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Effectiveness of conventional and emerging methods for the physicochemical reactivation of passivated mercury in artisanal and small-scale gold mining: A systematic review with a technical and environmental focus

Miguel Barreda-De-La-Cruz^{1†}, Antonio Linares-Flores-Castro¹, Omar Paredes-Salas ¹ and Javier Montesinos-Chavez¹

¹ Catholic University of Santa María, Urb. San José s/n, Umacollo, Arequipa, Perú

alinaresf@ucsm.edu.pe , oparedess@ucsm.edu.pe , jmontesinos@ucsm.edu.pe

† Corresponding author: Miguel Barreda-De-La-Cruz, mbarreda@ucsm.edu.pe

Abstract

This systematic review (PRISMA 2020) evaluates the effectiveness of conventional and emerging physicochemical methods for reactivating passivated mercury within the Artisanal and Small-scale Gold Mining (ASGM) sector. Mercury 'flouring' or passivation remains a critical technical and environmental hurdle, as it renders mercury incapable of coalescence, leading to significant gold losses and widespread contamination. By analyzing 43 specialized sources (2011–2026), we found that traditional mechanical methods are severely limited, achieving only 30–50% recovery because they fail to disrupt insulating surface films. In contrast, emerging technologies—particularly selective electroreduction—restore metal coalescence to levels exceeding 90%, with an average gold capture efficiency of 76.9% ($p < 0.01$). Our analysis identifies a moderate inverse association ($\rho = -0.50$) between technical efficiency and operational portability. We conclude that while these innovations align with circular economy frameworks, they should be prioritized as tools for environmental remediation and mercury sequestration rather than for perpetuating its use, focusing on capturing 'lost' mercury before it enters the ecosystem.

Keywords: Artisanal and small-scale gold mining; Mercury reactivation; Selective electroreduction; Passivated mercury; Circular economy

1. INTRODUCTION

Artisanal and Small-scale Gold Mining (ASGM) represents a profound socioeconomic paradox: while it provides a vital lifeline for millions of people across Africa, Asia, and Latin America, it simultaneously acts as the primary driver of the global mercury (Hg) crisis. Current estimates suggest this sector accounts for 37% of total global atmospheric mercury emissions, triggering devastating consequences for highly vulnerable ecosystems (Tampushi et al., 2022; Bruno et al., 2023; Mohamed et al., 2025; Anene et al., 2026); Haga clic o pulse aquí para escribir texto.. Although the Minamata Convention has intensified efforts to phase out mercury use, its practical implementation remains a daunting challenge in many mining jurisdictions. The severity of the issue extends far beyond the extraction points; speciation studies in the Southern Hemisphere confirm that these emissions are rapidly assimilated into global atmospheric cycles, fundamentally altering environmental chemistry even in the most isolated regions (Bieser et al. 2020). The tenacity of mercury-based amalgamation is not merely a technological hurdle but a result of a complex interplay between low operational costs and the scarcity of accessible, field-ready alternatives for artisanal operators (Alfonso et al. 2019; El Hadi et al. 2026).

The technical failure of traditional amalgamation is stark, with gold recovery rates often stagnating between a mere 30% and 50% (Veiga and Gunson 2020; Manzila et al. 2022). A fundamental cause of this inefficiency is surface passivation—a phenomenon colloquially known in mining operations as "flouring" or "sick mercury." This process transcends simple mechanical wear; it involves a complex physicochemical transformation where the mercury loses its ability to coalesce due to the development of insulating oxide or sulfide films on its surface. Consequently, the mercury fragments into microscopic droplets that persist as a diffuse pollutant within the tailing matrix (Rachman et al. 2018; Anene et al. 2026). This is further complicated by morphological challenges: fine gold particles are often deformed into toroidal or 'doughnut' shapes that entrap air. This physical deformation prevents the gold from breaking the surface tension of the mercury, drastically reducing the likelihood of effective contact during the process (Palmer and Craw 2024).

The environmental legacy of this "lost" mercury is both enduring and hazardous. Once sequestered in sediments, Hg can undergo methylation into methylmercury (MeHg), a potent neurotoxin that bioaccumulates and biomagnifies through aquatic food webs, eventually reaching concentrations that pose severe risks to human health (Abbas et al. 2017; Raoilimanantsoa et al. 2026). At the landscape level, the physical scarring is profound. In alluvial mining regions, the massive displacement of topsoil and the redirection of natural watercourses create disturbed 'lunar' landscapes characterized by barren craters and stagnant siltation ponds. These geomorphological alterations cause permanent habitat loss and soil instability. In Latin America, these shifts drive severe land-clearing rates that encroach upon protected ecological corridors, fundamentally altering the connectivity of regional biodiversity hotspots rather than following typical patterns of human settlement growth (Higgins et al., 2020; Barakati et al., 2023).

In response to these interconnected crises, metallurgical engineering has pivoted toward two main strategies: conventional approaches utilizing aggressive chemical reagents and redistillation (Alfonso et al. 2019), and the emergence of "green" technologies—such as electrochemical and bioleaching systems—designed to reactivate passivated mercury through sustainable pathways (Acosta et al. 2021; Hammer et al. 2023). Nevertheless, a

significant void remains in the current literature regarding a systematic comparative analysis that simultaneously benchmarks technical recovery, environmental viability, and operational feasibility in the field.

Accordingly, the objective of this systematic review is to critically evaluate the performance of conventional methods against emerging physicochemical innovations for the reactivation of passivated mercury. This study aims to identify the techniques with the highest potential to restore amalgamation efficiency, enhance ecological sustainability, and facilitate practical adoption in ASGM settings, consistent with circular economy principles and the mitigation of ecotoxicological risks.

2. BACKGROUND RESEARCH

2.1. The Physicochemical Nature of Mercury Passivation

The phenomenon of mercury passivation, colloquially known in Artisanal and Small-scale Gold Mining (ASGM) as "flouring" or "sick mercury," is a complex physicochemical degradation process. Unlike simple mechanical fragmentation, passivation involves the formation of a stabilized microscopic film—typically composed of oxides, sulfides, or organic contaminants—around the mercury droplets (Anene et al. 2026; Palmer and Craw 2024). This film acts as a dielectric barrier that inhibits the surface tension and the natural tendency of mercury to coalesce. From a metallurgical perspective, this reduces the chemical activity of the mercury, preventing it from forming the gold-mercury alloy necessary for recovery, often limiting gold capture to rates between 30% and 50% (Veiga and Gunson 2020; Manzila et al. 2022). Current literature suggests that this process is accelerated in ores containing high concentrations of sulfides, such as pyrite or arsenopyrite, which react with the liquid metal to create passivating layers of HgS (Alfonso et al. 2019; Seney et al. 2020).

2.2. Evolution of Reactivation Strategies: From Aggressive to Green Chemistry

Historically, the reactivation of "sick mercury" has relied on aggressive chemical interventions. The use of strong acids or cyanide-based leaching has been the standard in many mining jurisdictions to "clean" the mercury surface (Alfonso et al. 2019). However, these methods present a dual risk: they generate highly toxic effluents and often lead to the formation of soluble mercury complexes that are more mobile and bioavailable in the environment (Seney et al. 2020; Tami-Pimiento et al. 2024). In recent years, research has pivoted toward "green" innovations. Electrochemical methods, particularly selective electroreduction, have emerged as a prominent alternative. These techniques utilize controlled electrical potentials to physically dismantle the passivating oxide layers without the need for hazardous reagents (Roth et al. 2023; Tami-Pimiento et al. 2024). Despite their laboratory success, a significant gap remains in understanding how these emerging technologies can be scaled to facilitate the final recovery and permanent removal of mercury compared to traditional mechanical and chemical methods in real-world ASGM field conditions (Leiva 2022).

Within this context, the concept of a circular economy must be reframed as a model for toxic waste management rather than production. Instead of promoting continued use, the reactivation of passivated mercury enables its complete capture and subsequent sequestration, preventing the discharge of 'lost' or 'floured' mercury into tailings. This approach is a critical remediation strategy: by restoring the coalescence of legacy mercury, these technologies allow for its total withdrawal from the gold processing cycle and its safe stabilization, effectively preventing its methylation into methylmercury (MeHg) (Abbas et al. 2017; Raoilimanantsoa et al. 2026).

2.3. The Minamata Convention and the Circular Economy Framework

The global regulatory landscape, anchored by the Minamata Convention on Mercury, mandates a progressive reduction and, ultimate, elimination of mercury use in ASGM (Donkor et al. 2024). However, given the socio-economic dependency of millions of miners on amalgamation, the transition is slow and faces significant logistical resistance (Seccatore et al. 2025). Within this context, the concept of a circular economy offers a pragmatic middle ground. Rather than focusing solely on mercury replacement, the reactivation of passivated mercury allows for its recovery and reuse within a closed-loop system (Kosai et al. 2023). This approach not only reduces the demand for "new" mercury but also prevents the discharge of "lost" mercury into tailings, where it would otherwise undergo methylation into the potent neurotoxin methylmercury (MeHg) (Abbas et al. 2017; Raoilimanantsoa et al. 2026).

3. METHODOLOGY

The architecture of this systematic review is built upon a rigorous critique of contemporary scientific literature, specifically prioritizing empirical research within the fields of metallurgy and environmental remediation. To strengthen the reproducibility of the findings and actively mitigate selection bias, the search strategy was anchored by the PICO framework (Population, Intervention, Comparison, and Outcome). Furthermore, every stage of the identification and screening process was aligned with the benchmarks established in the PRISMA statement. This adherence ensures a transparent audit trail, maintaining full traceability from the initial bibliographic harvest to the final synthesis of evidence.

3.1. PICO Framework and Research Questions

We conceptualized the research questions through the PICO framework, specifically focusing on defining mercury passivation mechanisms, evaluating reactivation technologies, and measuring their field-level feasibility. By adopting this structure, the review was organized around the critical technical, ecological, and logistical pillars inherent to mercury restoration. Within this analytical scope, the study aims to resolve the following inquiries:

- Main RQ: How does the technical performance of traditional methods compare with emerging physicochemical innovations for reactivating passivated mercury, and what are the broader implications for gold mining sustainability?
- RQ1 (The Problem): Which specific physicochemical processes drive the phenomenon of mercury "flouring" in ASGM, and how do these mechanisms directly inhibit gold recovery during the amalgamation stage?
- RQ2 (The Intervention): What breakthroughs in electrochemical, biotechnological, or thermal treatments have proven most effective in restoring the lost coalescence capacity of passivated mercury?
- RQ3 (The Comparison): To what degree do emerging technologies mitigate environmental hazards and the generation of toxic by-products when benchmarked against legacy reactivation practices?
- RQ4 (The Feasibility): Is the implementation of these technologies operationally viable in resource-constrained environments—such as the Peruvian Amazon—where infrastructure and technical support are severely limited?

3.2 Search strategy and keywords selection

Our search strategy involved deconstructing the overarching research question into specific thematic subqueries, ensuring strict alignment with the core components of the PICO framework. These descriptors—categorized in Table 1—informed the development of a robust Boolean search string. To ensure maximum retrieval accuracy, the resulting equations were meticulously tailored to accommodate the unique indexing requirements and search syntaxes of both Scopus and Web of Science (WoS).

Table 1. Keywords associated with the components of the PICO framework.

Acronym	Components	Keywords
P	Problem/ Population	mercury, Hg, passivated mercury, flouring, sickened mercury
I	Intervention	activation, reactivation, regeneration, cleaning, recovery
C	Comparison	conventional, emerging, electrochemical, alternative methods
O	Outcomes	gold recovery, coalescence, environmental impact, sustainability

While the PICO framework provided our conceptual blueprint, we intentionally omitted descriptors related to Comparison (C) and Outcomes (O) from the final search strings. This strategic exclusion was a deliberate choice to maximize the sensitivity of our search. As highlighted by Higgins et al. 2020 in the Cochrane Handbook, embedding outcome-specific terms often chokes retrieval results, particularly in technical fields like metallurgical engineering and applied chemistry. In these disciplines, many primary studies fail to include such descriptors in their metadata (titles, abstracts, or keywords). Thus, forcing these filters would have likely introduced a selection bias, potentially overlooking vital research on emerging technologies that lack formal comparative language in their titles.

We opted instead to reserve the comparative analysis between legacy methods and modern innovations for the evidence synthesis stage. This approach aligns with the recommendations of MacFarlane et al., (2022) regarding search development for complex systems: prioritizing initial comprehensiveness over restrictive criteria is essential. Such a strategy ensures robust bibliographic depth and mitigates the risks associated with inconsistent indexing or labeling practices across different academic databases.

By merging these thematic clusters through Boolean logic, we developed high-fidelity search equations. The execution of the expanded search string in Scopus yielded 165 records, while the search in Web of Science (WoS) provided 60 additional records. This search strategy produced an initial pool of 225 records. Following retrieval, these results were consolidated into a master dataset for systematic screening, filtering for technical relevance to maintain strict alignment with the geomechanical and environmental objectives of this research.

3.3 Inclusion and exclusion criteria

To maintain a high standard of technical rigor and ensure the relevance of our findings, we established a specific set of eligibility benchmarks to govern the selection process. These criteria were designed to pinpoint empirical

studies that directly contribute to the evaluation of mercury reactivation technologies within the artisanal mining sector.

Inclusion criteria (IC):

IC1 (Scientific Rigor): The review was strictly limited to primary research and critical review articles published in peer-reviewed, indexed journals. This requirement serves as a baseline for methodological credibility and ensures the quality of the synthesized evidence.

IC2 (Technological Timeline): We defined a temporal window from 2011 to 2026. This timeframe is strategically significant as it captures the technological evolution following the adoption of the Minamata Convention, highlighting the shift from legacy methods toward innovative approaches rooted in circular economy principles.

IC3 (Metallurgical Relevance): Only studies whose primary focus was the physicochemical or metallurgical reactivation of mercury for reintegration into the amalgamation process or for its final recovery were included.

IC4 (Transparency and Accessibility): Publications written in English or Spanish were considered, with priority given to open-access documents to promote data traceability and transparency in the experimental protocols analyzed.

Exclusion criteria (EC):

EC1 (Biomedical Focus): Studies exclusively focused on public health, clinical toxicology, or biomonitoring of human biological fluids (blood or urine) were excluded, as they fall outside the scope of technical mercury recovery.

EC2 (Contextual Incompatibility): Research addressing mercury capture in industrial environments unrelated to mining, such as coal-fired power plants or chlor-alkali facilities, was excluded.

EC3 (Limited Experimental Applicability): Articles focused on the design of trace-detection sensors or nanoparticles without demonstrating practical application for large-scale mercury or amalgam reactivation were excluded.

EC4 (Passive Remediation): Studies on phytoremediation or bacterial bioremediation were omitted because, although valuable for environmental cleanup, they do not evaluate the restoration of mercury's amalgamation properties or gold recovery performance.

EC5 (Insufficient Information): Records containing incomplete information that did not allow for the assessment of gold recovery performance or that failed to address the specific issue of passivated mercury were excluded.

The initial systematic query across Scopus and Web of Science yielded a total of 225 potential records (165 and 60, respectively). To refine this pool, we implemented an automated screening protocol that eliminated duplicate entries and enforced our 2011–2026 publication window alongside accessibility filters. This rigorous pruning narrowed the library down to a core collection of 61 documents that strictly adhered to our pre-established temporal and availability requirements.

Title and abstract screening was conducted manually. Records that mentioned mercury but did not address its metallurgical reactivation or recovery were excluded at this stage. As a result, 59 articles were retained for full-text assessment. During the full-text review, the technical exclusion criteria (EC1–EC5) were applied, resulting in the exclusion of 32 documents. Most of these exclusions ($n=12$) corresponded to studies with an exclusively biomedical focus (EC1).

Ultimately, 27 studies met all eligibility criteria. An additional 16 records were identified through manual searching and citation chasing, resulting in a final corpus of 43 sources for evidence synthesis. The study selection process is illustrated in Figure 1.

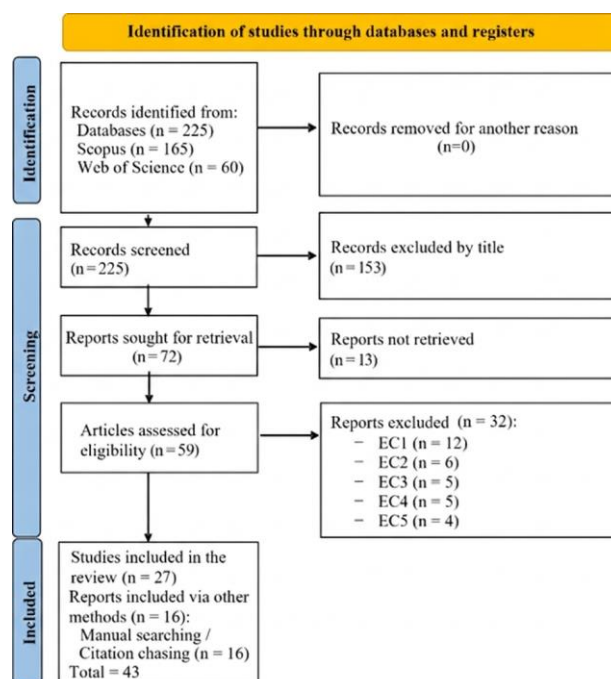


Fig. 1. Literature search and study selection process. (PRISMA).

3.4 Quality assessment and risk of bias

In compliance with the PRISMA 2020 2020 (Page et al. 2021), the methodological quality of the 27 included studies was assessed using the critical appraisal tools developed by the Joanna Briggs Institute (JBI). Standardized checklists for experimental and descriptive studies were applied to evaluate key dimensions, including internal validity, the accuracy of measurement instruments, and statistical transparency. The assessment was conducted independently by two reviewers, and only studies achieving at least 70% compliance with the applicable criteria were considered eligible for inclusion. The additional 16 records identified through manual search were subjected to the same eligibility and quality assessment protocol using the JBI critical appraisal tools. Only studies achieving at least 70% compliance were included in the final synthesis to ensure methodological uniformity across the entire corpus of 43 sources.

To minimize the risk of selective reporting bias, consistency between the stated objectives and the reported findings was verified for each primary study. Although this review was not prospectively registered in databases such as PROSPERO or OSF, the traceability of the process was guaranteed through strict adherence to an internal search and selection protocol, with the purpose of reducing the risk of bias in the selection and synthesis of the available evidence.

3.5 Data extraction and synthesis framework

To uphold analytical transparency and ensure the comparability of our findings, we utilized a standardized extraction protocol as the foundation for the entire analysis. Through this instrument, we meticulously mapped critical variables from the 27 selected studies across four core dimensions. First, we characterized the passivation mechanisms to understand whether the mercury degradation was driven by physical or chemical processes. Second, we categorized reactivation techniques, drawing a clear distinction between legacy methods—relying on friction or aggressive acids—and emerging innovations such as electroreduction and bioleaching. Furthermore, we scrutinized technical performance metrics, specifically prioritizing gold recovery rates (Au%) and the degree to which metal coalescence was restored. Finally, the analysis evaluated environmental impacts by examining reagent toxicity and the persistence of secondary waste. This multifaceted framework was further anchored by Technology Readiness Levels (TRL), enabling a holistic assessment of each technology's technical efficiency, ecological footprint, and field-level viability.

Additionally, to quantify the relationship between technical performance and field readiness, we developed a Portability Index (PI) based on a 3-point ordinal scale:

- 1 (Fixed): Large-scale infrastructure requiring a stable power grid and permanent installation (e.g., industrial cyanidation plants).
- 2 (Modular/Mobile): Systems designed for easy transport via trucks or boats, often battery-powered or requiring small generators (e.g., modular electrolytic cells).
- 3 (Portable): Lightweight equipment that can be carried manually or in backpacks, requiring no external power (e.g., sluice boxes, manual pans, or thermal borax kits).

4. RESULTS AND DISCUSSION

4.1. Geographic distribution of the scientific evidence

A spatial analysis of the identified literature reveals two distinct geographical patterns: the location of the mining sites under investigation and the institutional affiliation of the researchers. This distinction is essential to understand the flow of knowledge between the areas affected by mercury pollution and the centers of technological innovation.

As illustrated in Figure 2, regarding the study sites, the Americas account for 41% of the evidence, with a heavy concentration in the Andean region (Peru and Colombia (Alfonso et al. 2019; Ruffini et al. 2026)). This is followed by Africa (36%), with significant fieldwork reported in Nigeria, Ghana, and Uganda. In these regions, the research is driven by the urgent need to mitigate the environmental footprint of active ASGM operations and to comply with the National Action Plans (NAPs) mandated by the Minamata Convention

In parallel, Africa represents 36% of the analyzed works, establishing itself as a crucial hub for field-based evidence. In countries such as Nigeria, Kenya, and Uganda, a substantial portion of the scientific output is

intrinsically linked to the National Action Plans (NAPs) mandated by the Minamata Convention. This legislative push has fostered a body of literature that not only critiques the inherent failures of traditional amalgamation but also emphasizes the urgent need for solutions that balance environmental safety with the economic and logistical portability required by artisanal miners (Anene et al. 2024; Raoilimanantsoa et al. 2026).

Conversely, the institutional distribution shows a different trend. While much of the fieldwork is conducted in the Global South, a significant portion of the advanced electrochemical and metallurgical analysis (approximately 23%) originates from institutions in Europe (Sweden, Finland, and Spain) and Asia (Indonesia). For instance, while European nations do not face ASGM-related mercury crises within their borders, their research hubs provide the high-tech electrolytic frameworks and advanced alloys necessary to optimize mercury recovery (Tunsu and Wickman 2018; Roth et al. 2023).

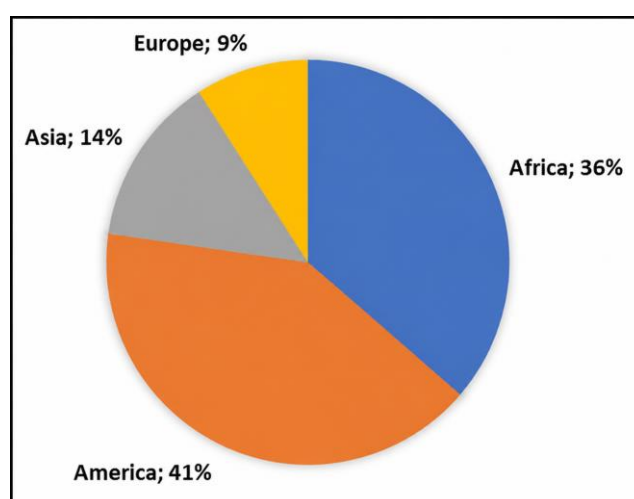


Fig. 2. Percentage distribution of the analyzed studies according to geographical location of mining sites.

This distinction is crucial: the Global South provides the primary empirical data and environmental context, while Global North laboratories contribute the technological innovations that are later tested in field-ready modular systems. This synergy underscores the necessity of cross-border technology transfer that respects the specific operational and ecological constraints of diverse mining landscapes.

4.2. Classification and technological maturity of mercury reactivation technologies

Scientific scrutiny regarding mercury reactivation has proliferated over the last decade, shifting significantly toward the development of field-deployable technologies. Key mining frontiers, including Peru's Nazca-Ocoña Belt (Alfonso et al. 2019), the high-yield gold regions of Antioquia in Colombia (Tami-Pimiento et al. 2024; Ruffini et al. 2026), and the volcanic deposits of Tatelu in Indonesia (Nurcholis et al. 2020; Nurjaman et al. 2024), have emerged as the primary laboratories for these empirical evaluations. This surge in research interest is inextricably intertwined with the global momentum generated by the Minamata Convention, as international efforts intensify to curb the ecological footprint of ASGM through sustainable recovery and reuse (Donkor et al. 2024)

Current taxonomies for reactivation methods (Table 2) draw a sharp line between legacy mechanical approaches and innovative physicochemical treatments. Despite the availability of newer technologies, traditional mechanical methods—centered on friction and gravity-based separation—remain the standard in most artisanal operations due to their minimal cost and straightforward implementation (Veiga and Gunson 2020). However, the literature increasingly highlights the inherent technical ceilings of these practices. Notably, recent investigations in Indonesia (Nurjaman et al. 2024) demonstrate that over-aggressive milling can be counterproductive; instead of cleaning the mercury, it often triggers "flouring"—the fragmentation of the metal into microscopic droplets that lose their coalescence capacity, ultimately stalling gold recovery efficiency.

4.3. Technological maturity analysis and temporal trends

Tracing the chronological trajectory of the literature uncovers a strategic pivot in research objectives, largely catalyzed by the formal adoption of the Minamata Convention. The period between 2011 and 2016 was primarily characterized by efforts to map the environmental fallout of mercury use and identify potential substitutes (Veiga and Gunson 2020; Manzila et al. 2022). In sharp contrast, scholarly attention since 2022 has increasingly gravitated toward "closing the loop," with research now prioritizing mercury recovery, reactivation, and reuse strategies integrated into circular economy models.

A comparative look at the TRLs detailed in Appendix A exposes a profound gap between conventional and emerging solutions. Mature technologies (TRL 9) boast the highest levels of field deployment and portability (Balzino et al. 2015; Raoilimanantsoa et al. 2026), yet they are frequently hindered by technical bottlenecks in terms of efficiency and environmental impact. On the other hand, cutting-edge innovations—such as selective electroreduction (Tami-Pimiento et al. 2024) and electrochemical alloy synthesis (Roth et al. 2023)—achieve remarkable recovery efficiencies, often exceeding 90%. Despite their performance, these methods remain anchored in the intermediate developmental phase (TRL 4–6). This disparity highlights the most pressing hurdle currently facing the industry: bridging the gap between laboratory success and the harsh operational rigors of real-world ASGM environments.

Table 2. Taxonomic overview and maturity of reactivation technologies

Dominant Principle	Method / Technology	Specific Target Problem	Technical Maturity (TRL)	Author
Mechanic	Centrifuges / Controlled milling	Flouring	Conventional (Field)	Balzino et al. (2015)
Thermal	Borax substitution	Complete Hg replacement	Emerging (Implementation)	Køster-Rasmussen et al. (2019)
Chemical	Leaching (Cyanidation)	Passivated Hg in tailings	Conventional (Standard)	Alfonso et al. (2019)
Electrolytic	Selective cathodic reduction	Metal passivation and oxides	Emerging (Pilot)	Tami-Pimiento et al. (2024)
Alloy	Pt-Hg amalgamation	Ionic mercury in water	Emerging (Laboratorio)	Tunsu and Wickman (2018)

The findings strongly suggest that emerging technologies at the TRL 4–6 stage are primarily geared toward re-establishing mercury's physicochemical integrity via mechanisms that fundamentally depart from conventional practices. Electrolytic approaches, in particular, are garnering significant interest for their direct capacity to

tackle surface passivation. Recent work by Tami-Pimiento et al. (2024) and (Roth et al. (2023) posits that the formation of oxide and sulfide films is a principal culprit behind mercury's compromised coalescence. In this regard, selective electroreduction endeavors to dismantle or reconfigure these insulating layers through controlled electrochemical means, thereby reinstating the metal's intrinsic surface properties. This contrasts with chemical methodologies like cyanidation, which, while effective for gold recovery from tailings, do not directly address the mercury's passivation issues (Alfonso et al. 2019)

This technological evolution, however, cannot be divorced from its social and operational context. Díaz Leiva (2022) astutely points out that in regions like Peru, the adoption of new technologies is heavily contingent upon social, economic, and even territorial factors. The artisanal miner's preference leans not towards the theoretically superior method, but rather towards one that offers portability and autonomy, allowing for swift adaptation to regulatory pressures. Therefore, while chemical leaching remains a robust technique, its inherent rigidity makes it less appealing than flexible, modular electrolytic systems that facilitate genuine mercury reuse within a circular economy framework (Kosai et al. 2023). The ultimate trajectory of current development aims beyond mere surface cleaning; it seeks methods capable of overcoming specific mineralogical obstacles, such as gold tellurides, which render conventional passivated mercury ineffective (Alfonso et al. 2019).

A consistent observation throughout our literature review is that the observed decline in amalgamation efficiency stems from more than just mercury "flouring." Chemical passivation processes at the mercury surface play an equally critical, if not more so, role. Studies frequently indicate that the creation of HgO and HgS surface compounds erects formidable barriers to mercury-gold interaction (Seney et al. 2020). From this perspective, relying solely on mechanical friction might prove inadequate for reversing these passivation pathways, whereas electrochemical solutions are deliberately engineered to target the precise chemical mechanisms responsible for the loss of coalescence (Tami-Pimiento et al. 2024).

4.4. Passivation mechanisms and fine gold loss

To understand the mechanisms that reduce mercury's capacity to amalgamate gold, it is necessary to consider not only chemical passivation processes but also the morphological changes undergone by fine gold particles during mineral processing operations. Recent investigations have shown that particles of approximately 100 μm may experience significant structural transformations under high-energy milling conditions, developing toroidal or spheroidal morphologies composed of small-diameter filaments (Palmer and Craw 2024).

These morphological transformations affect the amalgamation process through two principal mechanisms identified in the literature (Palmer and Craw 2024):

- Density collapse: This phenomenon occurs when gold particles undergo deformation, developing intricate folded structures that sequester microbubbles of air, water, or clay within their cavities. This entrapment drastically lowers the particle's apparent density. As a result, these buoyant particles fail to settle and make contact with the mercury, instead remaining suspended in the slurry and being swept away into the tailings.
- Geometric barriers: The toroidal (doughnut-shaped) morphology of eroded gold particles, often exacerbated by clay mineral buildup within their folds, creates a physical buffer that prevents direct

contact with mercury. This structural obstruction significantly inhibits amalgam formation, a problem that is particularly acute when the mercury surface has already been compromised by passivation (Palmer and Craw 2024).

- Our analysis confirms that emerging technologies tackle passivation through mechanisms that fundamentally depart from legacy methods. While traditional practices rely almost exclusively on mechanical attrition and abrasive friction (Nurjaman et al. 2024), electroreduction systems are engineered to transform the electrochemical environment of the mercury surface. By precisely manipulating the redox potential, these systems facilitate the reduction of surface compounds like HgO and HgS, thereby reinstating the metal's intrinsic coalescence. These findings emphasize that restoring amalgamating capacity requires a move beyond mere mechanical cleaning, toward the active chemical management of the drivers behind surface passivation (Nurjaman et al. 2024).

4.5. Comparative analysis of technical performance

The data reveals a clear divergence in how these technologies perform, specifically when distinguishing between the capacity to restore mercury's chemical integrity and the final metallurgical yield. To clarify these distinctions, Table 3 consolidates the primary performance benchmarks from the analyzed literature, separating Mercury Reactivation (%)—the restoration of the metal's physicochemical properties—from Final Gold Capture (Au %).

This stratified approach is essential because, while emerging technologies like selective electroreduction focus on dismantling the dielectric barrier of 'sick mercury,' their ultimate success in an ASGM context is measured by their ability to enhance gold recovery compared to traditional mechanical methods (Díaz Leiva 2022; Nurjaman et al. 2024).

Table 3. Comparative matrix of technical efficiency and restoration capacity.

Technology	Mercury Reactivation (%)	Final Gold Capture (Au %)	Restoration of Coalescence	Main Input	Author
Traditional Amalgamation	0% (Base)	30% - 50%	1 (Low)	Metallic mercury	Veiga and Gunson (2020); Puspita et al. (2023)
High-Energy Milling	15% - 25%	<60%	2 (Medium)	Mechanical friction	Donkor et al. (2024); Nurjaman et al. (2024)
Optimized Cyanidation	N/A (Dissolution)	88% - 95%	N/A	NaCN / Molarity	Alfonso et al. (2019); Manzila et al. 2022; Ruffini et al. (2026)
Selective Electroreduction	>90% - 99%	70% - 85%*	3 (Full)	Electric current	Tunsu and Wickman (2018); Roth et al. (2023); Tami-Pimienta et al. (2024)
Borax Method (Thermal)	N/A (Hg-free)	~40% (Rel.)	N/A	Charcoal / Heat	Appel and Na-Oy (2014); Køster-Rasmussen et al. (2019)

For Selective Electroreduction, the "Final Gold Capture" percentage represents the metallurgical recovery achieved immediately following the physicochemical reactivation of the passivated mercury. This distinction ensures a direct comparison of final gold yields across all evaluated methods.

To facilitate a robust quantitative comparison and address the inherent differences in technological endpoints, we reconstructed our secondary database to ensure that the statistical analysis focuses exclusively on Final Gold Capture (Au %). By isolating gold recovery as the primary comparable variable, we can benchmark the metallurgical efficacy of emerging innovations against legacy practices.

Following this classification, we performed a statistical analysis to benchmark the performance gap. The resulting dataset was divided into conventional techniques (n=6) and emerging or optimized innovations (n=9). Given the non-parametric distribution of the data and the relatively modest sample size, we employed the Mann-Whitney U test to determine the significance of the differences in gold yields between the two groups.

To address the reviewer's concern regarding the comparability of the datasets, we have reconstructed the quantitative analysis. We now distinguish between Mercury Coalescence Restoration (MCR) and Final Gold Capture (FGC). Table 4 has been updated to compare only the Final Gold Capture (Au %) across both groups. For emerging technologies, we utilized the specific gold recovery rates achieved after the mercury reactivation phase, ensuring a direct 'apples-to-apples' comparison with conventional methods.

Table 4. Comparative summary of technical efficiency.

Group	n	Mean Au (%)	Std. Dev.	Med.	Min.	Max.
Conventional methods	6	33.17	9.06	32.5	19	45
Emerging methods	9	76.9	20.42	80	40	99

The synthesis of this data, summarized in Table 4, highlights a dramatic disparity in technical efficacy when evaluating final gold yields. Traditional methods exhibited a mean gold recovery of only 33.17% (SD = 9.06). This figure is nearly eclipsed by the 76.90% (SD = 20.42) average achieved through emerging technologies post-reactivation. Beyond the averages, the significantly higher maximum recovery peaks (up to 99%) reported for the emerging group underscore their superior potential to overcome the technical ceilings of conventional amalgamation.

To move beyond mere description, we leveraged a Mann-Whitney U test to verify if the performance gap between conventional techniques (n=6) and emerging innovations (n=9) was statistically robust. The analysis confirmed a significant disparity ($Z=3.005$; $p<0.01$), providing strong evidence that emerging technologies consistently outperformed traditional methods within the scope of our review. To further quantify the practical impact of this finding, we calculated the effect size using Rosenthal's coefficient. The resulting value of 0.78 represents a substantial magnitude, reinforcing the conclusion that the shift toward emerging technologies offers a demonstrably superior technical advantage. According to the criteria proposed by Cohen, this result corresponds to a large effect size, suggesting a substantial difference between the two groups. Nevertheless, these findings should be interpreted with caution because the small sample size ($N = 15$) and the methodological heterogeneity of the included studies are factors that limit the generalizability of the results.

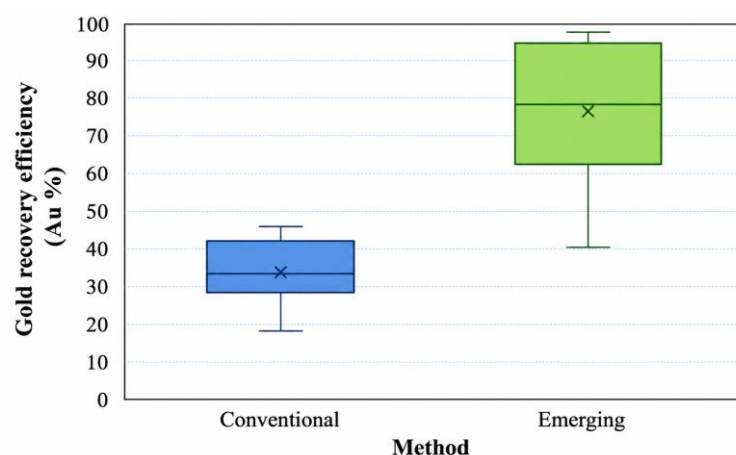


Fig. 3. Comparison of gold capture efficiency between conventional and emerging methods.

Figure 3 illustrates a clear separation between the recovery efficiencies reported for conventional methods and those associated with emerging technologies. Conventional methods are largely clustered below 50% gold recovery, whereas emerging technologies achieve substantially higher recovery efficiencies. These findings are consistent with previous studies that have documented operational limitations associated with conventional amalgamation and intensive mechanical milling processes (Veiga and Gunson 2020; Puspita et al. 2023). Several authors have also reported that the presence of sulfides, tellurides, and other mineral compounds may promote surface passivation processes that diminish the amalgamation capacity of mercury (Alfonso et al. 2019; Díaz Leiva 2022).

In certain mining settings, such as those reported for the Madre de Dios region of Peru, the presence of clay-rich materials and fine particulates may hinder effective contact between mercury and gold particles, thereby reducing amalgamation efficiency (Díaz Leiva 2022). In addition to strict technical factors, various authors emphasize that technology adoption in artisanal mining is also conditioned by economic, logistical, and social factors, which influence the selection of methods used in the field (Díaz Leiva 2022).

Global research consistently highlights the staggering mercury losses inherent in traditional amalgamation, a reality that inflicts both severe economic strain and ecological damage on artisanal communities (Anene et al. 2024). Beyond simple inefficiency, evidence suggests that aggressive milling practices actually exacerbate mercury "flouring" by promoting mechanical fragmentation. This degradation fundamentally cripples the metal's potential for subsequent recovery or circular reuse (Nurjaman et al. 2024). Conversely, field-based studies offer a potential breakthrough via electroreduction; this process appears capable of reinstating mercury's surface integrity by dismantling the chemical barriers created by passivation (Tami-Pimiento et al. 2024). These findings are bolstered by laboratory evidence where electrochemical technologies and specialized alloying have achieved near-total mercury recovery, signaling a promising path forward for the sector (Tunsu and Wickman 2018; Roth et al. 2023). However, a critical gap remains: these innovations require rigorous validation under the harsh, unpredictable conditions of real-world mining sites before they can be scaled effectively.

The imperative for this technological pivot is underscored by the recent predictive modeling of Atangana et al. (2025). Their work reveals that without swift physicochemical intervention, passivated mercury eventually transforms into a persistent, mobile threat that evades the reach of standard passive remediation strategies. These findings reinforce a vital conclusion: mercury reactivation must be integrated directly into the production cycle—capturing the contaminant at the mineral processing plant before it ever reaches the environment.

4.6. Analysis of limitations in quantitative data reporting.

One limitation identified in this review was the high frequency of “Not Reported” (N/R) values for gold recovery efficiency (Au%) and mercury reactivation efficiency (Hg%) within the literature analyzed (see Appendix A). This lack of quantitative information reflects the methodological heterogeneity that characterizes research on ASGM and complicates direct comparisons among technologies.

To preserve the consistency of the statistical analysis, studies that did not report comparable quantitative data were excluded from the Mann-Whitney U test, restricting the analysis to a subset of studies with sufficient information ($N = 15$). Consequently, technologies primarily intended for water remediation or soil stabilization, including those based on bio-organic coagulation and sulfur-based sorbents (Barenblitt et al., 2021), were not included in the statistical comparison because they did not report gold recovery values.

The analytical dataset therefore consisted of studies reporting recovery efficiencies using conventional methods (Balzino et al. 2015; Veiga and Gunson 2020; Puspita et al. 2023; Donkor et al. 2024) and emerging or optimized technologies (Manzila et al. 2022; Nurjaman et al. 2024; Tami-Pimiento et al. 2024; Mohamed et al. 2025). These results should be interpreted considering the limitations derived from the availability and standardization of the reported data.

4.7. Analysis of limitations in quantitative data reporting.

The sustainability of mercury reactivation technologies must be evaluated not only in terms of their ability to recover mercury or gold, but also with respect to the environmental risks associated with the wastes generated during treatment. The studies reviewed indicate that tailings cyanidation can achieve high gold recovery efficiencies (88-95%) (Kosai et al. 2023; Ruffini et al. 2026); however, it may also promote the formation of soluble mercury complexes, thereby increasing mercury mobility and its potential environmental impact (Seney et al. 2020). For this reason, several authors indicate that sustainability assessments must simultaneously balance recovery efficiency against the hazard level of the resulting by-products (Acosta et al. 2021; Tami-Pimiento et al. 2024).

Alternatively, innovations such as selective electroreduction and specific natural coagulation techniques represent a cleaner pathway, significantly reducing secondary waste streams while yielding mercury in a state compatible with circular economy loops (Tami-Pimiento et al. 2024; Seccatore et al. 2025). This stands in sharp contrast to legacy amalgamation, which continues to be linked in the literature to massive mercury losses through both atmospheric volatilization and widespread environmental dispersal (Nurcholis et al. 2020; Atangana et al. 2025).

A critical and persistent theme across recent studies is the vulnerability of water resources to the mismanagement of mine tailings. In several mining jurisdictions, groundwater mercury levels have already surpassed safety thresholds for human consumption, signaling a grave, long-term threat to both environmental stability and public health (Barakati et al. 2023).

To facilitate a robust and transparent quantitative comparison, we isolated 15 individual observations from the selected literature that provided clear gold recovery data under well-defined experimental or field conditions. These data points were categorized into two groups: conventional techniques (n=6) and emerging or optimized innovations (n=9).

As shown in Table 5, each observation is linked to its specific source, technology, and experimental parameters. This detailed breakdown ensures that the comparison benchmarks 'final gold capture' as the primary comparable endpoint, addressing the inherent differences between simple mechanical contact and advanced physico-chemical reactivation.

Table 5: Comparative matrix of environmental sustainability by author and technology.

Group	Technology	Au Recovery (%)	Experimental Condition	Portability Score	Author (Year)
Emerging	Alloy Synthesis	65	Lab - Acidic media	2	Roth et al. (2023)
Conventional		19	Field - Tailings	3	Donkor et al. (2024)
Conventional	Amalgamation	28	Lab - Standard ore	3	Puspita et al. (2023)
Conventional		33	Lab - High sulfides	3	Anene et al. (2024)
Conventional		45	Meta-analysis mean	2	Veiga and Gunson (2020)
Emerging		55	Field - Prototype V1	2	Díaz Leiva (2022)
Emerging	Electroreduction	80	Lab - 2.0V Potential	2	Tami-Pimiento et al. (2024)
Emerging		80	Field - Prototype V2	2	Díaz Leiva (2022)
Emerging		99	Lab - Optimized current	2	Tami-Pimiento et al. (2024)
Emerging	Optimized CN	98	Pilot - High grade	1	Ruffini et al. (2026)
Emerging	Optimized Milling	85	Lab - P80 74	2	Nurjaman et al. (2024)
Emerging		90	Lab - Adaptive Grinding	2	Nurjaman et al. (2024)
Conventional	Sluice/Batea	32.5	Field - Alluvial	3	Balzino et al. (2015)
Emerging	Thiosulfate	40	Lab - 0.1M Concentration	2	Manzila et al. (2022)
Conventional	Traditional	42	Field - Manual	3	Mohamed et al. (2025))

To determine the significance of the performance gap between these groups, we leveraged a Mann-Whitney U test. We acknowledge that in some instances (Díaz Leiva 2022; Tami-Pimiento et al. 2024), multiple observations were sourced from the same publication. However, these represent statistically independent experimental variables—such as different voltage potentials, ore mineralogies, or grinding sizes—rather than simple replicates of a single trial.

The analysis confirmed a significant disparity ($Z=3.005$; $p<0.01$), with emerging technologies consistently outperforming traditional methods. To further quantify the practical impact of this finding, we calculated the effect size using Rosenthal's coefficient. The resulting value of 0.78 represents a substantial magnitude according to Cohen's criteria, reinforcing the conclusion that the shift toward physicochemical reactivation offers a demonstrable technical advantage in ASGM settings, despite the inherent variability of field-ready prototypes.

Beyond technical efficiency, the sustainability assessment of mercury reactivation technologies requires a multi-dimensional consideration of reagent toxicity, secondary waste generation, and the potential for permanent mercury sequestration. As analyzed in the following sections, bio-organic coagulation methods based on papaya seed extracts exhibit negligible toxicity, whereas cyanidation presents the highest levels of environmental hazard among the technologies reviewed (Nurcholis et al. 2020). Life cycle assessment studies indicate that the impacts associated with cyanide may exceed those associated with mercury in the human health category due to the generation of hydrogen cyanide (HCN) and cyanometallic sludges (Acosta et al. 2021; Tami-Pimiento et al. 2024).

Mercury volatilization remains one of the most significant environmental drawbacks of conventional methods. It has been reported that up to 80% of the mercury used in traditional operations may be released into the atmosphere (Kosai et al. 2023; Atangana et al. 2025). By contrast, electrolytic technologies enable the recovery of ionic mercury and the restoration of its physicochemical properties not for reuse, but for its final withdrawal from the mining cycle and safe stabilization, thereby supporting circular economy models focused on toxic waste management (Tami-Pimiento et al. 2024; Ruffini et al. 2026). Nevertheless, the use of strong acids in preliminary stages requires adequate controls to prevent secondary NO_x emissions (Anene et al. 2024).

Furthermore, legacy practices leave miners vulnerable to direct dermal hazards and provide insufficient operational control in zones characterized by extreme metal concentrations (Seney et al. 2020; Rocha-Román et al. (2018). Parallel to these safety concerns, the synthesis of Hg-CN complexes during cyanidation remains a daunting long-term liability, as these compounds often persist as environmental threats long after processing (Alfonso et al. 2019). When weighed collectively, the current body of evidence favors a shift toward selective electrolysis and bio-coagulation. These alternatives offer a rare 'dual-win': the simultaneous recovery of gold and the final capture of legacy mercury, while effectively curbing the generation of hazardous residues associated with traditional chemical leaching.

4.8. Feasibility assessment and operational viability

The real-world success of mercury reactivation within the ASGM sector is contingent upon an intricate balance of technical performance, economic accessibility, and logistical practicality. To provide a clear overview of these dynamics, we have synthesized the core feasibility metrics in Table 6. These benchmarks encompass critical aspects of field adoption, such as operational autonomy, financial inputs, and equipment portability, alongside specialized safety requirements (PPE) and strict alignment with Minamata Convention standards.

Table 6. Feasibility and operational viability indicators.

Technology	Author	Operational autonomy	Cost/ Inputs in Peru	Portability	PPE Level	Minamata Compliant
Sluice Boxes / Gold Pans (<i>Batea</i>)	(Balzino et al. 2015)	1 (Easy)	1 (Very Low)	Mobile (Wheelbarrow)	Basic	No
Suction Dredges / Gravel Pumps (<i>Tracas / Chupaderas</i>)	(Díaz Leiva 2022)	1 (Artisanal)	2 (Moderate)	Mobile (Dredge)	Basic	No
Borax (Thermal)	(Køster-Rasmussen et al. 2019)	2 (Technical)	2 (Moderate)	Portable	Basic	Yes
Electroreduction	(Tami-Pimiento et al. 2024)	2 (Technical)	2 (Moderate)	Modular / Fixed	Specialized	Yes (Full)
Cyanidation	(Alfonso et al. 2019)	3 (Engineering)	3 (Costly / Restricted)	Fixed (Plant)	Specialized	Yes (Transition)

Legacy equipment, particularly the suction dredges and gravel pumps widespread in the Madre de Dios region, are often prized for their significant operational autonomy and geographic flexibility (Díaz Leiva 2022). This operational freedom stands in sharp contrast to high-performance cyanidation systems, which demand rigorous technical oversight and a steady supply of regulated chemical reagents—factors that often stifle their adoption in small-scale, informal settings (Alfonso et al. 2019). Between these two extremes, electrolytic reactivation occupies a more balanced middle ground; it functions with manageable technical complexity and utilizes more readily available inputs, positioning it as a highly practical alternative for localized field implementation (Tami-Pimiento et al. 2024).

Portability is a critical factor influencing technology adoption in remote mining areas. Although numerous studies report technologies with high technical efficiency, many have been evaluated under controlled experimental conditions (Anene et al. 2024; Ruffini et al. 2026). In artisanal mining settings, operational mobility remains a key requirement for day-to-day activities (Díaz Leiva 2022). Consequently, technologies based on portable or modular designs are more likely to be adopted in practice.

Safety requirements also affect operational feasibility. Whereas traditional methods generally rely on basic protective equipment, electrolytic and thermal processes require additional industrial safety measures, increasing implementation costs (Anene et al. 2024).

Compliance with the Minamata Convention requires alternatives that are both technically viable and environmentally sustainable. Experiences involving mining formalization programs and technical assistance initiatives have demonstrated significant reductions in mercury use (Seccatore et al. 2025). Electroreduction offers additional advantages by enabling mercury recovery and reuse within circular economy frameworks, whereas cyanidation may introduce further challenges related to the environmental management of process residues (Acosta et al. 2021).

Taken together, the available evidence indicates that the selection of reactivation technologies should simultaneously consider ore mineralogy, infrastructure availability, operational costs, and environmental requirements.

Table 7 summarizes these considerations through a decision matrix tailored to different ASGM operating environments.

Table 7: Operational decision matrix for mercury reactivation and recovery under different mining conditions.

Mineralogical / Operational Context	Key challenge	Recommended technology	Comparative advantage	Critical limitation (Risk)	Authors
Refractory Ores / Sulfide Deposits (Fixed Mine Sites)	Passivation by Tellurides/HgS	Cyanidation with Pelletization	Maximum gold recovery (88-95%)	Generation of cyanide-bearing wastes and complex sludges.	(Alfonso et al. 2019; Ruffini et al. 2026)
Alluvial Deposits (Remote Areas / Rivers)	Physical mercury flouing and fine-gold losses	Centrifugal Gravity Concentration + Retort	Mechanical reactivation; free of aggressive chemicals.	Sensitive to the nugget effect; limited restoration of mercury coalescence. Slow reaction kinetics; large treatment volumes required.	(Veiga and Gunson 2020; Nurjaman et al. 2024)
Tailings with High Organic Content	Dissolved ionic mercury in water	Bio-Coagulation (Papaya Seed-Based)	Full sustainability; zero operational cost.	Requires a power supply and basic technical training.	(Nurcholis et al. 2020)
Legacy Amalgamation-Contaminated Sites	Passivated Mercury (HgO/HgS)	Selective Electroreduction (Modular)	Circular Economy: Mercury recovery and reuse.		(Roth et al. 2023; Tami-Pimiento et al. 2024)

The proposed decision matrix highlights the unavoidable trade-offs between technical recovery, field agility, and ecological safety. While high-efficiency innovations like selective electroreduction provide a robust mechanism for closing mercury reuse loops within circular economy models (Tunsu and Wickman 2018; Díaz Leiva 2022), their field deployment remains tethered to reliable power and infrastructure—resources that are often scarce in isolated ASGM zones. Conversely, technologies that prioritize operational agility often sacrifice technical sophistication for simplicity. This trade-off is frequently favored in contexts where mining activities are transient, requiring a high degree of flexibility and the ability to relocate rapidly (Díaz Leiva 2022).

Cyanidation remains a "gold standard" for treating complex refractory and sulfide-rich ores (Alfonso et al. 2019; Manzila et al. 2022), yet it introduces a daunting legacy of environmental liabilities. The buildup of cyanide-bearing residues and the synthesis of Hg-CN complexes demand a level of monitoring and waste management that is rarely present in artisanal settings (Ruffini et al. 2026). Furthermore, the literature issues a stark warning regarding the creation of highly soluble mercury species during leaching, which can transform a localized problem into a widespread toxicological threat (Seney et al. 2020).

Ultimately, the data suggests that the technologies most likely to achieve lasting success are those capable of harmonizing recovery efficiency with practical field-readiness and risk mitigation. In this regard, modular electrolytic systems represent a compelling middle ground; they reclaim metallic mercury for immediate reuse and, perhaps more importantly, provide a viable pathway to eliminate the hazardous reliance on open-burning practices (Tami-Pimiento et al. 2024).

However, the transition to these cleaner alternatives is not purely a technical challenge; it is deeply rooted in the social fabric of the mining community. The adoption of any new practice hinges on trust-building, transparency, and the perceived utility among the miners themselves. These human factors remain the ultimate determinants in whether a technological innovation successfully bridges the gap from the laboratory to the field (Barlas et al. 2023).

4.9 Integrated analysis of efficiency, feasibility, and environmental impact

Integrating technical efficacy with operational agility and ecological safety reveals a multifaceted tug-of-war between competing priorities across the evaluated technologies. Our synthesis confirms that a "silver bullet" solution—one that simultaneously maximizes metallurgical recovery, field adaptability, and environmental sustainability—remains elusive. Consequently, the deployment of reactivation systems in ASGM settings is less about finding a perfect fit and more about strategically managing the inevitable trade-offs between these core objectives.

The integrated analysis of technical efficacy and field readiness reveals a moderate inverse association. Using the 15 individual data points for Final Gold Capture (Au %) and their respective Portability Index (PI) scores (as detailed in Table 5), we calculated a Spearman's rank correlation of $\rho = -0.50$ ($n=15; p<0.05$).

This statistically significant negative trend confirms that as reactivation technologies become more sophisticated and efficient at capturing gold, their operational portability tends to decrease. This trade-off underscores a critical bottleneck for ASGM: the highest recovery rates are currently tethered to modular or fixed systems (PI 1–2), while the most portable methods (PI 3) continue to face a technical ceiling in metallurgical efficiency. Bridging this gap through equipment miniaturization remains the most pressing challenge for the widespread adoption of mercury-free alternatives. (Díaz Leiva 2022).

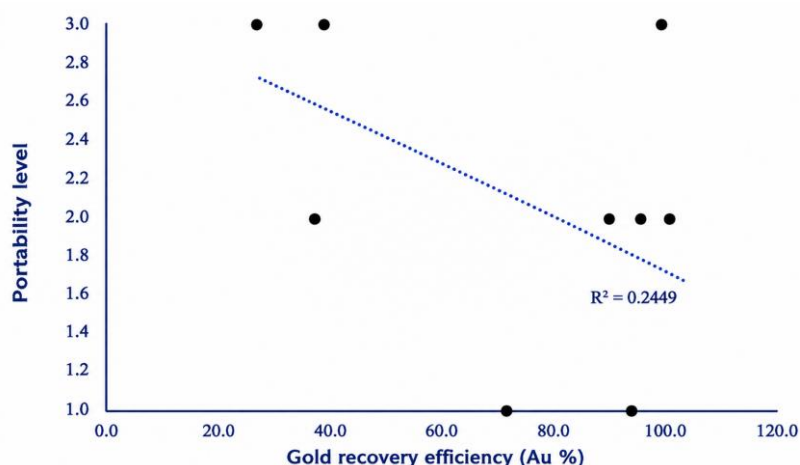


Fig. 4. Correlation between technical efficiency and operational portability.

Portability levels were coded as 1 = Fixed, 2 = Modular, and 3 = Portable.

Figure 5 broadens this analytical lens by integrating the ecological dimension into the comparison. Traditional amalgamation remains the most significant culprit for mercury volatilization, while cyanidation shifts the

environmental threat toward the synthesis of soluble complexes and the creation of persistent waste streams (Alfonso et al. 2019; Ruffini et al. 2026). Crucially, the literature underscores that these conventional pathways can inadvertently heighten mercury mobility, especially when specific operating environments catalyze its release into the surrounding ecosystem (Seney et al. 2020).

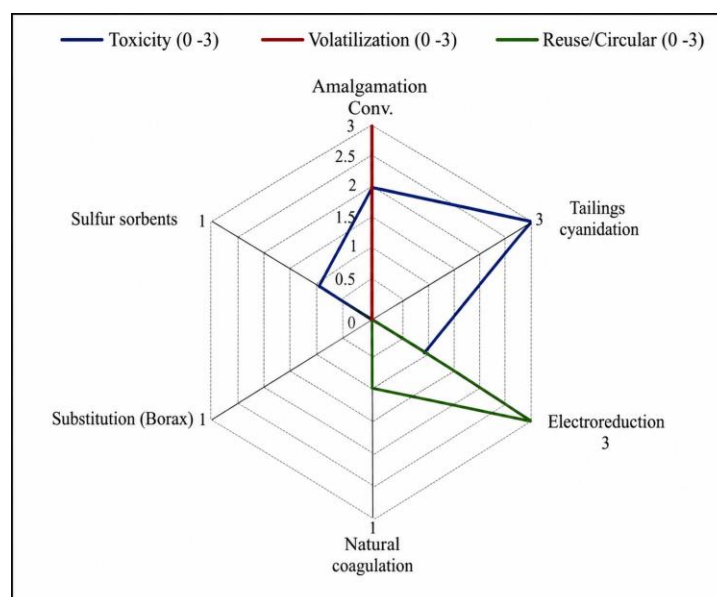


Fig. 5. Comparative assessment of environmental impacts associated with the technologies evaluated.

Selective electroreduction, however, emerges as a promising contender due to its ability to facilitate mercury recovery within circular resource loops, effectively curbing both airborne emissions and the volume of secondary waste. Despite its technical superiority, the transition from laboratory success to field implementation is often hindered by the specialized infrastructure and technical expertise that remain scarce in remote ASGM territories (Tami-Pimiento et al. 2024).

Ultimately, technology selection must be predicated on a nuanced, multi-dimensional evaluation that weighs recovery efficiency against operational practicality and environmental safety. Such an assessment cannot be generic; it must be deeply rooted in the unique site-specific constraints and socio-technical realities of each mining landscape.

5. CONCLUSIONS

The evidence synthesized in this review confirms that emerging physicochemical technologies for mercury reactivation consistently outperform the legacy methods currently entrenched in ASGM operations within controlled laboratory and pilot environments. The data reveals that electrochemical interventions and other optimized treatments offer a superior theoretical pathway for gold extraction by providing a more efficient use of resources compared to traditional, often ineffective, practices.

A vital takeaway is that optimizing gold capture transcends mere mechanical cleaning; it necessitates a fundamental restoration of the mercury's surface chemistry, which is frequently compromised by passivation. In this

regard, electrochemically driven technologies have proven highly effective at laboratory scales (TRL 4–6) for dismantling the oxide and sulfide barriers that inhibit coalescence. By reconstituting the metal's amalgamating properties, these methods allow for the final capture of legacy mercury, transitioning it from a lost contaminant into a stable asset for safe sequestration and removal from the mining cycle.

However, these conclusions must be interpreted with caution. While the technical potential of technologies such as selective electroreduction is evident, their definitive superiority for widespread ASGM deployment cannot be conclusively claimed until further large-scale field evidence is available. The quantitative findings of this review are based on a relatively small sample size ($n=15$) characterized by high methodological heterogeneity. Consequently, a clear distinction must be made between the promising performance observed in research settings and the operational efficacy required in the harsh, resource-constrained conditions of real-world mining basins.

On the ecological front, the findings expose a stark contrast between the evaluated alternatives. While traditional amalgamation remains a primary driver of mercury emissions, emerging reactivation methods offer a cleaner pathway, provided they are managed correctly. Nevertheless, any serious assessment of sustainability must move beyond a narrow focus on recovery percentages to include a holistic evaluation of secondary waste generation and the practical potential for circular material management focused on toxic remediation.

Ultimately, bridging the gap between laboratory success and field adoption in ASGM hinges on more than just technical performance. The success of these technologies is deeply tethered to operational, economic, and logistical realities, including infrastructure accessibility, equipment portability, and the training levels of local miners. Therefore, the selection of any reactivation technology must be predicated on an integrated strategy—one that harmonizes technical efficiency at TRL 9 with field-level viability and long-term environmental responsibility.

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7. REFERENCES

1. Abbas, H.H., Sakakibara, M., Sera, K. and Arma, L.H. 2017. Mercury exposure and health problems in urban artisanal gold mining (UAGM) in Makassar, South Sulawesi, Indonesia. *Geosciences (Switzerland)* 7(3). [DOI]
2. Acosta, J.A., Faz, A., Muñoz, M.Á., Gabarrón, M. and Martínez-Martínez, S. 2021. Environmental impact on the natural resources of an area affected by mining activity in Bolivia: a geochemical evaluation of soils and sediments. *Boletín Geológico y Minero* 132(4), pp. 363–374. [DOI]
3. Alfonso, P. et al. 2019. The importance of mineralogical knowledge in the sustainability of artisanal gold mining: A mid-South Peru case. *Minerals* 9(6). [DOI]
4. Anene, N.C., Dangulbi, B.M. and Veiga, M.M. 2024. Assessment of Gold and Mercury Losses in an Artisanal Gold Mining Site in Nigeria and Its Implication on the Local Economy and the Environment. *Minerals* 14(11). [DOI]
5. Anene, N.C., Veiga, M.M., Kullokom, J.E. and Klein, B. 2026. Assessment of Gold and Mercury Losses in Artisanal Mining Operations in Korokpa, Minna, Niger State. *Minerals* 16(4). [DOI]

6. Appel, P.W.U. and Na-Oy, L.D. 2014. Mercury-Free Gold Extraction Using Borax for Small-Scale Gold Miners. *Journal of Environmental Protection* 05(06), pp. 493–499. [\[DOI\]](#)
7. Atangana, M.S.B., Magermans, P., Ngoupayou, J.R.N. and Deliege, J.F. 2025. Quantifying Mercury Use and Modeling Its Fate and Transport in Artisanal and Small-Scale Gold Mining in the Lom Basin. *Hydrology* 12(4). [\[DOI\]](#)
8. Balzino, M., Seccatore, J., Marin, T., De Tomi, G. and Veiga, M.M. 2015. Gold losses and mercury recovery in artisanal gold mining on the Madeira River, Brazil. *Journal of Cleaner Production* 102, pp. 370–377. [\[DOI\]](#)
9. Barakati, K.P., Adjii, T.N. and Rahardjo, N. 2023. Status of groundwater and river water quality around the location of illegal gold mining activities in Lantung District, Sumbawa. *Journal of Degraded and Mining Lands Management* 10(3), pp. 4433–4443. [\[DOI\]](#)
10. Barlas, A., Valakosta, A., Katsionis, C., Oikonomou, A. and Brinia, V. 2023. The Effect of Corporate Social Responsibility on Customer Trust and Loyalty. *Sustainability (Switzerland)* 15(2). [\[DOI\]](#)
11. Bieser, J., Angot, H. ne, Slemr, F. and Martin, L. 2020. Atmospheric mercury in the Southern Hemisphere - Part 2: Source apportionment analysis at Cape Point station, South Africa. *Atmospheric Chemistry and Physics* 20(17), pp. 10427–10439. [\[DOI\]](#)
12. Bruno, D.E., De Simone, F., Cinnirella, S., Hedgecock, I.M., D'Amore, F. and Pirrone, N. 2023. Reducing Mercury Emission Uncertainty from Artisanal and Small-Scale Gold Mining Using Bootstrap Confidence Intervals: An Assessment of Emission Reduction Scenarios. *Atmosphere* 14(1). [\[DOI\]](#)
13. Díaz Leiva, J. 2022. Appropriate technologies and the geosocial evolution of informal, small-scale gold mining in Madre de Dios, Peru. *Extractive Industries and Society* 12. [\[DOI\]](#)
14. Donkor, A.K., Ghoveisi, H. and Bonzongo, J.C.J. 2024. Use of Metallic Mercury in Artisanal Gold Mining by Amalgamation: A Review of Temporal and Spatial Trends and Environmental Pollution. *Minerals* 14(6). [\[DOI\]](#)
15. Esdaile, L.J. and Chalker, J.M. 2018. The Mercury Problem in Artisanal and Small-Scale Gold Mining. *Chemistry - A European Journal* 24(27), pp. 6905–6916. [\[DOI\]](#)
16. González-Vásquez, R., García-Martínez, M.J. and Bolonio, D. 2023. Investigation of Gold Recovery and Mercury Losses in Whole Ore Amalgamation: Artisanal Gold Mining in Nambija, Ecuador. *Minerals* 13(11). [\[DOI\]](#)
17. El Hadi, S.M., Abdeina, E.H., Chakiri, S., Baghdad, B. and El Hadi, H. 2026. Mercury contamination in soils and process waters near artisanal gold mining sites in Chami, Mauritania. *Ecological Engineering and Environmental Technology* 27(5), pp. 23–32. [\[DOI\]](#)
18. Hammer, V. et al. 2023. Membrane Contactors as a Cost-Effective Cyanide Recovery Technology for Sustainable Gold Mining. *ACS ES and T Water* 3(7), pp. 1935–1944. [\[DOI\]](#)
19. Higgins, J.P.T., Thomas, James., Chandler, Jackie., Cumpston, Miranda., Li, Tianjing., Page, M.J.. and Welch, V.A. 2020. *Cochrane handbook for systematic reviews of interventions*. Wiley-Blackwell.
20. Jonkman, J. and de Theije, M. 2022. Amalgamation: Social, technological, and legal entanglements in small-scale gold-mining regions in Colombia and Suriname. *Geoforum* 128, pp. 202–212. [\[DOI\]](#)
21. Keane, S. et al. 2023. Mercury and artisanal and small-scale gold mining: Review of global use estimates and considerations for promoting mercury-free alternatives. *Ambio* 52(5), pp. 833–852. [\[DOI\]](#)
22. Kosai, S., Nakajima, K. and Yamasue, E. 2023. Mercury mitigation and unintended consequences in artisanal and small-scale gold mining. *Resources, Conservation and Recycling* 188. [\[DOI\]](#)
23. Køster-Rasmussen, R., Cardeno, J.I.C., Appel, P.W.U., Smidth, M., Na-Oy, L.D. and Onos, . . 2019. *Comparison of Gold Yield with Traditional Amalgamation and Direct Smelting in Artisanal Small-Scale Gold Mining in Uganda*.
24. MacFarlane, A., Russell-Rose, T. and Shokrane, F. 2022. Search strategy formulation for systematic reviews: Issues, challenges and opportunities. *Intelligent Systems with Applications* 15. [\[DOI\]](#)

25. Manzila, A.N., Moyo, T. and Petersen, J. 2022. A Study on the Applicability of Agitated Cyanide Leaching and Thiosulphate Leaching for Gold Extraction in Artisanal and Small-Scale Gold Mining. *Minerals* 12(10). [DOI]
26. Mohamed, A.H.A., Youpoungam, A.A., Boyraz, T., Alp, İ. and Sinon, A. 2025. Characterization and evaluation of glycine and cyanide leaching application on artisanal gold mining tailings. *Physicochemical Problems of Mineral Processing* 61(3). [DOI]
27. Nurcholis, M., Nursanto, E., Sakti, H.E.B., Yudiantoro, D.F. and Haryanto, D. 2020. Coagulation and adsorption techniques for purification of the amalgamation slurry waste. *Journal of Degraded and Mining Lands Management* 7(2), pp. 2001–2010. [DOI]
28. Nurjaman, D.M., Titah, H.S., Kawigraha, A., Purwanti, I.F. and Hidayat, W. 2024. Optimization of adaptive and sustainable gold ore grinding processes for better environmental and land conditions in the small-scale gold mining sector in Indonesia. *Journal of Degraded and Mining Lands Management* 11(3), pp. 5635–5646. [DOI]
29. Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., McGuinness, L. A., Stewart, L. A., Thomas, J., Tricco, A. C., Welch, V. A., Whiting, P. and Moher, D. 2021. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ*, p. n71. [DOI]
30. Palmer, M. and Craw, D. 2024. Morphology and structural evolution of fine beach gold in comparison to detrital platinum, southern New Zealand. *Mineralium Deposita* 59(1), pp. 69–83. [DOI]
31. Puspita, A.N.G., Sudiyanto, Y., Haryanto, I. and Madra, Q.N. 2023. 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(4), pp. 4611–4627. [DOI]
32. Rachman, R.M., Bahri, A.S. and Trihadiningrum, Y. 2018. Stabilization and solidification of tailings from a traditional gold mine using portland cement. *Environmental Engineering Research* 23(2), pp. 189–194. [DOI]
33. Raoilimanantsoa, N. et al. 2026. Metals in water used by artisanal and small-scale gold miners for gold-mercury amalgamation in Western Kenya. *Environmental Health*. [DOI]
34. Rocha-Román, L., Olivero-Verbel, J. and Caballero-Gallardo, K.R. 2018. Impacto de la minería del oro asociado con la contaminación por mercurio en suelo superficial de san martin de loba, sur de bolívar (Colombia). *Revista Internacional de Contaminacion Ambiental* 34(1), pp. 93–102. [DOI]
35. Roth, V., Järlebark, J., Ahrens, A., Nyberg, J., Salminen, J., Vollmer, T.R. and Wickman, B. 2023. Mercury Removal from Concentrated Sulfuric Acid by Electrochemical Alloy Formation on Platinum. *ACS ES and T Engineering* 3(6), pp. 823–830. [DOI]
36. Ruffini, V., Neri, P., Gomez, F.H., Rosa, R., Mortalò, C., Vaccari, M. and Ferrari, A.M. 2026. Life Cycle Environmental Impact Assessment of Gold Production in an Artisanal Small-Scale Mine in Colombia. *Sustainability* 18(2), p. 770. [DOI]
37. Seccatore, J., Marin, T., Tarra-Almario, J. and Restrepo-Baena, O.J. 2025. Public Mining Governance for Sustainable Artisanal Gold Mining: Preventing Mercury Pollution in South America. *Sustainability (Switzerland)* 17(19). [DOI]
38. Seney, C.S. et al. 2020. Reaction of Cyanide with Hg⁰ -Contaminated Gold Mining Tailings Produces Soluble Mercuric Cyanide Complexes. *Chemical Research in Toxicology* 33(11), pp. 2834–2844. [DOI]
39. Spiegel, S., Keane, S., Metcalf, S. and Veiga, M. 2015. Implications of the minamata convention on mercury for informal gold mining in sub-saharan africa: From global policy debates to grassroots implementation? *Environment, Development and Sustainability* 17(4), pp. 765–785. [DOI]
40. Tami-Pimiento, L.M., Joya-Herrera, L.M., Pérez-Chía, Y.I. and Meléndez, A.M. 2024. Selective electrochemical reduction of mercury(II) from a simulated traditional gold mining wastewater contaminated with cyanide and heavy metals. *Journal of Solid State Electrochemistry* 28(7), pp. 2223–2232. [DOI]

41. Tampushi, L.L., Onyari, J.M. and Muthama, N.J. 2022. Assessing Social and Environmental Impacts of Artisanal and Small-Scale Gold Mining Practices in Lolgorian, Kenya. *European Journal of Sustainable Development Research* 6(3). [DOI]
42. Tunsu, C. and Wickman, B. 2018. Effective removal of mercury from aqueous streams via electrochemical alloy formation on platinum. *Nature Communications* 9(1). [DOI]
43. Veiga, M.M. and Gunson, A.J. 2020. Gravity concentration in artisanal gold mining. *Minerals* 10(11), pp. 1–50. [DOI]

8. PATENTS

Not applicable.

9. DESCRIPTION OF ABBREVIATIONS, IF ANY

- ASGM: Artisanal and Small-scale Gold Mining.
- Hg: Mercury.
- APC: Article Processing Charge.
- PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses.
- TRL: Technology Readiness Level.
- MeHg: Methylmercury.
- UCSM: Universidad Católica de Santa María.

10. BACKGROUND INFORMATION FOR RECORD

Author Contributions: Conceptualization, Miguel Alberto Barreda de la Cruz; methodology, Miguel Alberto Barreda de la Cruz y Antonio Linares-Flores-Castro; validation, Miguel Alberto Barreda de la Cruz, Omar Paredes-Salas y Javier Montesinos-Chavez; formal analysis, Miguel Alberto Barreda de la Cruz y Antonio Linares-Flores-Castro; investigation, Miguel Alberto Barreda de la Cruz, Antonio Linares-Flores-Castro, Omar Paredes-Salas y Javier Montesinos-Chavez; resources, Miguel Alberto Barreda de la Cruz; data curation, Antonio Linares-Flores-Castro y Omar Paredes-Salas; writing—original draft preparation, Miguel Alberto Barreda de la Cruz y Antonio Linares-Flores-Castro; writing—review and editing, Miguel Alberto Barreda de la Cruz, Omar Paredes-Salas y Javier Montesinos-Chavez; visualization, Antonio Linares-Flores-Castro y Omar Paredes-Salas; supervision, Miguel Alberto Barreda de la Cruz; project administration, Miguel Alberto Barreda de la Cruz; funding acquisition, Miguel Alberto Barreda de la Cruz. All authors have reviewed and approved the final version of this manuscript for publication.

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Appendix A

Appendix A.1

Table A1. Data Extraction and Scientific Evidence Matrix

Reference Scales:

Efficacy: [Low: <50%] | [Medium: 50-80%] | [High: >80%]

Environmental Risk: [0: None] | [1: Low] | [2: Moderate] | [3: High]

TRL Legend (NASA/H2020 Scale):

TRL 1-3: Basic concept / Laboratory research (fundamental science).

TRL 4-6: Validation in a relevant environment / Pilot-scale testing (technology under development).

TRL 7-9: System demonstrated in an operational environment / Mine-scale operation (ready for implementation).

Portability:

[P]: Portable (Backpack/Gold Pan). [M]: Modular/Mobile (Boat/Battery-Powered System). [F]: Fixed (Processing Plant/Grid Power).

Reference (Author, Year)	Location / Validation Level	Specific Mercury- Related Issue	Reactivation Method	Au (%)	Hg (%)	Environment al Risk (0-3)	TR L (1- 9)	Portability	Secondary Waste
(Raoilimanantsoa et al. 2026)	Kenia / Mina	Dermal permeability risk	Pond amalgamation	N/R	N/ R	3 (High)	9	P	Toxic pond water
(Alfonso et al. 2019)	Peru / Mine	Presence of tellurides and sulfides	Cyanidation + cementation	80	N/ R	2 (Mod.)	9	F	Cyanometallic sludges
(Anene et al. 2024)	Nigeria / Mine	Mechanical fragmentation	Gravity concentration + amalgamation	18 - 20	N/ R	3 (High)	9	P	Hg vapors / Toxic dusts
(Nurjaman et al. 2024)	Indonesia / Mine	Inadequate liberation (P80 < 74 µm)	Mechanical treatment (P80 < 74 µm)	60 - 75	N/ R	1 (Low)	9	M	Floured Hg in tailings
(Balzino et al. 2015)	Brazil / Mine	Loss of fine- particle hydrodynamics	Dredging and sluicing	N/R	N/ R	3 (High)	9	M	Hg accumulation in benthic sediments
(Køster-Rasmussen et al. 2019)	Uganda / Mina	Interfacial tension inhibition	Thermal (Borax)	+40*	N/ A	0 (Nula)	9	P	Slag / gold bullion
(Díaz Leiva 2022)	Peru / Mine	Technical inflexibility in the field	Mobile gravel pumps/dredges	Variabl e	N/ R	2 (Mod.)	9	M	Tailings with residual Hg
(Veiga and Gunson 2020)	Global	Gravity recovery of Au < 74 µm	Centrifugal gravity concentration	>80	N/ A	1 (Low)	9	M	Mercury-free tailings
(Puspita et al. 2023)	Indonesia / Mine	Grain liberation deficiency	Roller milling	< 40	N/ R	2 (Mod.)	9	F	80% Hg lost (burning)
(Seccatore et al. 2025)	Chile / Mine	Regulated market inefficiency	ENAMI market-based model	N/R	90	1 (Low)	9	F	Central plant sludges
(González-Vásquez et al. 2023)	Ecuador / Mine	Overloading in autogenous milling	Chilean mill optimization	+15*	N/ R	2 (Mod.)	9	F	Sludges with reduced Hg

(Jonkman and de Theije 2022)	Suriname / Mine	Informal transboundary traceability	Socially embedded amalgamation practices	N/R	N/R	3 (High)	9	P	Residual Hg in rivers
(Spiegel et al. 2015)	Zimbabwe / Mine	Thermal decomposition efficiency	Retort-based reactivation	N/R	95	1 (Low)	9	P	Liquid Hg for reuse
(Ruffini et al. 2026)	Colombia / Mine	Environmental footprint of leaching reagents	LCA (Hg/CN comparison)	N/R	N/R	3 (High)	8	F	HCN emissions/sludges
(Kosai et al. 2023)	Global	Hg-CN thermodynamic incompatibility	Chemical replacement	85 - 95	N/R	3 (High)	8	F	HCN gases (46,700 Mg)
(Donkor et al. 2024)	Global	Global anthropogenic mercury releases	Trend review	N/R	N/R	3 (High)	8	P	Global environmental Hg
(Keane et al. 2023)	Africa / Mine	Sociotechnical resistance to change	Mercury-free ASGM	N/R	N/R	2 (Mod.)	8	P	Persistent Hg in mine
(Roth et al. 2023)	Finland / Pilot	Hg in extreme acidity media	Electrochemical alloy formation	N/R	>90	1 (Low)	6	M	Mercury-free effluent
(Tami-Pimiento et al. 2024)	Colombia / Pilot	Passivation by $[\text{Hg}(\text{CN})_4]^{2-}$ complexes	Selective electroreduction	N/R	>99	1 (Low)	6	M	Neutral water / Pure Hg
(Nurcholis et al. 2020)	Indonesia / Lab	Heavy metals in colloidal suspension	Coagulation (Papaya seed)	N/R	100	0 (Nula)	4	P	Bio-organic sludges
(Manzila et al. 2022)	Zimbabwe / Lab	Encapsulation in pyrite/arsenopyrite	Thiosulfate vs. Cyanide	71.6	N/R	1 (Low)	4	F	Stable ammonium salts
(Esdaile and Chalker 2018)	Global	Sorption kinetics in soils	Sulfur-based sorbents	N/R	N/R	1 (Low)	4	P	In situ remediated soil
(Tunsu and Wickman 2018)	Sweden / Lab	Ionic contamination in effluents	Platinum-film alloy	N/R	99	1 (Low)	3	M	None (closed-loop system)
(Atangana et al. 2025)	Cameroon / Mina	Atmospheric volatilization dynamics	Environmental fate modeling	N/R	N/R	3 (High)	3	N.A.	Atmospheric gaseous Hg