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Assessment of Gold and Mercury Losses in an Artisanal Gold Mining Site in Nigeria and Its Implication on the Local Economy and the Environment

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Abstract: The objective of this work was to establish the gold and mercury losses in an artisanal mining deposit (Uke) in Nigeria to convince miners about their inefficiency and suggest changes in their gold extraction practices. Samples of feeds and tailings from five sluice box concentration processes previously ground in hammer mills below 1 mm (P80 = 0.5 mm) were systematically sampled every 15 min. for 4 h and sent for gold analyses by a fire assay and intensive cyanidation. Dry grain size analyses of primary and amalgamation tailings allowed us to find out in which size fraction gold and mercury are lost. Total mercury losses in sixteen operations were obtained by weighing mercury at the beginning and in all steps of the concentrates' amalgamation. After analyses, the average gold grade in the feed resulted in 3.80 ± 1.52 ppm (two standard deviations). The gold recovery was 29.24 ± 13.24%, which is low due to a lack of liberation of the fine gold particles from the gangue (silicates). Finer grinding would be necessary. The mercury balance revealed that 42% of the mercury added is lost, in which 26% involves tailings and 16% evaporated. The Hg_{Lost}-to-$Au_{Produced}$ ratio was found to be 3.35 ± 9.46, which is exceedingly high for this type of amalgamation process that should have this ratio around 1. One reason is the excessive amount of mercury in the amalgams, 76.5 ± 38.12%, when the normal is around 40%–50%. Mercury lost by evaporation in open bonfires is clearly contaminating amalgamation operators (usually children), neighbours, and the environment. The Hg-contaminated tailings and primary tailings are sold to local cyanidation plants, and this can form toxic soluble $Hg(CN)_2$ in the process. The results of this research were brought to the attention of the miners and other stakeholders, including the regulatory agencies of the government. The % gold recovery by amalgamation was not established in this study, but if this process recovers 50 to 60% of the liberated gold particles in a concentrate and 30% of gold was recovered in the sluice boxes, then the total gold recovery should be between 15 and 20; i.e., 80 to 85% of gold mined is lost. On average, an operation produces 8.26 g of gold/month, which is split to six miners, representing USD 69/month/miner or USD 2.3/day. It was discussed with miners, authorities, and community members (in particular female miners) how to avoid exposure to mercury, how to improve gold recovery without mercury, and the health and environmental effects of this pollutant.

Keywords: artisanal mining; metallurgical balance; mercury; gold; Nigeria

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1. Introduction

Artisanal and Small-scale Mining (ASM) is widespread throughout Nigeria. The decline in conventional mining, triggered by policy decisions made shortly after the country's independence in the 1960s (including the indigenization policy), resulted in the departure of foreign mining companies. Additionally, the windfall from the oil and gas sector at the time diverted the attention of the then government away from the mining sector, leading to ineffective control of the mining by the State. The combination of these factors in the 1980s marked the onset of ASM in Nigeria [1]. Although a precise figure may not be available, it is believed that ASM plays a significant role in mineral production in Nigeria where over 90% production of important minerals such as gold, cassiterite, and gemstones is attributed to ASM activities [2–4]. Therefore, the conventional mining industry remains in its early stages, as evidenced by its contribution of just 0.9% to the nation's GDP.

Despite some explorations from conventional mining companies, the country's gold mining subsector is rife with typical issues associated with ASM, such as informality, low mineral production, inefficiency, and social and environmental problems. Major issues that highlight the importance of this study are poor mineral production (in this case gold), a lack of requisite ore processing skills, contaminations from mercury and cyanide, as well as the apparent inefficiency in managing and regulating the artisanal and small-scale gold mining (ASGM) industry and the government's pursuit to improve gold production from ASGM through cleaner and mercury-free production practices.

The poorly regulated ASGM in the country resulted in the use of unwholesome gold extraction processing, which led to widespread pollution that caused the lead poisoning that occurred in Zamfara State in the northwestern part of the country in 2010 [5] and in Niger State in the north-central part of the country in 2015 [6]. In both cases, miners used a dry milling process to pulverize the lead-rich gold ore, resulting in the release of lead laden dust that polluted the host communities. Although attention was focused on de-escalating the incident, which claimed the lives of more than 400 children of an age below 5 years, through remediation and treatments of impacted individuals [7], it was also observed at the time that the inappropriate use of mercury by miners within households was another impending public health risk [8].

According to the NAP—National Action Plan of Nigeria (2021) [9] to the UNEP—United Nations Environment Programme, the artisanal gold mines in seven States of the country produced annually 17 t of gold, releasing 20 t of mercury to the environment. The artisanal gold mining operations in the country are under evaluated with some inconsistencies in the available information about the official gold production. Yoshimura et al. [10] mentioned that some technical publications reported in 2014 and 2017 gold productions of 4 to 8 t, respectively. The US Geological Survey [11] reported that the Nigerian gold production in 2019 was 160 kg. The number of artisanal gold miners in Nigeria is also unclear with estimates ranging from 260,000 [9] to 500,000 [12]. The Director of the Artisanal and Small-scale Mining department of the Ministry of Solid Minerals Development, Mr. Yunusa Mohammed (personal comm., 2024), believes that there are over 2 million artisanal miners in the country in which half are directly involved in gold production. Field inventory was never conducted in the country.

The environmental assessment of mercury and other heavy metals in artisanal gold mining in Nigeria has been studied by various authors, sometimes related to the soil degradation caused by mining, which reduced the floristic composition [13] or the possibility of soil reclamation for other uses such as agriculture [14,15] and sometimes related to the concentration of these metals in soils, highlighting the risks of bioavailability of the pollutants to plants and humans [14,16,17]. Despite being the main livelihood of individuals in rural areas of Nigeria, articles condemn the presence of artisanal miners. No article was found to suggest changes in miners' behaviour or alternative livelihoods or methods to improve their rudimentary gold ore processing.

Nigeria became the 88th Party to the UN in the Minamata Convention when it signed the treaty on October 10 2013, and ratified it on February 1 2018 [18]. To formalize the gold mining subsector, the government of Nigeria introduced several measures including the recognition of ASM by the country's mining law and policies as well as establishing a department for ASM in the Ministry of Solid Minerals Development (MSMD). Although the Nigerian government completed the National Action Plan for the elimination of mercury use in the ASGM sector in 2021 [9], it has yet to commence a structured programme to achieve the strategic plan. The ASM department with the Federal Ministry of Environment and the UNIDO are working on a new project to reduce the use of mercury in the ASGM sector in Nigeria through a multi-sectoral approach, which aims at institutionalizing sustainable mercury-free technologies and enhancing access to traceable gold supply chains, amongst others [19].

The country's regulatory department in charge of ASM may not have adequate infrastructure to provide technical support to the miners on how to improve their operations and reduce pollution [8]. The need to build the capacity of the officers of this department to effectively discharge their functions has been noted; e.g., the US Environmental Law Institute [8] recommended that the personnel of the ASM department must be trained to be well versed in the range of alternative mining technologies available to reduce as well as eliminate mercury use. This is one of many aspects of the ASGM problems in the country.

Worldwide, there have been many intervention projects disparately aiming to address one problem of ASGM, in which mercury pollution is the main centrepiece [20,21]. Usually, the project approaches have been a single viewpoint and no attempt has been made to combine them in a holistic socioeconomic–technical approach [22]. None of these approaches, when individually applied, have brought substantial improvements to the artisanal gold mining sector in particular, in terms of mercury pollution reduction. For a more positive effect, any intervention must take into cognizance the fact that artisanal miners, by default, do not have any interest in understanding the environmental, social, and health problems they cause, let alone improving their methods based on the arguments of introducing cleaner techniques. Miners are usually suspicious of the intentions of projects with environmental and health objectives. It is usually not easy for them to be implemented in a safe way by artisanal miners; therefore, it is crucial to understand the needs of the miners, the source of their perceptions, and the knowledge to engage them in a fruitful discussion [21]. Projects promoting better and cleaner technologies to artisanal gold miners are important but changes in the polluting behaviour are only temporary [23]. In most cases, the projects bring pieces of equipment to demonstrate to miners without even knowing the current gold recoveries and the ore characteristics. Projects have temporary effects as when miners face problems, they return to their polluting methods [24]. From the technical point of view, it is important to engage with miners in bringing solutions to improve their gold recoveries whilst aiming to eliminate amalgamation.

But to proffer appropriate and site-specific interventions to upgrade the skills and to integrate cleaner production concepts in gold extraction techniques for artisanal miners, it is imperative to carry out a thorough assessment of the existing processes, the level of gold recovery, amounts of mercury losses, skills of the miners, and who are the main vulnerable people to mercury pollution. It is necessary to fully understand what the necessities are regarding gaps in knowledge, technical know-how, and educational deficiencies. Only with a clear understanding of the mining (and community) needs can a successful project be designed. This can be achieved by conducting a thorough Needs Assessment to establish the level of skills and understanding of the relevant stakeholders (government interventionists and the artisanal miners) [25].

The main hurdle to suggesting any change in the processing steps, including amalgamation, is the lack of information about the current gold recoveries and mercury losses. Miners usually believe that they extract 90 to 100% of the gold from the ore they mine. They also believe that the amount of gold produced is the main parameter to control their operations, but this depends on the grade of the ore (feed) and the percentage of gold recovery, which is a parameter of efficiency. As the grade of the ores varies constantly in artisanal mining operations, the amount of gold produced is not an indicator of efficiency. In order to obtain the gold recovery and mercury losses, it is important to conduct in the field some simple metallurgical balances of the existing operations [26,27]. Only with this information and the trust of miners it is possible to prove the amounts of gold and mercury lost. This information is basic to suggest methods to improve their techniques. Mercury elimination is the last step in this process of building trust, building capacity, and increasing processing efficiency. It is on this premise that this study was carried out with the aim to comprehensively assess the existing processes regarding artisanal gold mining and processing to obtain the requisite information on metallurgical balances for gold and mercury in a primary concentration step in artisanal gold mines in Nigeria towards supporting the drive to advance cleaner ASGM operations.

This article is part of a short-term project sponsored by Global Affairs Canada and implemented by Alinea International, executed in Nigeria under the Technical Assistance Partnership—Expert Deployment Mechanism (TAP-EDM) from 2023 to 2024. The programme aimed to render technical assistance to the Nigerian Ministry of Solid Minerals Development towards addressing mercury use in the Nigeria artisanal and small-scale gold mining sector.

2. Overview of ASGM in Uke Artisanal Gold Mining/Processing Site

Uke is a small town located on latitude 8.91722°, longitude 7.6975° in Karu Local Government, Nasarawa State, some 37 km southeast of Nigeria's Capital City, Abuja (Figure 1). According to the Nigerian Geological Survey Agency [28], gold in Uke occurs as primary ore deposits within quartz and quartz-felspathic veins, which are hosted in the biotite-gneiss suits of the rocks of the Basement Complex. It is estimated that about 20–30 troy oz (0.62 to 0.93 kg) of gold are recovered daily through artisanal gold mining operations [28].

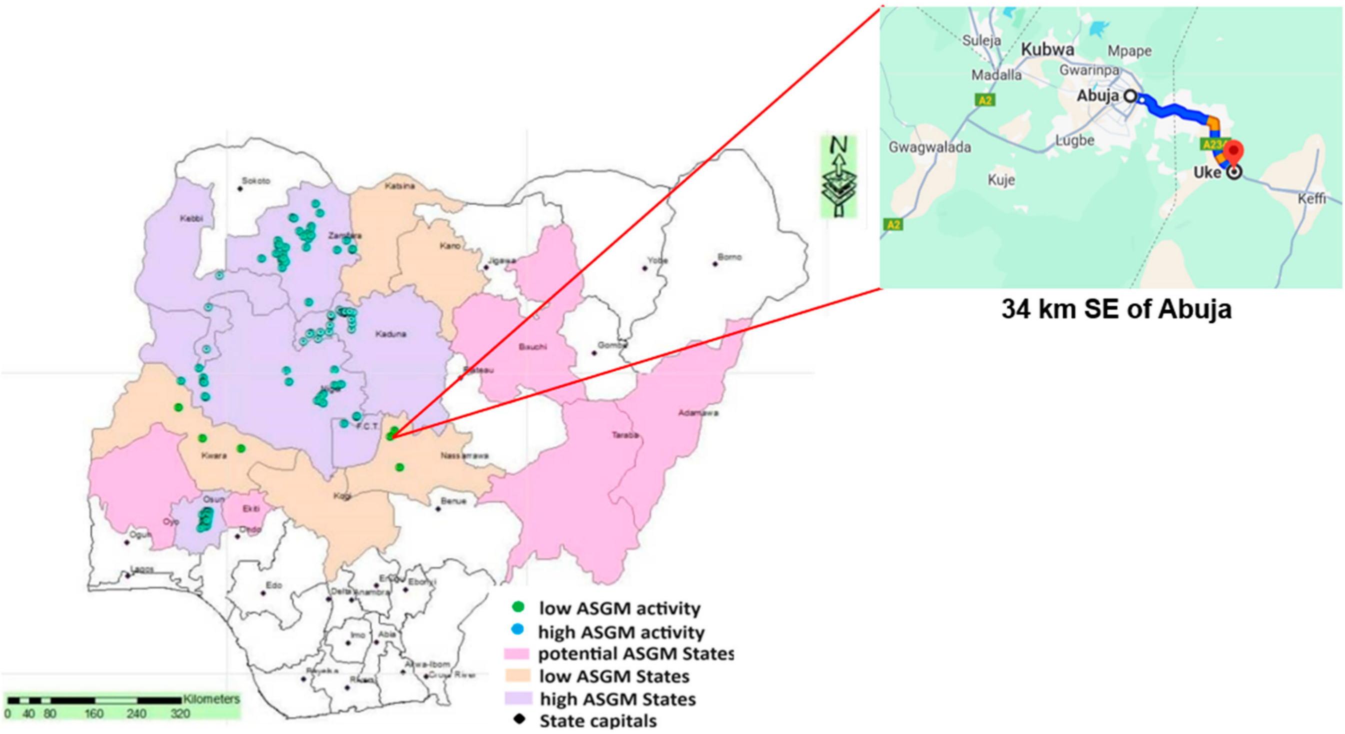


Figure 1. The location of the Uke town and mine. Sources: [9,29].

The Uke artisanal gold mining region provides a direct source of livelihoods to about 4000 miners at the mines and processing centres. The working conditions at the mines and processing areas were found to be extremely poor and with equipment spread all over the ground (Figure 2). The mining method is underground (Figure 3), reaching a depth of 20 m and operated by six miners per group that blast, muck the ore, and pull buckets to the surface. There are 60 miners from different groups working underground in a specific mineralized zone. The ore is carried manually to a truck that transports it to the processing area 4 km away (Figure 4). The mining operation involves seven days of blasting, mucking, hauling, and transporting the ore to the surface and to processing plants by truck. The typical load of ore in a truck is 6 tonnes per a shift of one week. Another week is used by the group of miners to process the ore. In total, it takes about two weeks to have the gold in the miners' hands.

Figure 2. Ore to be ground in the Nasarawa mine site.

Figure 3. The underground mine in Nasarawa. Ore is hauled to the surface and carried to the plant.

(**a**) (**b**)

Figure 4. (**a**) Boy crushing ore and (**b**) dry hammer mills dry-grinding it below 1 mm.

The ore processing area is located adjacent to a perennial stream. The 6 t of ore, brought by a truck, is crushed manually (at a price of NGN 200/bag of up to 148 kg or USD 0.26 as in June 2023) mostly by women and young girls and boys using hand hammers. The crushed pieces of ore are then carried to be ground by dry hammer mills to particle sizes below 1 mm (Figure 4), obtaining P80 = 0.5 mm (80% of mass below 0.5 mm). The dry ground ore is stored in large bags to be transported to the concentration sites using sluice boxes that are 4 m long and 0.3 m wide (Figure 5). These sluice boxes process, on average, the 6 tonnes of ore in one week (50 bags of 110–148 kg), resulting in 20–30 kg of concentrate that is amalgamated.

Figure 5. Gold concentration in sluice boxes at Uke mine site.

The gravity concentrates retained on the wool carpets of the sluice boxes are manually amalgamated in bateas, and the excess mercury is squeezed off, i.e., manually filtered with a piece of fabric (Figure 6). The decomposition of the gold amalgam is conducted in small bonfires. A boy was witnessed blowing into a bonfire to increase the temperature and speed up mercury evaporation. The occupational hazard is evident (Figure 7). This seems not to be an accidental event as it has also been reported by Odukoya et al. [30] that boys are the ones in charge of the amalgam decomposition. In many artisanal mining sites, kids and women are those doing the dirty work of amalgamation with the poor "excuses" of the male miners that "*they do a better job*". In many cases, male miners know the dangers of mercury but they do not pass the information to women and kids [31].

Figure 6. Manual amalgamation and filtration with a fabric to remove excess mercury.

(**a**) (**b**)

Figure 7. (**a**) Buying mercury at the Uke mining site. (**b**) A boy burning an amalgam in a bonfire.

Less than 0.01% of elemental mercury is absorbed by ingestion [32]. The main pathway of the bioaccumulation of metallic mercury to miners and community members is through inhalation. Elemental mercury vapour is absorbed through the lungs and oxidized, forming Hg (II) complexes soluble in the blood. These complexes can cross the blood–brain barrier, causing neurological problems. The biological half-life of Hg in blood is short, about 2–4 days, when 90% is excreted through urine (and feces). In the kidneys, the half-life of mercury is from 15 up to 60 days, which is a reason why urine is better than blood as a bioindicator for metallic mercury vapour exposure [33–36]. Nutfall [37] mentioned that 80% of inhaled mercury is retained in the human body and the median peak of urine excretion in the studied subjects was 19 days after exposure with a median half-life of 40 days. Bose-O'Reilly et al. [38] outlined the health impacts of mercury vapour from ASGM in the Philippines, Mongolia, Tanzania, Zimbabwe, and Indonesia. Correlating data of urine analyses with neuropsychological exams, the authors identified chronic intoxication symptoms such as a tremor, ataxia, coordination problems, excessive salivation, and a metallic taste. These symptoms were more evident in individuals burning amalgams without retorts or personal protection. Another interesting review of the health impacts of mercury was conducted by Taux et al. [39]. After screening 10,589 articles describing occupational health mercury impacts, the authors selected 19 cases of quality to mention. The authors stressed the importance of considering bias and confounding factors in health assessments as well as the lack of high-quality studies on this subject, such as a lack of a defined control group, lack of a clear definition of mercury-related diseases, and lack of a diagnostic standard to detect mercury intoxication. A suggestion of a sound health assessment of artisanal gold miners was published by Veiga and Baker [40], where the authors stressed the importance of assessing control groups, life, and work styles, and always returning the results to the individuals who provided biological samples such as hair (for assessment of methymercury from fish ingestion) and urine (for assessment of mercury vapour exposure). Levels above 20 μg Hg/L of urine is considered prone to be observed alongside neurological symptoms such as an early indication of a tremor and problems in neuropsychological tests [41].

The local price of mercury in Uke was NGN 12,000 (USD 15.4 as in June 2023) per 10 mL, representing USD 113 per kg of mercury, which is equivalent to 2.3 g of gold. Mercury is openly and freely sold at the site.

Inquiries at the mine indicated that part of the Uke geological deposit belongs to a group of investors from Burkina Faso and several other shafts belong to different owners. Local miners must pay to owners a fee of three ore bags of 110–148 kg each per truck of 6 t of ore they mined. There is no standard for the weight of the bags of ore as they were found to vary greatly. We randomly weighed 14 bags of ore before processing and the average weight was found to be 127.8 ± 25.8 kg (two standard deviations) (Table 1). The tailings from the processing area are sold to the Burkinabes who buy them at a low price of NGN

300,000 (USD 385 as in June 2023) per truck of 6 t or USD 64/t. The miners sell the tailings without knowing the gold grades in the material. Gold *doré* is easily and freely sold at the processing area at a price of USD 50/g (as of 19 June 2023). The international gold price on this day was USD 1950.09/oz or USD 62.7 per g.

Table 1. The determination of the average weight of a bag of ore in Uke.

Sample #	Weight (kg)
1	121.00
2	123.80
3	147.00
4	148.00
5	135.80
6	118.20
7	116.60
8	127.60
9	137.80
10	137.60
11	137.20
12	120.60
13	107.40
14	110.80
AVERAGE	**127.81**
STD	**12.90**

Conversations with local mining leaders about the origin of the artisanal miners encountered in Uke indicated that most of the miners are migrants. According to these leaders, many miners migrated from the northwestern part of Nigeria, notably, Zamfara, Kebbi, and Kaduna States. Nigeria's northwest has for many years become a hotbed of insecurity characterized by activities of bandits [42]. The effect of the insecurity on gold mining activities in the region is huge. MSMD reported a loss of about NGN 353 billion, equivalent today (20 October 2024) to USD 217 million, to the government, from the illicit activities of miners and gold smugglers across the northwest [43]. The loss of economic activities in the region triggered the migration of people to other parts of the country. The insecurity and the subsequent ban on mining activities in the northwest stimulated the migration of many artisanal gold miners to other parts of the country such as to Osun State in the southwest and Nasarawa State, in the northcentral parts of the country [44].

It was noted that gold mining in Uke was a recent development, which attracted many miners from across other regions to Uke. Being an alien activity, this explains why most of the locals are not actively involved in mining or processing but rather concerned with maintenance of order and control at the mine. Others are engaged in ancillary activities such as using motorbikes to haul ore or concentrates from short distances and in faring commuters in and out of the mine. The manual and primary crushing of ores and providing catering services are almost exclusive jobs to local kids and women. As noted in other studies, artisanal gold mining has brought some positive economic impact to the Uke community; notable is the creation of job opportunities for the local youths, most of whom have become commercial motorcyclists and truck drivers [45]. Like the situation in Niger State in the northwestern part of the country, artisanal gold mining in Uke has also come with an upsurge in social vices, notably drug abuse, that were probably previously unknown to the communities [46].

3. Materials and Methods

The research was field-based, comprising collections and laboratory analyses of samples, meetings, and interviews with miners and participants' observations. The main goal was to obtain metallurgical gold and mercury balances, enabling the determination of the mercury lost to the environment, mercury-to-gold ratio, gold recoveries, and gold losses.

The following methods were applied: (a) gold balance using a fire assay and intensive cyanidation, (b) mercury balance weighing all products of the amalgamation step, and (c) a Dry Grain Size Analysis of a sluice box tailing and an amalgamation tailing, to observe in which size fractions gold and mercury were lost.

3.1. Procedure for Gold Balance

Gold balance is an important step to check the gold (Au) recovery the artisanal miners have in their processing operations. Usually, miners believe that the percentage of gold recovery is the same as the grams of gold they produce per day or month, but in fact the percentage of gold recovery is only one parameter, and should not be the only one, to assess performance of a processing plant. The % gold recovery is calculated by

$$\mathrm{Rec}_{\mathrm{Au}}(\%) = \frac{\mathrm{W_p} \cdot \mathrm{Y_p}}{\mathrm{W_i} \cdot \mathrm{Y_i}} \cdot 100$$

where W_p is the product (concentrate) mass (kg or t), W_i is the mass of ore in the feed (kg or t), Y_i is the Au grade of the feed in ppm (mg/kg or g/t), and Y_p is the Au grade of the concentrate in ppm.

Analyses of gold grades in concentrates are not recommended as this produces high variations in the grade due to the nugget effect and miners are suspicious to see anyone else touching their concentrates. In this case, the best solution is to obtain the % gold recovery by an indirect method, i.e., analyzing the feeds and tailings. The mass of concentrate (~0.02–0.03 t) in a sluice box is insignificant compared with the mass of material being processed per batch, around 6 t; then, it is possible to make the mass of tailings (W_t) equal to the mass of feed (W_i). The percentage of gold recovery, $\%\mathrm{Rec}_{\mathrm{Au}}$ (in concentrates), is obtained indirectly:

$$\%\ \mathrm{Rec}_{\mathrm{Au}} = 100 - \left(\frac{\mathrm{W_t} \cdot \mathrm{Y_t}}{\mathrm{W_i} \cdot \mathrm{Y_i}} \cdot 100\right) \text{ If } \mathrm{W_t} \approx \mathrm{W_i}, \text{ then: } \%\ \mathrm{Rec}_{\mathrm{Au}} = 100 - \left(\frac{\mathrm{Y_t}}{\mathrm{Y_i}} \cdot 100\right)$$

The Y_t is the gold grade of the tailing and Y_i gold grade of the feed. The % gold recovery, in this case, is the amount of gold recovered in the concentrate relative to the amount of gold entering the concentration process. The gold recovered in the concentration process is not the amount of gold extracted. Miners use amalgamation to extract gold from the concentrates. Amalgamation is very inefficient, as it traps only the fully liberated (free) gold particles [47]. The % gold extraction in the amalgamation process was not the focus of this article.

The following process was followed to determine the gold balance in the concentration step. This technique requires chemical analyses (in a lab) of FEED and TAILING samples. Usually, replicates (triplicates) are desirable to confirm the results and eliminate any nugget effect. The following steps were applied:

1. Five gold concentration processing operations in use (sluice boxes) were identified and sampled.
2. Sampling in each sluice box was performed by collecting, every 15 min. with a mug, a sample of approximately 250 mL of pulp of feeding material (a cup of pulp) entering the sluice box. The sample was tossed into a 20 kg bucket (designated for Feed samples). After 15 min, another feed sample was collected in the same operation and added to the same bucket. Concomitantly, samples of 250 mL of pulp with 20% solids leaving the process (tailings) were collected and added into another bucket: the Tailing bucket. Samples of Feed and Tailings were collected for 4 h in each operation and added into the respective buckets (Figure 8).
3. The solid materials collected were allowed to settle in the buckets and water was syphoned off. The two composite samples per operation, Feeds and Tailings, were separately dried under the sun.

4. Two dry samples per operation, of approximately 1.5–2 kg/sample, were sent to a chemical lab.

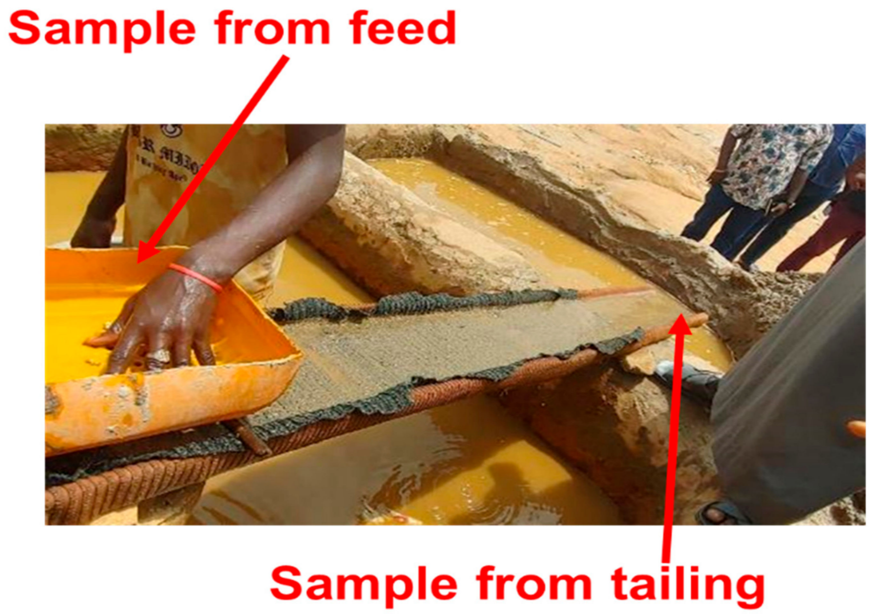


Figure 8. Sampling for gold balance in Uke.

The chemical lab (SGS laboratory in Accra, Ghana) prepared the samples (ground below 200 mesh—0.074 mm) and used two methods for gold analyses that they already have protocols for. Triplicate samples were used in each analytical method:

A. Fire assay of 50 g of sample: A gold bead was dissolved with aqua regia, and the gold grade was read in an Atomic Absorption Spectrometer at SGS Lab in Accra, Ghana.

B. An intensive cyanidation of 500 g of a sample ground below 0.074 mm and 1 L of water with 10 g of Leachwell©, which is 75% NaCN; 25% Sodium M-Nitrobenzene Sulphonic Acid, a strong oxidant; and ~0.5% Lead Nitrate, to speed up the cyanidation process. The leaching was conducted in rolling bottles for 2 h and solubilized gold was analyzed by Atomic Absorption Spectrometry.

3.2. Methodology for Mercury Balance

Mercury balance is also important to quantify the mercury losses to tailings and evaporation when the amalgams are decomposed. The mercury balance does not need any chemical analysis, just a small scale (operated by battery). The following protocol was used:

1. The weight of mercury before the miners adding it to amalgamate the concentrates was determined in a scale (this is the Mercury Entering).
2. The weight of the recovered mercury after the miners squeezed the amalgam off in a piece of fabric was determined (this is the Mercury Recovered by Filtering).
3. The weight of the amalgam the miners obtained after squeezing out the excess mercury was determined.
4. The weight of the gold doré after the amalgam was burned was measured (the difference between this weight and the previous weight is the Mercury Lost by Evaporation). This is the mercury with high potential to cause health problems.
5. The difference among Mercury Entering-Mercury Recovered-Mercury Evaporated = Mercury Lost with Tailings was the mercury with high potential to create environmental problems, such as that to be oxidized, complexed, methylated, and incorporated into the aquatic biota. This is also the mercury that forms toxic forms of complexes in the cyanidation plants.

The protocol for mercury balance was repeated in 16 operations and it is summarized in Figure 9.

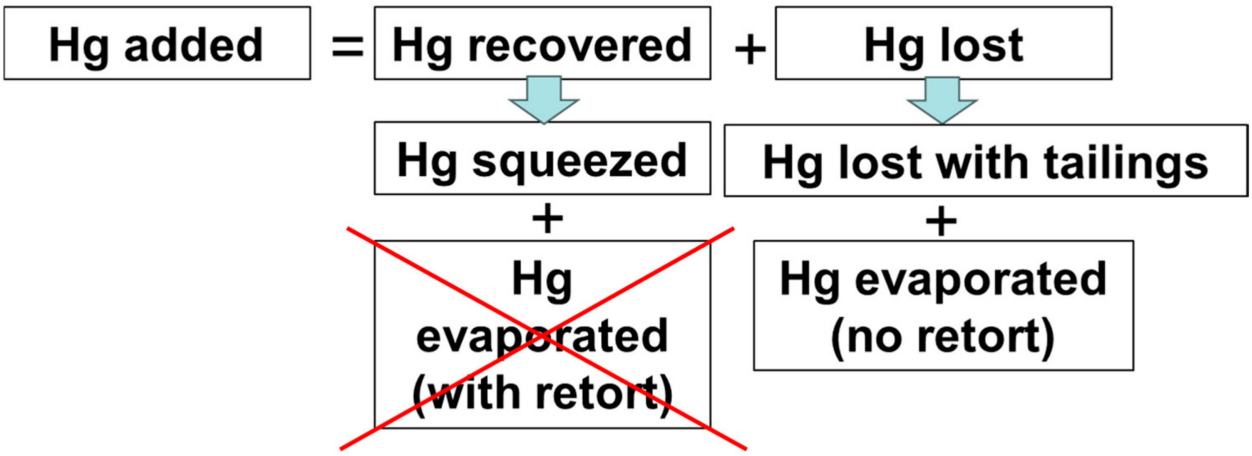


Figure 9. The scheme of the procedure for the mercury balance in Uke. No retorts were used in Uke.

This information might provide a clear idea about the mercury going to the environment with tailings and mercury vapour that can cause intoxication. This was brought to the attention of the miners as well as the loss of money that this causes.

4. Results and Discussion

4.1. Gold Results

The gold grades using both analytical methods were similar (Table 2. Average gold grades of the Feeds and Tailings of five operations in Uke.), but the intensive cyanidation (CN) extracted less gold (6.6%) than the fire assay (FA).

Table 2. Average gold grades of the Feeds and Tailings of five operations in Uke.

Method of Analysis	Average Gold Grade (g/t)		STD
Fire Assay (FA)	FEED	3.80	0.76
	TAILING	2.67	0.49
Intensive Cyanidation (CN)	FEED	3.55	0.65
	TAILING	2.39	0.43

A correlation between both analytical methods is shown in Figure 10. The intention of using intensive cyanidation was to provide more representativity as it uses a larger amount of a sample in the analytical procedure than the fire assay. The good correlation between the two analytical methods and the small standard deviation among triplicates indicate that gold nuggets are uncommon in the Uke deposit and the gold in the ore is fairly accessible to cyanidation when the ore is ground below 200 mesh (0.074 mm).

The gold recoveries from five sluice box operations in Uke, using both analytical methods, ranged from 19.6 to 36.8% with an average of 29.2 ± 13.26% (Figure 11). This means that the gold losses were around 70%.

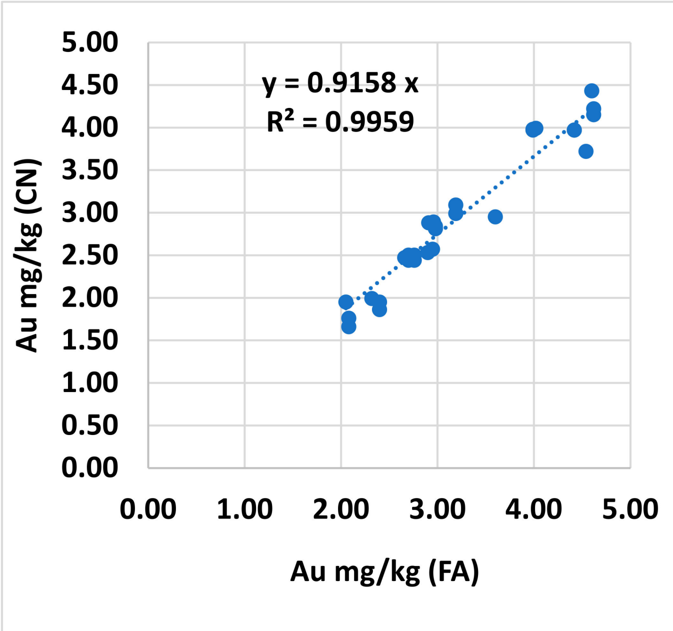


Figure 10. Correlation between fire assay and intensive cyanidation gold analyses.

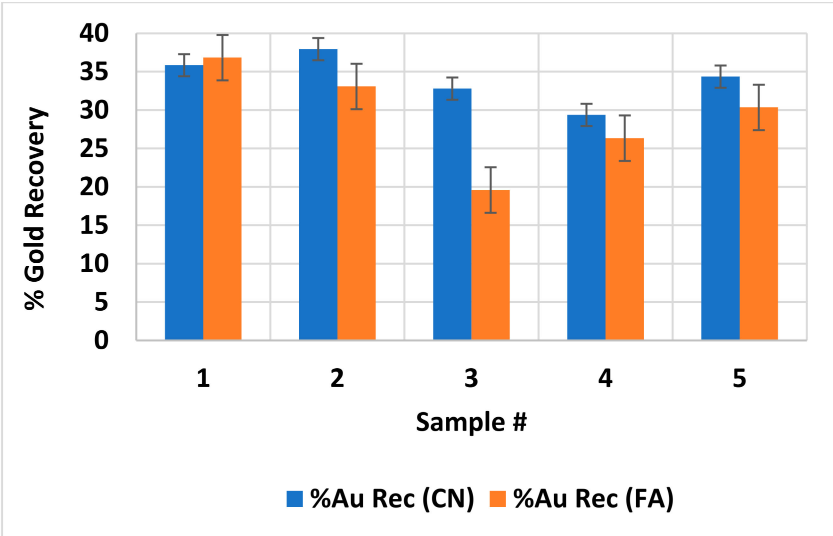


Figure 11. % gold recoveries in five processing concentration plants in Uke.

Dry grain size analyses (Ro-Tap) of a sluice box tailing with chemical analyses by a fire assay of the fractions revealed that most gold particles might be finer than 1 mm, a size ground by miners with the hammer mills (P80 = 0.5 mm). This grinding size is not enough for a full or partial liberation of gold particles from the gangue minerals (predominantly quartz). The degree of liberation of gold was not determined but it seems reasonable to believe that the loss of gold in the coarse fraction is due to a lack of liberation of the precious metal from the gangue minerals as the distribution of gold from tailings shows that 73% of the gold is in the −1.2 + 0.15 mm fractions. Finer grinding (e.g., <0.1 mm) is recommended using Chilean mills or ball mills. The grain size analysis cannot determine whether the gold in the −200 mesh (0.074 mm), not captured by the sluice box, is liberated or not (Figure 12). In further studies, methods to determine the gold liberation size, such as GRG (Gravity Recoverable Gold) suggested by prof A. Laplante [48] as well as microscopy of the concentrates, will be applied to find out the best grinding size for this ore to increase gold recovery.

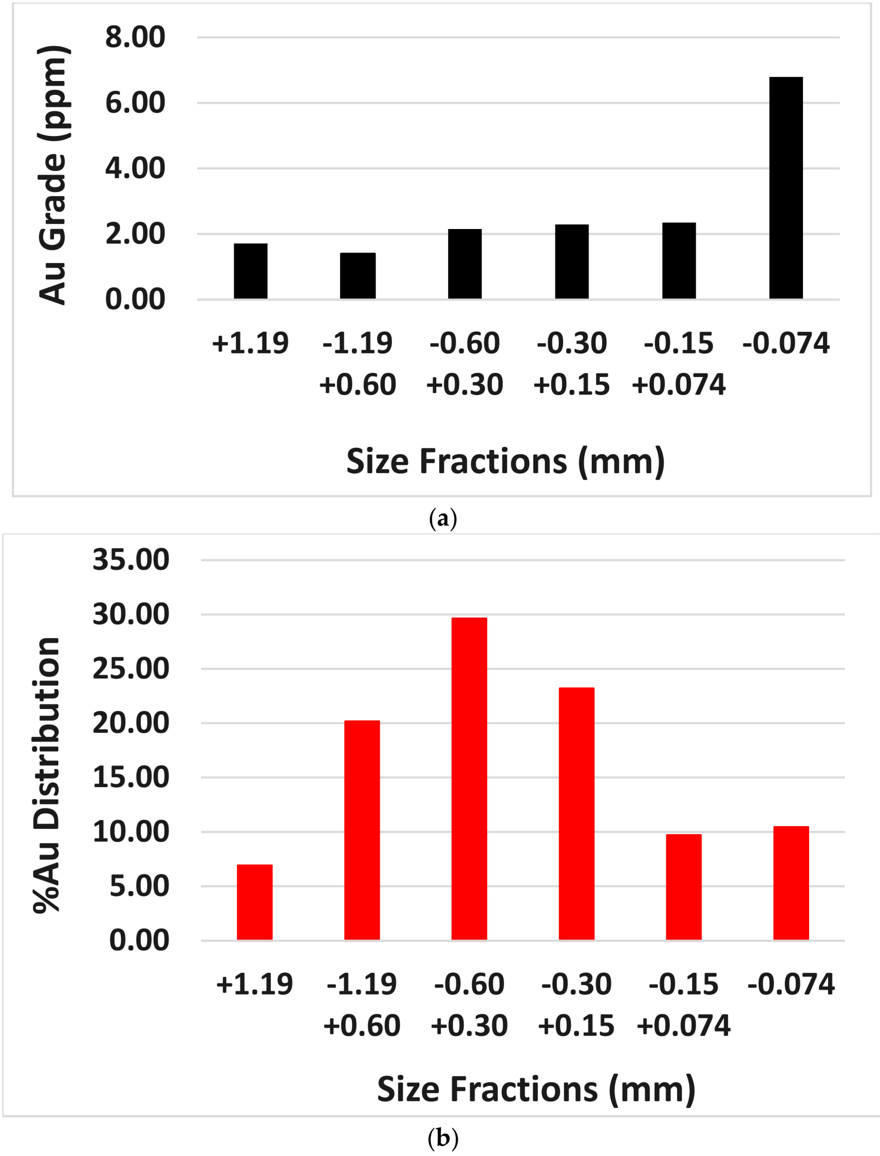


Figure 12. Grain size analysis of Uke tailing from sluice box. (**a**) Gold grades. (**b**) %Au distribution.

Brought to the attention of about 50 artisanal miners in Uke was a small-scale processing plant using six small Chilean mills and two or three centrifuges in series that was installed in Sudan to work with primary ores. The gold recovery increased from 30% (as per whole ore amalgamation used by the local Sudanese artisanal miners) to 70%–80%. With similar configuration (Figure 13), a mercury-free plant is being installed in an ASGM site in a country in South America. The Sudanese plant, processing 12 t/day (tpd) of ore, cost USD 110,000 in equipment and close to USD 100,000 for installation (Hassan Elnour, from Artisan Mining Co., Sudan, pers. comm., 2023). The plant, in Figure 13, configuration can process 15 t of ore per hour with capital costs close to USD 700,000, including all pieces of equipment and ancillaries installed; water and electric systems; civil- and earthwork; Engineering, Procurement, and Construction Management (EPCM); dormitories; a chemical lab; and contingencies. No chemical process, such as the cyanidation of concentrates or primary tailings, is included. This is not quite affordable for the Nigerian artisanal gold miners, unless a private company works in coexistence with them, which has been promoted.

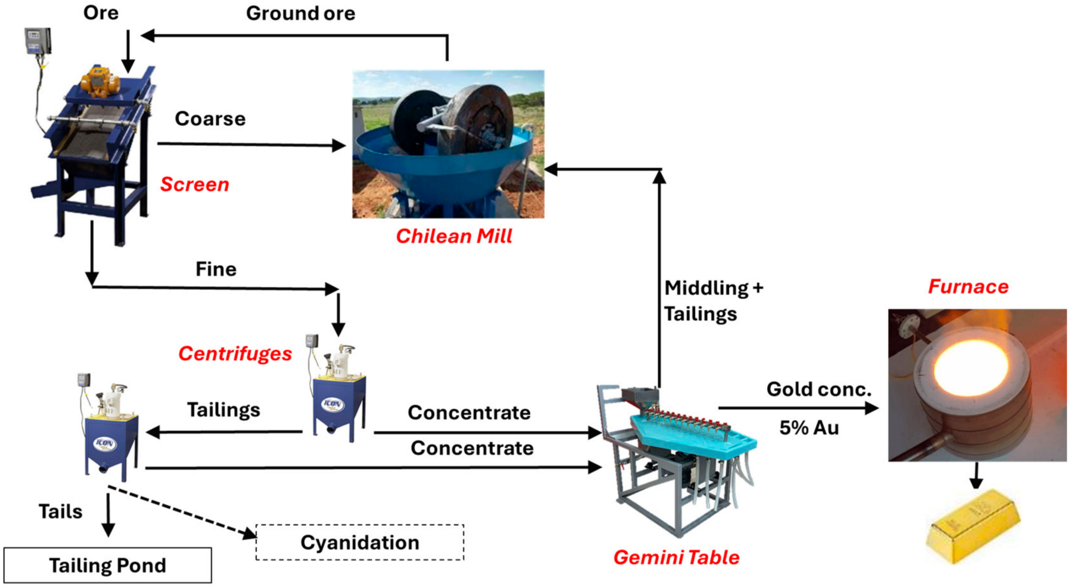


Figure 13. Suggestion of mercury-free processing plant using Chilean mills and centrifuges.

4.2. Mercury Loss Results

Amalgamation occurs in 20 to 30 kg of gravity concentrate obtained from sluice boxes. The mercury balance in 16 amalgamation circuits showed that on average 15.8 ± 25.8% of the initial mercury added to the process is emitted to the atmosphere and 26.0 ± 32.8% is lost with tailings (Table 3). The 16 amalgams studied had on average 76.5 ± 38.12% of Hg in the amalgam, which is very high, as the amalgams usually have 40%–50% Hg and 50%–60% Au and Ag when well manually squeezed [25]. Amalgams with higher than 40% Hg indicate that excess mercury, not combined with the precious metals, was not well removed.

There is a large variation in the quantity of mercury introduced in the amalgamation process as some miners add more mercury supposing that there is a large amount of gold in the concentrate. On average, miners use 18 ± 70.8 g of Hg to amalgamate 20–30 kg of concentrate. On average, 58.3 ± 33% of the mercury entering the amalgamation process is recovered (not combined with gold) when the amalgam is manually squeezed, which is normal.

The average ratio Hg_{lost} to $Au_{produced}$ of 3.35 ± 9.46 is remarkably high as this ratio should be around or below 1, when only concentrates are amalgamated [47]. One reason for this is the loss of nearly 26% of Hg with amalgamation tailings, which is an indication of the inadequacy of the "batea" panning method to separate the amalgams (with excess mercury) from the heavy minerals of the gravity concentrates. Also, as the amalgams with an excessive content of mercury are evaporated in bonfires, the mercury is lost to the atmosphere.

The mercury lost by evaporation is a health threat for operators and neighbours, especially pregnant women. Mercury is a neurotoxicant that has serious health effects on humans [49]. Simple retorts, using salad bowls and locally made, were demonstrated and donated to miners in Uke. The functioning of these retorts was thoroughly discussed with miners in the field and in presentations showing the advantages of avoiding contamination and recycling mercury. The retort condenses up to 95% mercury evaporated when an amalgam is burned, and it protects the operators from mercury vapour inhalation [50]. All these concepts were also discussed with a group of Nigerian female miners in a 3-day seminar in Abuja as well as in a 5-day course for MMSD employees and others. The education and distribution of simple retorts are key to increasing knowledge about the harmful impacts of the mercury vapours and reducing exposure [51,52]. The salad bowl retort, previously conceived by Veiga et al. [21], was modified by Chen et al. [53] using a condenser pipe to recover the liquid mercury. This good device was successfully demonstrated to Senegalese artisanal miners.

Table 3. Mercury balance in 16 amalgamation points in Uke.

Sample Point	Hg Added (g)	Hg Recovered by Filtration (g)	Hg Lost by Evaporation (g)	Hg Lost with Tailings (g)	%Hg Lost by Evaporation	%Hg Lost with Tailings	%Hg Recovered	Amalgam Obtained (g)	Doré Obtained (g)	%Hg In Amalgam	Hg Lost to Au Produced	%Total Hg Lost
1	8.78	4.83	0.25	3.70	2.85	42.14	55.01	0.47	0.22	46.81	17.95	44.99
2	152.00	33.00	44.00	75.00	28.95	49.34	21.71	75.00	31.00	41.33	3.84	78.29
3	33.00	13.00	5.00	15.00	15.15	45.45	39.39	7.00	2.00	28.57	10.00	60.61
4	25.00	19.00	1.19	4.81	4.76	19.24	76.00	2.00	0.81	40.50	7.41	24.00
4	7.50	4.99	0.50	2.01	6.67	26.80	66.53	4.10	3.60	87.80	0.70	33.47
5	2.40	1.26	1.13	0.01	47.08	0.42	52.50	2.03	0.90	44.33	1.27	47.50
6	9.46	6.47	0.30	2.69	3.17	28.44	68.39	3.10	2.80	90.32	1.07	31.61
1	8.48	2.96	0.77	4.75	9.08	56.01	34.91	1.60	0.83	51.88	6.65	65.09
3	9.45	6.32	0.40	2.73	4.23	28.89	66.88	2.20	1.80	81.82	1.74	33.12
8	6.58	4.45	1.90	0.23	28.88	3.50	67.63	5.60	3.70	66.07	0.58	32.37
9	3.12	1.25	1.07	0.80	34.29	25.64	40.06	3.09	2.02	65.37	0.93	59.94
10	7.13	4.87	1.10	1.16	15.43	16.27	68.30	4.90	3.80	77.55	0.59	31.70
11	11.38	8.18	1.48	1.72	13.01	15.11	71.88	7.08	5.60	79.10	0.57	28.12
12	2.95	1.73	0.23	0.99	7.80	33.56	58.64	1.03	0.80	77.67	1.53	41.36
13	8.56	6.42	1.88	0.26	21.96	3.04	75.00	8.08	6.20	76.73	0.35	25.00
14	5.63	4.47	0.40	0.76	7.10	13.50	79.40	1.80	1.40	77.78	0.83	20.60
16	4.81	2.31	0.86	1.64	17.88	34.10	48.02	3.66	2.80	76.50	0.89	51.98
AVE	**18.01**	**7.38**	**3.67**	**6.96**	**15.78**	**25.97**	**58.25**	**7.81**	**4.13**	**76.50**	**3.35**	**41.75**
STD	**35.41**	**7.96**	**10.14**	**17.35**	**12.66**	**16.44**	**16.54**	**17.46**	**7.13**	**19.06**	**4.73**	**16.54**

The salad bowl retort was initially covered with a glass bowl to facilitate the view of the mercury evaporation process, but this slows the cooling process of amalgam retorting; then, a cover with a stainless steel bowl was also demonstrated (Figure 14) [21].

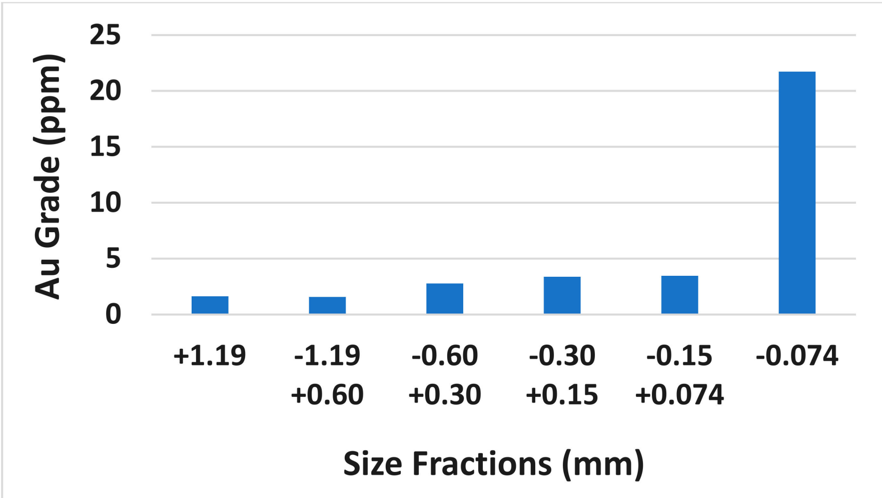
Figure 14. Salad bowl retorts made in Nigeria with glass and with stainless steel cover.

It was highlighted that mercury corrodes all metals but not iron, so the bowls cannot be made of aluminum. The use of small stainless steel bowls to hold the amalgam during the mercury evaporation normally results in yellow gold doré. Using ordinary steel, the gold comes out with a thin brown surficial layer, due to a reaction with iron. This is not appreciated by the miners as the gold buyers pay less for the gold. However, this layer is easily removed when the doré is hammered [54].

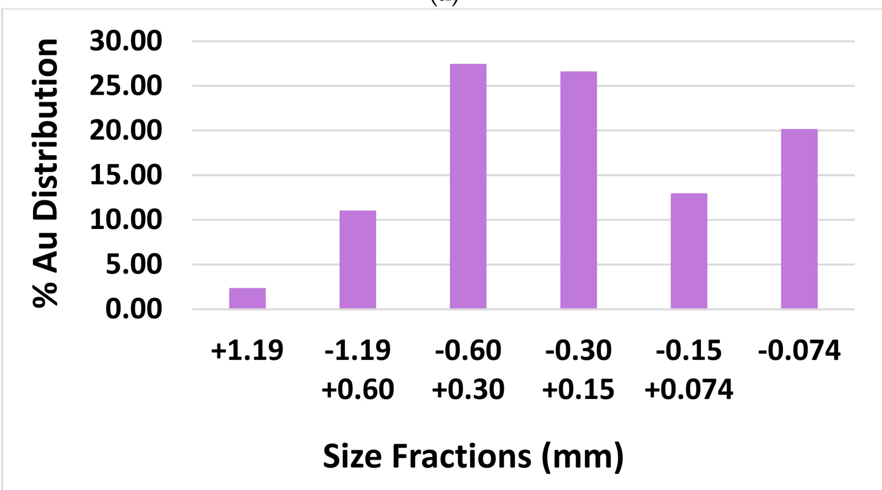
4.3. Gold and Mercury in an Amalgamation Tailing

One amalgamation tailing from Uke was separated by dry screening and each fraction was analyzed for gold and mercury with aqua regia digestion followed by Atomic Absorption Spectrometry. With the grades and weight of each fraction, it was possible to obtain the distribution of gold and mercury in this amalgamation tailing.

A reasonable part of free gold in the coarse fractions, −1.19 to +0.15 mm, was recovered by amalgamation, as the gold grades in the amalgamation tailing are lower than 5 ppm but still there is 65% of the gold lost in these fractions, likely not liberated from the gangue minerals (e.g., quartz) (Figure 15). The fine fraction, −200 mesh (0.074 mm), has almost 22 ppm Au and has 20% of the lost gold. Either mercury could not trap the free particles of gold, or the gold was not liberated even in this fine fraction. Mitchell et al. [55] mentioned that the free gold recovery by amalgamation fails for particles smaller than 0.070 mm probably by the surface tension of the mercury in contact with fine free gold particles. Andrade-Lima et al. [56] investigating an amalgamation tailing using dry grain size analyses and scanning electron microscopy also observed gold and mercury lost in the coarsest and finest fractions. A free gold particle of 0.03 mm was identified in the SEM.



(**a**)



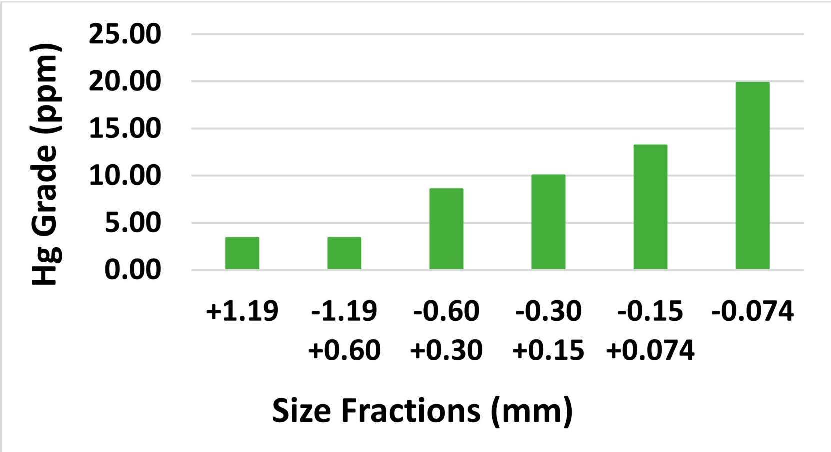
(**b**)

Figure 15. Grain size distribution of gold in amalgamation tailing from Uke. (**a**) Gold grades. (**b**) %Au distribution.

Sulphides were not visibly identified in the ore, but a detailed mineralogy will be conducted soon. The lost gold, if exposed in the gangue particles, can be extracted by leaching with cyanide, which is an advantage for the cyanidation processing centres in Uke and in other regions of artisanal mining in Nigeria.

Mercury was also analyzed in the size fractions of this amalgamation tailing. It is observed in Figure 16 that mercury was lost in finer fractions, indicating the loss of coalescence of the liquid metal, likely forming droplets that could not be recovered by panning [21]. However, it is odd that 82% of the mercury was lost in the fractions, −0.6 to +0.074 mm. It is interesting that the % Au distribution (Figure 15) and % Hg distribution

(Figure 16) have a similar pattern. This raises a question: Is it possible that the lost mercury is attached to unliberated gold particles? This is unknown and deserves more investigation. Esdaile and Chalker [57] mentioned based on a Scanning Electron Microscope exam that microscopic droplets of metallic mercury become trapped in the tailings not necessarily bounded to any mineral phase. So far, the only likely reason is that the miners do not carefully pan the amalgamated concentrate to recover the amalgam and residual mercury. A spiral wheel or an elutriator could be more useful to separate the mercury and amalgam from the heavy mineral after amalgamation, leaving less residual mercury in the tailings. In addition, the use of activated mercury with NaCl [21] is a viable alternative to avoid flouring of mercury in droplets and less mercury is lost with tailings. In the process, known as Dr. Pantoja's method [58], metallic mercury is connected via a cover copper wire to the negative pole of a 12 V motorbike battery and a rod of graphite that can be obtained from an old radio battery connected to the positive pole for 15 min. "Activated" mercury forms a sodium amalgam, which is much more coalescent than metallic mercury. This process mimics the industrial process used to manufacture caustic soda [21,47].



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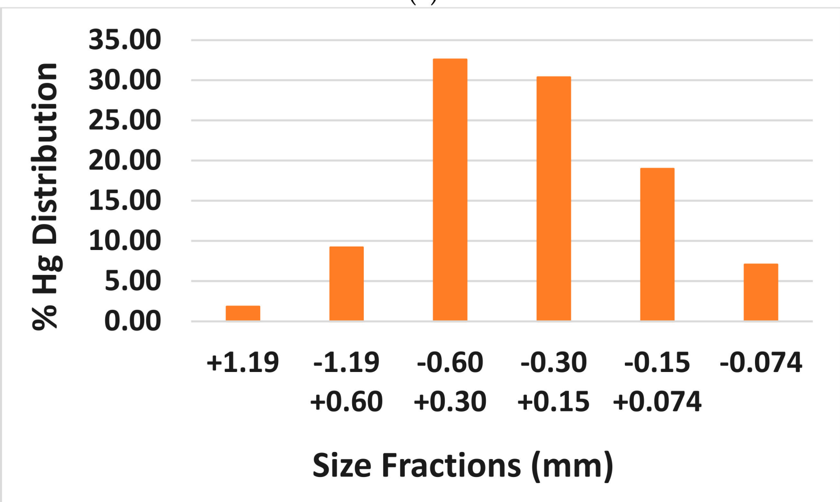

(**b**)

Figure 16. Grain size distribution of mercury in amalgamation tailing from Uke. (**a**) Mercury grades. (**b**) %Hg distribution.

Officially, as observed in the UN COMTRADE [59], Nigeria does not import high quantities of mercury. In 2013, it was imported at 28.3 t from South Africa; in 2014, it was imported at 0.655 from the USA; and only in 2022, the official imports reported were 0.103 t, also from the USA. In contrast, another signatory of the Minamata Convention, Togo, has been consistently importing massive tonnes of mercury since 2013. In 2022, Togo imported 159 t and in 2023, 486 t. With a low number of artisanal gold mines in this country, it is obvious that the imported mercury from Togo is reaching neighbouring countries.

5. Conclusions

This study showed that gold miners are losing on average 42% of mercury to the environment, 16% of which is emitted when amalgams are burned in bonfires and 26% to the tailings during the amalgamation process. It was found that in Uke, the mercury lost (Hg_{lost}) to gold produced ($Au_{produced}$) ratio was very high at 3.35, when this should be around 1 for this type of operation [47]. The mercury losses with tailings can be avoided using a better process (e.g., spiral wheels or elutriators) than panning to separate an amalgam from the heavy minerals. The losses of 16% of Hg by evaporation can also be practically eliminated if retorts are employed.

The main problem with metallic mercury vapour is the surrounding public and miners' exposure. Metallic Hg is not strongly absorbed by the skin, but miners must avoid working with bare hands as allergic dermatitis can occur [35]. Nigerian children directly exposed to mercury vapours, when burning amalgams, can be subject to acute poisoning, which can cause permanent damage to the nervous system and affect the lungs and kidneys [60–62]. By applying a simple retort and activated mercury, a significant amount of mercury would be recovered, protecting operators and surrounding individuals. Inexpensive masks with activated charcoal cartridges could also be used [63,64], but these are not very accessible in rural areas and miners usually do not believe that mercury vapours are so harmful. In addition, the masks would be safe for amalgamation operators but not for the neighbours.

The efficiency of the amalgamation in extracting gold from concentrates was not assessed in this preliminary study but, if the amalgamation extracts 50 to 60% of the (liberated) gold particles in a concentrate and 30% of gold is recovered through the gravity concentration, then the total gold recovery might be between 15 and 20%, or 80 to 85% of gold is lost. In another calculation, based on Table 3, each operation produces on average 4.13 ± 14.6 g Au per two weeks of processing 6 t of ore. If they process 12 t/month of ore with a grade of 3.8 g/t of gold, there are 45.6 g/month of gold entering the process of concentration and amalgamation. If they extract only 8.26 g, the total gold recovery is around 18%.

Amalgamation is not an effective way to extract gold from concentrates. Torkaman and Veiga [65], conducting a lab amalgamation of a ground (P80 = 0.13 mm) high-grade (approximately 49 ppm Au) Colombian artisanal mining ore, even using 28 times more mercury than what is normally used by the miners, found that the gold extraction was not higher than 19%.

Estimating that a group of six miners produces on average 8.26 g of *doré* a month, this is equivalent to USD 69 per miner per month (USD 2.3/day). Improving the gold recovery with better techniques, the economic benefit for the miners can be 4–5 times higher than this. The main challenge is the access of miners to capital for building decent mercury-free processing plants as well as skills to manage and operate these plants.

The information about how much gold is produced in the region and how much mercury is bought per month (which is equivalent to the amount lost) was not available. According to information from miners, gold is smuggled out of the country by the gold buyers and mercury is smuggled into the country probably from Togo. The loss of mercury is also an economic burden for the miners. The open burning of an amalgam and use of cyanidation by processing centres on amalgamation tailing, forming mercury–cyanide complexes, clearly show the dangers the host communities are being exposed to. The MSMD needs to do more to educate the miners to adopt cleaner technologies in line with the tenets of the Minamata Convention on Mercury for which Nigeria is a signatory [18].

More investigation is needed to elucidate the mechanisms of gold and mercury losses in the concentration and amalgamation processes. The ore mineralogy apparently has no or little visible sulphides but a detailed mineralogical analysis will be conducted using the

X-Ray diffraction of concentrates and tailings. The process to obtain indirect information about gold liberation, such as GRG (Gravity Recoverable Gold), is also to be conducted. The use of scanning electron microscopy is also considered to observe the losses of mercury in the amalgamation process. The idea of this first article was to demonstrate to miners their losses and the reasons for them.

The results of the metallurgical balances were presented to 50 miners in Uke. Suggestions about improving the concentration process, such as using zigzag sluices, controlling pulp density, use of vinyl 3M unbacked carpets, use of an Icon 150 centrifuge, and a Chilean mill with a screen of 0.1 or 0.2 mm, were presented to the audience. Other stakeholders including members of staff of the Ministry of Solid Minerals Development (MSMD), miners' association, and Federal Ministry of Environment were also presented with the findings of the study. Miners were shown how a demonstration plant could be established by the government or NGOs or private companies for the training of miners. Also explained was how the concept of coexistence would also work with a small, organized company, where the miners can sell their ores based on the gold content and the company processes the ore using better technology. This process has been shown to be working in many countries in Latin America [66] and miners make more money than concentrating and amalgamating the ore with low gold recovery.

The results of the gold and mercury losses of this study were shown to nearly 150 miners and authorities in the country with specific emphasis to female miners who are the most vulnerable parties to mercury vapour exposure. The environmental impacts of mercury were not deeply studied in the region but there are studies in similar sites in Nigeria [30,67–69]. The dispersion of mercury vapour in the region as well as the cyanidation of Hg-contaminated tailings must have a great impact on health and the environment. It was evident that artisanal gold mining in the study area is poorly regulated and that miners are clearly ignorant of the risks of harmful effects of mercury and dust that are being generated from their operations. They are also poorly informed of the necessary measures to change their practices. The ASGM activities in Nigeria, as in other developing countries, are expected to grow as the lack of economic alternatives is evident in the rural areas of the country [70–73].

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