM is an interconnected systemic phenomenon. The chain of impacts begins with the choice of primitive technology (amalgamation), which triggers a series of biogeochemical reactions (methylation, biomagnification), ultimately leading to an ecological and public health crisis. This problem is exacerbated and perpetuated by poor socio-economic conditions and weak governance. Therefore, effective solutions must be multi-sectoral, integrating technical, regulatory, economic, and social approaches simultaneously to break this complex chain.

RQ4: Comprehensive Analysis of the Effectiveness of Environmental Regulations in Controlling Illegal Gold Mining (ASGM): Between Normative Commitment and Governance Reality

A systematic literature review reveals a paradox: although the legal and policy framework for controlling ASGM has developed rapidly at the national and international levels, its effectiveness in practice is very limited. This analysis argues that the root cause of this ineffectiveness is not the absence of regulations, but rather a structural disjunction between policy design and implementation capacity within a complex governance system. In other words, the main problem is a governance deficit.

a. Regulatory Framework: A Solid Structure Built on Shaky Foundations

The Mining and Coal Law (Minerba Law) aims to regulate mining activities in a sustainable manner, with an emphasis on licensing procedures and legal responsibility (Rohman & Rustamaji, 2024). The Environmental Protection and Management Law (PPLH Law) provides a regulatory basis for preventing and addressing environmental pollution, including mercury-related hazards (Mestanza-ram et al., 2021).

The phased mercury reduction plan based on Presidential Regulation No. 21 requires the phased elimination of mercury use in the small-scale and traditional gold mining (ASGM) sector by 2030. The existing policy framework, when viewed in writing, appears comprehensive and progressive.

1. National Level: Ambitious but Fragmented Regulations

The Minerba Law and the PPLH Law do indeed form a legal basis. However, there is often overlapping jurisdiction and inconsistency in interpretation between these two laws. The Minerba Law, which is oriented towards resource exploitation, often conflicts with the conservation principles in the PPLH Law at the field level. Presidential Regulation (UU) No. 21/2019 on the RAN PPM is a strategic step forward, as it adopts a phase-out approach. However, this approach assumes strong monitoring and law enforcement capacities, as well as the availability of viable alternative technologies—assumptions that are often not met. Planning documents often remain aspirational policies without clear implementation roadmaps and adequate funding at the local level.

2. International Level: The Dilemma of Sovereignty vs. Compliance

The ratification of the Minamata Convention through Law No. 11/2017 is a strong political signal. However, the implementation of international agreements faces the challenge of translation into domestic law. Compliance with the convention requires the

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harmonization of regional regulations, the allocation of a special budget, and a robust reporting system—all of which are weak points in Indonesia's governance. The Minamata Convention itself recognizes the complexity of the ASGM/PETI sector by providing space for “national action plans,” but this can be a double-edged sword: on the one hand, it provides flexibility, but on the other, it opens the door to delays in effective implementation (regulatory delay).

b. Implementation Challenges: The Anatomy of Governance Failure
This is where good policy intentions collide with harsh and complex realities.
1. Weak Law Enforcement: A Symptom of a Deeper Disease

Limitations in law enforcement are not just a matter of personnel numbers, but a reflection of more systemic problems: Patronage and Local Corruption (Medium to large-scale gold mining activities are often protected by political-bureaucratic-business networks at the local level. This symbiotic relationship creates a “high-cost economy of uncertainty,” where law enforcement can be “softened” or policies deliberately left ambiguous to benefit certain parties) and Information Asymmetry and Monitoring (The central government is often blind to the dynamics on the ground. The lack of real-time data on the location of gold mines, production volumes, and mercury trading makes intervention ineffective. Meanwhile, illegal miners are highly agile and adaptable).
2. Socio-Technocratic Barriers: Bridging the Technical and Economic Gap

Technology Transfer Failure: The introduction of hydrometallurgical leaching or mercury-free gravity concentration techniques often fails due to its top-down and technocratic approach. Miners, who operate with a subsistence economic logic, are very rational in rejecting technologies that are capital intensive, complex to maintain, and have a steep learning curve. They need technologies that are appropriate, affordable, and accessible.

The Political Economy of Livelihoods: Prohibition without alternative solutions is a recipe for conflict. For many communities, illegal gold mining is a “buffer economy” amid the failure of the formal sector to create jobs. Repressive policies that close mines without comprehensive economic transition programs will only shift the problem, not solve it, and potentially trigger social unrest.

c. Trace Success: Going Beyond the Command-and-Control Approach
The literature shows that the silver lining actually comes from innovative and participatory approaches that recognize the multidimensional roots of the illegal gold mining problem.
1. Community Engagement Model: From Subject to Object to Partner Success in Brazil and Ghana, as well as several pilot projects in Indonesia, demonstrate the effectiveness of the co-management approach. In this model, the government acts not as an enforcer, but as a facilitator. The program includes: Economic Empowerment (Introducing economically competitive alternative livelihoods (such as high-value agriculture, ecotourism, or local creative industries) that are integrated with the market) and Guided Formalization (Bringing illegal gold mining out of the shadows of illegality into the semi-formal or

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formal zone by providing limited permits, technical guidance, and access to financing and fair markets. This creates economic incentives for compliance).

2. Supply-Chain Approach

Rather than focusing solely on scattered miners, breaking the mercury supply chain is a more effective strategy. International cooperation to control illegal mercury production and trade, combined with law enforcement at entry points (ports) and distributors, can significantly increase the cost and difficulty of obtaining mercury. This approach utilizes leverage points in a more centralized system.

The effectiveness of laws and policies in controlling illegal gold mining cannot be measured solely by their completeness on paper. The massive implementation gap is evidence of the failure of the conventional "command-and-control" regulatory approach in addressing the socio-economic-ecological complexity of ASGM.

A sustainable solution requires a paradigm shift from simply "eradicating ASGM" to inclusive and adaptive governance of the small-scale mining sector. This requires:

1. Policy Integration: Synchronizing policies on mining, the environment, labor, and economic empowerment.
2. Local Capacity Building: Strengthening the capacity of local governments and community organizations in monitoring, conflict mediation, and alternative economic development.
3. Hybrid Policy Innovation: Combining economic incentives, participatory approaches, and smart law enforcement focused on major actors in the supply chain.

Ultimately, controlling illegal mining is not merely a legal issue, but a governance challenge that requires a collaborative, flexible, and socially just approach.

CONCLUSION

This systematic literature review reveals the multidimensional complexity of illegal gold mining, which creates a paradox between systematic environmental damage and policy governance failures. Research on this topic has seen an increase in publications since 2020, with most researchers coming from Graha and Brazil. Ecologically, ASGM has become a major contributor to the global mercury pollution crisis—accounting for 37% of anthropogenic emissions—which then metamorphoses into highly toxic methylmercury, triggering a destructive chain through bioaccumulation and biomagnification in aquatic ecosystems that ends in neurological, renal, and fetal development disorders in local communities. Ironically, even though Indonesia has developed a comprehensive regulatory framework, such as the Minerba Law, the PPLH Law, and the RAN PPM, which are supported by international commitments through the Minamata Convention, the effectiveness of these policies is hampered by an implementation gap caused by weak law enforcement, structural corruption, suboptimal inter-agency coordination, and the lack of feasible technological and economic alternatives for the community. The root of the problem lies in governance deficits, where a repressive "command-and-control" approach fails to address the sociological reality of ASGM as a buffer economy for marginalized

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communities. Therefore, a sustainable solution requires a paradigm shift towards inclusive governance that integrates guided formalization, alternative economic empowerment, and a supply-chain approach to disrupt the distribution of illegal mercury.

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