From Mercury Amalgamation to Acid Refining: Gold Refinery Processes, Environmental Impacts, and Sustainable Alternatives in Artisanal and Small-Scale Gold Mining

Osabutey Freeman Tetteh [1], Owusu Panin Kwame Baah [2*], Daitey William [3], Kwabena Asomaning [4]
[1] Department of Art, Pennsylvania Western University, Edinboro, USA
[2, 4] Department of Jewellery Design, Techbridge University College, Ghana
[3] Department of Product Design and Entrepreneurship, Techbridge University College, Ghana

* Corresponding Author: **Owusu Panin Kwame Baah**

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Abstract
Historically, artisanal and small-scale miners (ASM) in Ghana have relied on the technique of amalgamation, a simple but effective method for purifying gold from crushed ore and ore concentrates using mercury. In recent years, a noticeable trend has emerged among some processors, especially those dealing with amalgam residues, jewellery scrap, and low-quality concentrates, to use acid-based refining methods, such as variations of aqua regia (a solution composed of nitric and hydrochloric acids). In this article, the researchers examine this transition in the theme of an artisanal refining sequence through field photographs. It provides an overview of the traditional amalgamation-and-torching process, the well-documented health and environmental impacts of mercury use, how acid-based alternatives work and why they are attractive, a comparative technical analysis of the two pathways, the policy architecture underpinning the Minamata Convention on Mercury, and socio-economic and cultural considerations influencing the selection of technologies at a local level. The study revealed that both methods informally practiced are not risk free and makes recommendations based on formalisation, technical training and access to safer mercury-free technologies.

Keywords: Acid refining, ASGM, Environmental contamination, Mercury amalgamation, Occupational health

1. Introduction

Ghana has been a major player in world economies and cultural expressions for centuries, before the colonial era, when it was known as the "Gold Coast" of the imagination. The boom in contemporary artisanal and small-scale gold mining (ASGM), locally known as galamsey, has been significant in the last two decades as prices for gold bullion went up, increased pressure on the land and a lack of alternative formal employment opportunities in mining communities.

Ore is usually mined in two phases in this industry. Ore is then crushed, milled and concentrated by gravity methods like sluicing and panning and the concentrate is treated to release the fine gold from the mineral matrix. This liberation process is historically and still predominantly today based on mercury amalgamation, in which the concentrate is mixed with liquid mercury, forming a gold-mercury amalgam, which is subsequently separated and the mercury volatilised by subjecting it to heat to leave a spongy, impure gold button (Afrifa *et al*., 2019) [2]. More of a secondary step, and more commonly observed in newer processors who are processing buttons, jewellery scrap, and other impure gold, is acid-based refining, whereby the impure gold is dissolved in strong acid, usually a mix of nitric and hydrochloric acid, commonly referred to as aqua regia; and chemically precipitated in a purer form (Delmer Group, 2025; ishor, n.d.) [4].

The field photographs in this sequence are used to provide a thematic exploration of practices and hazards of gold refining in this industry, with reflections on the transitions that can be observed. It is structured in six themes: traditional mercury

amalgamation process; health and environmental risks of mercury use; the development of acid-based refining as a secondary or alternative method; a comparative technical comparison of the two pathways; policy and regulatory framework for mercury use in Ghana and socio-economic/cultural aspects of the choices of technology that miners make. Finally, the article provides a conclusion and a list of feasible suggestions.

2. The Traditional Mercury Amalgamation Process

By a long way the most common gold-recovery method in Ghana's ASGM sector is mercury amalgamation. Gold has a high natural affinity with mercury, and when exposed to very fine particles of gold in a concentrate it will combine to form a soft, silvery amalgam that can easily be separated from the waste rock by hand-panning, squeezing through cloth or by simple gravity separation. Whole-ore amalgamation, in which mercury is used directly on the unconcentrated ore, is relatively uncommon in Ghana, but the more widespread technique of amalgamating gravity concentrates is using significant amounts of mercury – around 2 grams per gram of gold recovered (Bansah, 2021; Donkor *et al*., 2006; Hilson *et al*., 2007 as cited in van Straaten, 2021).

After the amalgam has been formed and removed from the tailings, it is washed several times in water to wash off any remaining silt and organic matter and the resultant amalgam is visibly darker and denser, suitable for the next process. The amalgam is then placed in a small clay or ceramic crucible and subjected to open burning, typically using a handheld gas torch which is directed inside the crucible, whereby the mercury is volatilized, leaving a dull colored but porus gold button. This burning process is usually done on a large scale in artisanal operations, without any apparatus for capturing and condensing the fumes, thus emitting elemental mercury vapour into the immediate work area.

Fig 1: Washing recovered amalgam in shallow metal pans, a routine step that precedes the burning-off of mercury to isolate the gold sponge. (Researchers Fieldwork, 2026)

Fig 2: A handheld torch is used to burn mercury out of an amalgam held in a small clay crucible, producing the visible orange glow of the reaction and releasing mercury vapour into the open air. (Researchers Fieldwork, 2026)

The gold achieved from the burning of the amalgam is not often of a high chemical purity. It usually has some of the original mercury, silver, copper and other base metals from the ore body that it contains that show a dull, granular surface that looks nothing like refined bullion. It is this impure product which is increasingly used to produce a secondary acid based refining step.

3. Health and Environmental Consequences of Mercury Use

The health hazards of mercury amalgamation are well documented in the scientific literature and are particularly high during the stage of amalgam burning when mercury vapour is directly inhaled by the operator and others in the immediate vicinity. Human exposure is mostly through breathing in elemental mercury vapour which is easily absorbed into the blood stream (Afrifa, Essien-Baidoo, Ephraim, Nkrumah, & Dankyira, 2017) [1]. Chronic exposure has been associated with renal dysfunction, as evidenced by decreased estimated glomerular filtration rate (eGFR) and increased urinary protein levels in small-scale miners who were not compliant with personal protective equipment (PPE) use in Bibiani, Ghana (Afrifa *et al*., 2017) [1]. A wider literature search also identified organ damage and metabolic disturbances amongst the ASGM workers exposed to mercury, including renal, neurological and endocrine systems (Afrifa, Opoku, Gyamerah, Ashiagbor, & Sorkpor, 2019) [2].

It is not just people who work with mercury who are exposed to it. The indoor mercury vapour (iMv) concentrations in the homes of mining households in the study area (Upper East Region of Ghana) where the practice of amalgam burning is prevalent are significantly higher than the international reference doses and the highest recorded levels are much higher than the safe exposure limit (Rajaee *et al*., 2015, as cited in related indoor exposure studies). In addition to direct inhalation, open burning of amalgams in the environment and improper disposal of mercury contaminated tailings can also affect soil mercury concentrations, sometimes by over 100 times higher than background concentration, found in a joint assessment by Pure Earth and Ghana's Environmental Protection Agency (Pure Earth & Ghana EPA, cited in Business & Human Rights Resource Centre, 2025) [3].

These environmental results are supported by biomonitoring studies. Hair, urine and fingernail mercury levels among small-scale miners in the Amansie West District revealed that those who work close to the mines had significantly higher levels of mercury than those who lived further away, confirming both occupational and residential exposure as risks and that continued education was needed on cleaner mining processing options (as cited in the Amansie West assessment). In addition, chronic mercury exposure in Ghanaian small-scale miners has been correlated with changes in thyroid hormone regulation, highlighting the kidneys, nervous system, and endocrine system as another set of organs that are affected by chronic mercury exposure.

4. The Emergence of Acid-Based Refining

Acid-based refining has emerged as a visible and growing secondary process in artisanal and small-scale gold circuits, partly because of the poor quality of gold extracted from amalgams, but also because it is a standalone refining method for scrap and jewellery gold. The most common technique is the aqua regia refining, which involves dissolving impure gold in a mix of nitric acid and hydrochloric acid, often used in mediaeval alchemical writings and currently the most often used wet-chemical refining process (Shor International, n.d.). When a solution of nitric acid is added to the alloy, the nitric acid oxidises the gold, and hydrochloric acid provides chloride ions, which combine with the gold to form a soluble gold chloride complex; other metals in the alloy, such as copper, nickel, iron and zinc, dissolve along with the gold, and the silver is usually precipitated out as an insoluble silver chloride residue (Delmer Group, 2025) [4].

The impure gold button recovered from the amalgam burning is transferred to a metal container, along with some acid, and heated over an open charcoal fire until the solution vigorously boils, producing a dense and pungent orange-brown fume as it breaks down the metal. When the liquor is considered to be completely digested, then it is decanted or filtered and all the gold is precipitated out of solution in the liquor, usually by dissolving out the excess nitric acid and adding a reducing or precipitating agent, leaving at the bottom of the vessel tiny, dark, granular gold collectibles.

Fig 3: An acid solution containing dissolved gold is brought to a vigorous boil over an open charcoal fire, a step that drives off excess acid and concentrates the gold-bearing liquor. (Researchers Fieldwork, 2026

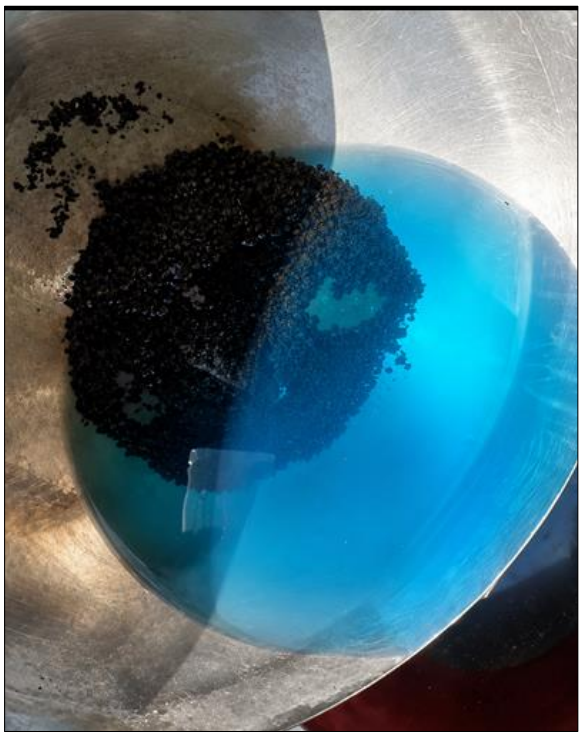

Fig 4: Fine, dark gold particles precipitate out of a blue-tinted acid solution in a metal basin, the visible product of the chemical precipitation stage of acid refining. (Researchers Fieldwork, 2026)

After washing, drying and melting the precipitated gold, a much purer, cleaner product than the button made from amalgam burning alone is obtained. This final product is in the form of a small polished nugget retrieved after the washing, and eventually a cast gold bar that is used by buyers and assayers to assess purity by a quick visual inspection.

Fig 5: A small refined gold nugget, cleaned of residual acid and sediment, displayed in a basin of water; the visible outcome of the precipitation-and-wash stage. (Researchers Fieldwork, 2026)

Fig 6: The final cast gold bar produced after melting the refined material, showing the characteristic lustre and form associated with higher-purity artisanal gold. (Researchers Fieldwork, 2026)

5. Comparative Technical Assessment of Mercury and Acid Refining

While both mercury amalgamation and acid-based refining are used informally, there are significant differences in their mechanism, product quality and hazards between these methods. A well-designed mechanism is crucial to ensure that products are of high quality.

5.1. Mechanism and Product Quality

Acid refining is a chemical dissolving and precipitation process while amalgamation is essentially a physical separation process based upon the affinity that mercury has to gold. When it is done correctly, aqua regia can dissolve up to 90-100% of exposed gold, including relatively coarse particles, and can be used to reach purities of nearly 99.99% (cited from Fine Gold Recovery literature) which is very rare when using amalgam burning alone, as the amalgam usually contains traces of mercury and base metal impurities.

5.2. Hazard Profile

The risks of acid refining differ from those of mercury, particularly if the mercury is a vapour; most of the applications are performed without fume hoods, the right ventilation, or protective equipment that is resistant to acid, or if the metal is heated in the presence of an acid mixture, the fumes can be toxic nitrogen oxides and chlorine gas, which is a different hazard. Closed-circuit operation and mechanical ventilation are emphasized as measures to avoid this direct type of fume exposure in industrial applications of aqua regia refining (Delmer Group, 2025) [4] which are rare in artisanal, small-scale, and open-air operations.

5.3. Environmental Persistence

Unlike the reagents employed in the conventional acid refining process, mercury is much more persistent in the environment. When released, elemental mercury can also be transformed by microbial activity into methylmercury, which is bioaccumulative, accumulates up the aquatic food chain and can be transported far from its point of release (ScienceDirect soil pollution literature 2021). Acid refining reagents, however, are typically reactive, and when added to water and soil, may not remain acid for long (unless they are disposed of incorrectly, which can cause acidic soils and watercourses, and mobilise, in the immediate vicinity of a refining site, heavy metals).

6. Policy and Regulatory Architecture

In March 2017, Ghana ratified the Minamata Convention on Mercury which requires Ghana, under Article 7 of the Convention, to draw up a National Action Plan with clear objectives and targets for reducing and, when feasible, eliminating mercury use in artisanal and small-scale gold mining (ASGM) (UNDP, 2017). The policy framework for the phase-down of mercury in Ghana is outlined in the National Action Plan (NAP) for ASGM, which was finalised in 2022, and which involves coordination of the Government, development partners and mining associations (Minamata Convention Secretariat, 2022) [6].

At the global level, the Minamata Convention works intentionally in an incremental way instead of being prohibitive because livelihoods in over eighty countries and an estimated fifteen million miners rely on the sector. (Keane *et al*., 2023) [5] The policy literature repeatedly suggests that health and environmental concerns are not enough to motivate miners to change their behaviour, because other arguments; such as improved gold-capture and lower costs—has proved more likely to change practice on the ground, for example through borax-flux smelting trials in the Philippines (Appel & Na-Oy, cited in ResearchGate discussion, 2018) [7].

Interestingly, formal policy attention of acid-based refining in the artisanal sector is still relatively limited. Large-scale, industrial scale aqua regia refining is currently under a different regulatory framework, with acid used under controlled conditions in closed circuits, with an increasing end-use of acid by small-scale processors, which is largely outside the same regulatory control that governs mercury use, implying an emerging governance gap that is not yet fully addressed by policy frameworks.

7. Socio-Economic and Cultural Dimensions

The selection of technology in artisanal gold processing is not a technical choice alone, but a necessity relating to economic, gender and community factors. One key to Mercury's continued dominance is that it is simple, inexpensive, and easy to use, with no need for specialised training or significant capital investment, when compared to mechanised, mercury-free alternatives like centrifugal concentrators which require more capital expenditure and technical capabilities (Keane *et al*., 2023) [5].

In sub-Saharan Africa, women also participate in ASGM processing, and in some cases, are the ones who are making the decisions regarding the use of the ASGM technology instead of men, however, they are still very much involved in the process, working in close and frequent contact with mercury, even though they are not the main decision makers about technology used for processing (Locating Female Voices literature, 2020) [11]. This division of labour is gendered and has implications for communication and adoption of safety information and other technologies in mining households or communities.

Concurrently, the transition to acid-based secondary refining is linked to the increasing sophistication and specialization of Ghana's ASGM value chain as distinct actors take on different roles within the chain; ore winners, amalgam processors and gold refiners rather than a single miner doing every step of the extraction and purification process. The focus of this specialisation reflects the historical division of labour in Akan gold-working communities in which smelting, casting and goldsmithing were regarded as distinct crafts with specific skills and dangers, despite the fact that the chemistry and danger of acid refining have vastly changed since precolonial days.

8. Conclusion

The photo sequence explored in this article follows a path of refining which starts with mercury amalgamation, moves further into the open-air burning process, and progressively makes its way into a secondary stage of acid-based refining, resulting in gold with progressively increasing levels of purity, from precipitated granules to a finished cast bar. The steps represent a sector that's going through a transition but hasn't entirely discarded mercury, but rather uses acid-based techniques to enhance product quality and consequently market value. Both steps in this composite operation, however, are very informal, under-regulated and quite without the safeguards that make each technique manageable in an industrial setting. Both the effects of mercury vapour exposure during the burning of amalgams and corrosive or toxic fume exposure during acid digestion are well documented and are serious threats to the health of the operators, their families and the surrounding environment. Solutions to these threats must involve policy and technical solutions that address the situation along the entire refining chain, not just its mercury-intensive first phase.

9. Recommendations

The following recommendations are put forward in the wake of the above themes:

1. Apply the same regulatory standards to acid-based refining. The National Action Plan in Ghana on mercury use should be supplemented with specific guidance on how to safely purchase, manage and dispose of the acids used for refining which are in the informal sector, bridging the governance gap identified in Theme Five.
2. Purchase retort and fume-capture technology. Simple, low-cost mercury retorts, which will condense and recover mercury vapour during the burning of the amalgams, and basic fume-extraction or scrubbing arrangements for acid digestion of the ore should be subsidised and promoted amongst the small-scale processors so as to minimise the inhalation exposure at both points in the refining chain.
3. Encourage the use of concentration technologies that do not use mercury. Investing in and subsidising gravity-based alternatives to mercury amalgamation, such as centrifugal concentrators, could help eliminate the need for mercury amalgamation entirely if there are cost and training challenges that need to be overcome (Keane *et al*., 2023) [5].
4. Enhance occupational health monitoring. Biomonitoring mercury and, if applicable, nitrogen oxide exposure should be included in routine community health programming in mining areas, and screening for renal, thyroid and neurological function should be made available to mining workers.
5. Design gender-responsive interventions. Women's role in handling of amalgams and washing of ores is important but is scarcely recognized, therefore, safety training and provision of safety equipment should be done with deliberate focus on reaching women processors as well as male mine operators.
6. Enable formalisation of refining value chain. It would be easier to promote small-scale refiners to form recognised cooperatives or licensed processing centres to effectively introduce shared safety infrastructure, monitor practice and provide training and subsidy resources.

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