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Optimizing Gold Recovery of Artisanal Mining: A Lesson Learned from Kenya

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Abstract

The metallurgical testings to treat the Kenyan artisanal gold mining samples were performed with several processes such as gravity concentration (i.e., Knelson Concentrator and panning), flotation, and cyanidation or leaching. These tests were conducted to find the best processing stages to improve the Kenyan artisanal mining recovery. Of the three categories of samples treated, sample A, which was processed through gravity concentration and flotation, produced 95.64% of gold recovery. Meanwhile, sample B could produce 98.74% of gold recovery with the cyanidation test. The results from sample A and sample B confirmed that the combination of the Knelson concentrator and flotation, which the Processing Center should handle, was the perfect combination to reduce the use of cyanide during the leaching process. On the other hand, the study also showed that the tailing sample (sample C) could still be recovered through flotation. With the results obtained, the best scenario was proposed. The government played a critical role in facilitating both the artisanal miners and the Processing Center for both cases in Kenya or Aceh.

Keywords: Artisanal mining, flotation, gold recovery, gravity concentration, leaching

1. Introduction

On a worldwide scale, there are at least 10 million artisanal miners in more than 70 countries working to extract gold (Veiga et al., 2009). According to Sousa et al. (2010), the artisanal and small-scale gold mining process is always associated with poverty. Therefore, it involves unskilled people, rudimentary techniques, and traditional equipment. To obtain gold, miners often do not consider environmental and safety factors. Sadly, this sector is deemed illegal in some places as miners also work without concession because of a lack of understanding of geological aspects.

Generally, artisanal miners in Kenya are migratory workers. They extract the mineral from site to site depending on: (1) life of mine; (2) high value of mineral strikes; (3) conflict and social issue; (4) restriction in the previous location; (5) existence of larger-scale miners; (6) quantity of rainfall and water; and (7) agricultural season (Anyona and Rop, 2015). They also sometimes work for landlords that pay them with food, water, and shelter with a share of the profit in the end (Anyona and Rop, 2015).

Like other countries, Kenyan artisanal mining has become a sector offering socio-economic benefits but causing land degradation, habitat damage, and soil and water contamination for a long time (Ngure et al., 2017). For example, Kenya's Migori Gold Belt, which contains a sulfide-associated mineral, is the area that contributes to the release of acid water in the form of sulphuric acid that harms the aquatic life and threatens people who consume the water around the mining site (Mutono, 2016; Ngure et al., 2017). Veiga et al. (2009) reported that one of the ways the miners use to obtain the gold quickly is through amalgamation. Unfortunately, this process discharges the waste containing annually 1000 tonnes of mercury (Hg) to the environment, resulting in even worse issues, especially regarding a health concerns. In detail, Veiga et al. (2009) highlighted that 30% of the mercury is vaporized during the roasting process, and the rest is during amalgamation.

To solve those issues, any technical solution to be implemented in artisanal mining regions must be simple, fast, inexpensive, and more efficient than amalgamation (Veiga et al., 2009). Few actions promoted in this case might effectively solve the complex problem (Sousa et al., 2010). The use of cyanide is one of the options that is thought to be a good solution in substituting mercury due to the less or non-toxic tailing production (Veiga et al., 2009). However, it still poisons the environment if it is not handled well and correctly. According to Veiga et al. (2009) and Veiga et al. (2014), it is challenging to fully achieve the safest process as the artisanal mining activities may depend on: (1) investment capacity; (2) level of education and motivation of miners; (3) environmentally friendly methods; and (4) good government policies toward those miners. Thus, although it does not fully replace the mercury process, Santos (2013) stated that a combination of concentrating the gold by gravity concentration (e.g., primary or secondary gravity concentration) or flotation is efficient and very promising to gain more recovery.

Veiga (2020) stated that concentration equipment is very effective for the gold particle size larger than 0.074 mm in the case of gravity concentration. However, some equipment such as tables, jigs, and elutriators are not efficient for fine gold particles. As a result, the recovery obtained tends to be low. Although using these machines is better than panning, the efficiency levels are still questionable compared to sluice boxes, which are cheaper (Veiga et al., 2006). One of the promising methods to solve the aforementioned complex issue is using the Knelson concentrator. Centrifugal concentrators, in this case, Knelson concentrator and magnetic sluice, for the Ecuadorian case have resulted in a recovery of 5 to 8%. This low recovery was due to the characteristic of fine gold particles.

The recovery obtained for the Canadian-made Knelson concentration can be up to 60% (Veiga et al., 2006). However, the price for a Knelson concentrator is higher than cheap centrifuges (e.g., the ones producing concentrates of 1000 g/t gold), as in the case of Brazilian artisanal mining. There were other similar centrifugal concentrators (i.e., Knudsen and GoldKacha concentrators) that were applied in Zimbabwe. However, mercury is still utilized in the process. Meanwhile, the use of flotation tends to produce higher recovery than concentration. However, flotation is quite complex in terms of operating variables (Hinton et al., 2003). For the fine and porous gold ore, cyanidation is even more promising than the use of flotation that also utilizes a certain number of reagents (as a frother, collector, depressant, pH modifier) (Veiga, 2020). Consequently, there is still a large potential for environmental damage due to the used reagents discharged without proper pretreatment. Based on the case in Indonesia, Veiga (2020) stated that the artisanal miners may need close technical assistance to conduct the flotation process. This then also similar to the case of the Knelson concentrator (Veiga, 2020).

Of all those trade-offs, the testings using a centrifugal concentrator (i.e., a Knelson concentrator) combined with flotation and cyanidation were expected to produce better results. For the case of artisanal mining in Kenya, the combination of those processes is also highly required and has never been investigated before. Therefore, this study will reveal some metallurgical processes' best mineral processing routes (i.e., Knelson concentrating, flotation, and cyanidation) in recovering the Kenyan artisanal gold mining ore. In this case, the gold ore's recovery and grade were the two main variables determining how better the metallurgical processes were conducted. Definitions and formulas to calculate the two variables were explained by (Wills and Finch, 2016).

It was expected that the study could suggest feasible and applicable processing steps to help the miners treat the ores more environmentally friendly. In this case, the feasibility and applicability of the overall or each individual process are indicated by the gold recovery. It is also likely that more stakeholders involved in direct activities and management of artisanal mining, particularly in Aceh, Indonesia, could be inspired by the result of this study. As a result, the artisanal mining activities, particularly in Aceh, can be better in the future.

2. Methodology

2.1. Materials

The main material used in this study was gold ore obtained from Kenya. This gold ore consists of 12 samples with different grades and a total weight of 25.5401 kg, as shown in Table 1.

Table 1. The Kenyan artisanal gold mining sample received.

No	Sample Label	Weight (g)
1.	AR1	2074.6
2.	AR1-3	1968.6
3.	AR2	1939.5
4.	AR3	1962.3
5.	AR9-1	1932.4
6.	AR9-5	3894.5
7.	AR10-1	1958.7
8.	AR10-2	1926.1
9.	AR10-3	1943.4
10.	AR10-5	1965.7
11.	AR10-9	2015.4
12.	Tailing	1958.9
	Total	25540.1

Initially, all samples were grouped based on the three grade classifications as follows:

a) Sample A with the grade > 20 g/t (high-grade sample)
b) Sample B with grade < 20 g/t (low grade sample)
c) Sample C with a grade of 2 g/t (tailing)

After being grouped according to the established grade, all sub-samples were homogenized. The summary of the first two groups of the sample (sample A and sample B) is shown in Table 2 and Table 3.

Table 2. Sample A (high-grade).

Sample Label	Grade (g/t)		Weight (g)
	Au	Ag	
AR-1	87.33 99.05	8.10 8.80	2074.6
AR9-1	25.63	6.40	1932.4
AR10-3	32.27	17.20	1943.4
Total	51.35	10.64	5950.4

Table 3. Sample B (low-grade).

Sample Label	Grade (g/t)		Weight (g)
	Au	Ag	
AR1-3	16.90	1.60	1968.6
AR2	6.23	0.80	1939.5
AR3	3.88	0.20	1962.3
AR9-5	13.42	0.50	3894.5
AR10-1	1.76 1.63	0.80 0.90	1958.7
AR10-2	16.06	2.30	1926.1
AR10-5	3.59	0.60	1965.7
AR10-9	6.63	0.90	2015.4
Total	9.07	0.91	17630.8

2.2. Sample Pretreatment

2.2.1. Splitting and Mixing

As in Figure 1, the splitting process was conducted to compare the result of metallurgical testings and methods conducted. The grades for samples A and B were calculated by mass balance, as shown in e and Table 3. Meanwhile, the gold and silver grades for the tailing were obtained from the metallurgical data provided before the sample was received, which are 2.45 and 0.30 g/t, respectively.

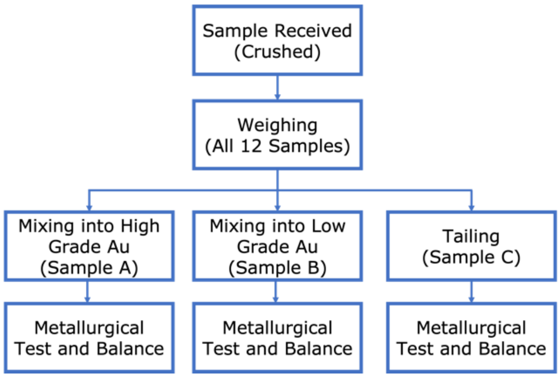

Figure 1. General testing procedure.

2.2.2. PSD Analysis

To get the best recovery, as each metallurgical test has a specific particle size characteristic treated, several Particle Size Distribution (PSD) analyses were conducted for those samples. The PSD analysis was done by screening the sample using Ro-Tap RX-29 Sieve Shaker and Screens. The size distribution in every screen was then plotted to get the F_{80}. This means that there were 80% of the material passed the sieve opening. The output of the PSD analysis was to ensure the material had the required size before being tested. For the material considered too coarse, the rod mill was used to crush the material. The milling process was continuously repeated until the required particle size for the operation was obtained. The operating particle sizes for this study are listed in Table 4.

Table 4. Particle size for every test.

Sample	Particle Size	Remarks
A	< 1 mm 94 microns	For GRG test For flotation test
B	< 1 mm 103 microns	For GRG test For flotation test
C	0.22 mm 94 microns	Initial sample size For flotation test

*GRG (Gravity Recoverable Gold)

2.2. Gravity Recoverable Gold (GRG) Test

A Gravity Recoverable Gold (GRG) testing process conducted consisted of two methods: (1) primary gravity concentration and (2) secondary gravity concentration. According to Dominy (2014), an ore sample's recovery from Gravity Recoverable Gold (GRG) indicates the ore sample's amenability to the gravity concentration method. In this study, the primary gravity concentration was performed using Knelson Concentrator Model KC-MD3 manufactured in Langley, British Columbia. This is due to its high-mass yield recovery (McLeavy et al., 2001).

In addition, to improve the recovery to over 50%, the secondary gravity concentration was done by panning. For sample C, as it was considered tailing material before the sample was received, the gravity concentration would not give a better recovery. Thus, the GRG test was skipped for this sample, and the step directly proceeded to the flotation test.

2.3. Flotation Test

The tailings from first and secondary gravity concentrations were mixed and concentrated in the Metso flotation cell. More recovery was expected to be achieved through this flotation test. For sample B, the flotation tailing was sent for the leaching process to improve the recovery further.

2.4. Cyanidation Test

The leaching or cyanidation process was conducted only for sample B. This was to extract, purify, and recover more gold from the flotation tailing. The pH condition set up for the leaching test was 11 to prevent the production of HCN gas and another reaction if the pH was below nine and higher than 11.5, respectively. The leaching process was done inside the beaker glass equipped with the agitator to increase the reaction kinetics and improve the extraction. The tailing product obtained was sent for fire assay. By using the head grade, the result was back-calculated to get the concentrate grade. The operating condition for the cyanidation test is summarized in Table 5.

Table 5. Cyanidation test condition

Variables	Value	Unit
Solids	300	g
Solution	450	g
Percent Solids	40	%
Slurry Wt	750	g
pH	8	
Bottle Wt	336.7	g

Figure **3** shows the treatment for Sample B in which a leaching test was involved. The feed for the leaching test was obtained from the tailings discharged from both gravity concentration processes.

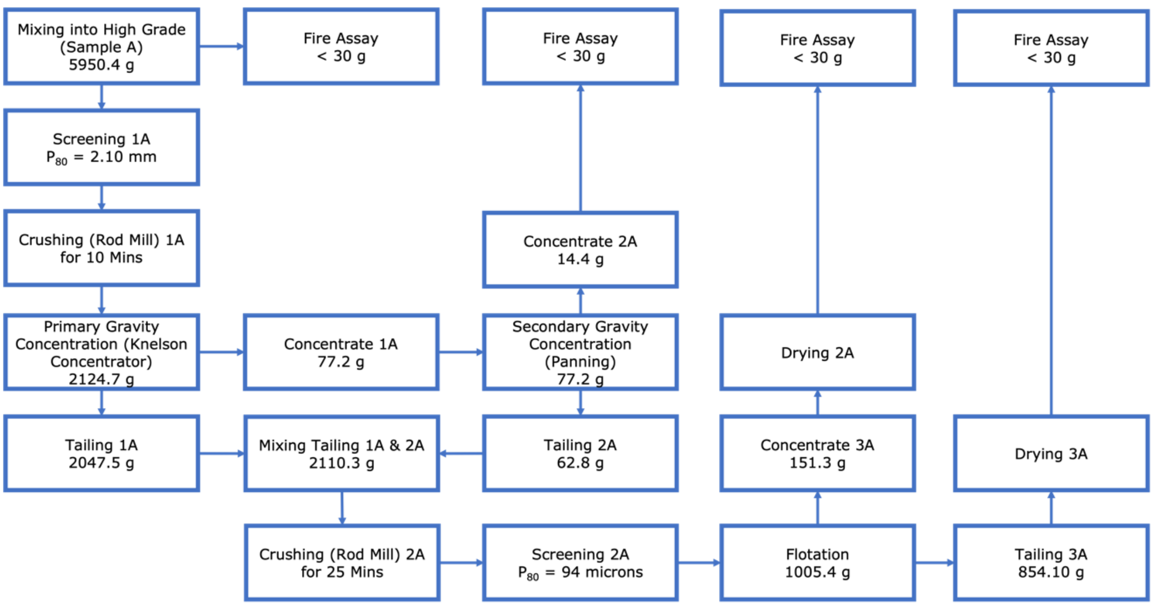

Figure 2. Sample A procedure.

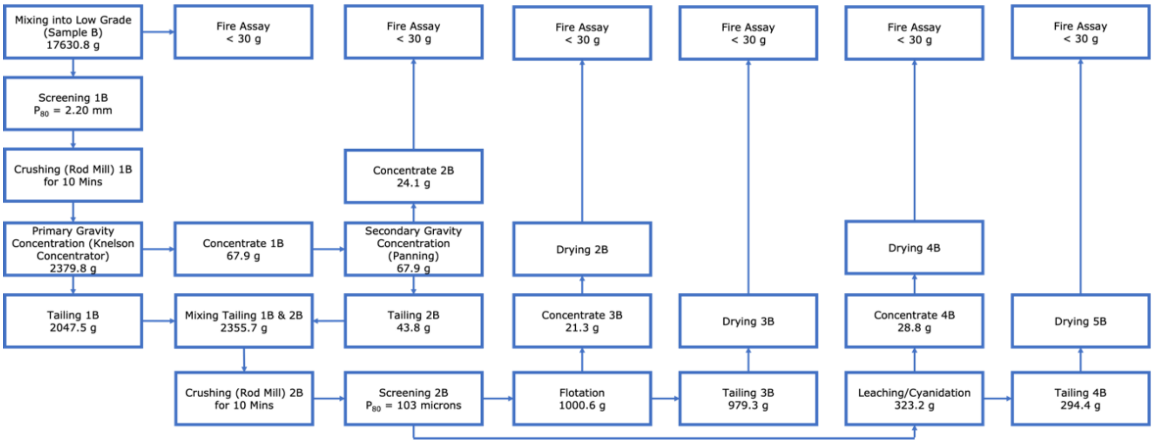

Figure 3. Sample B procedure.

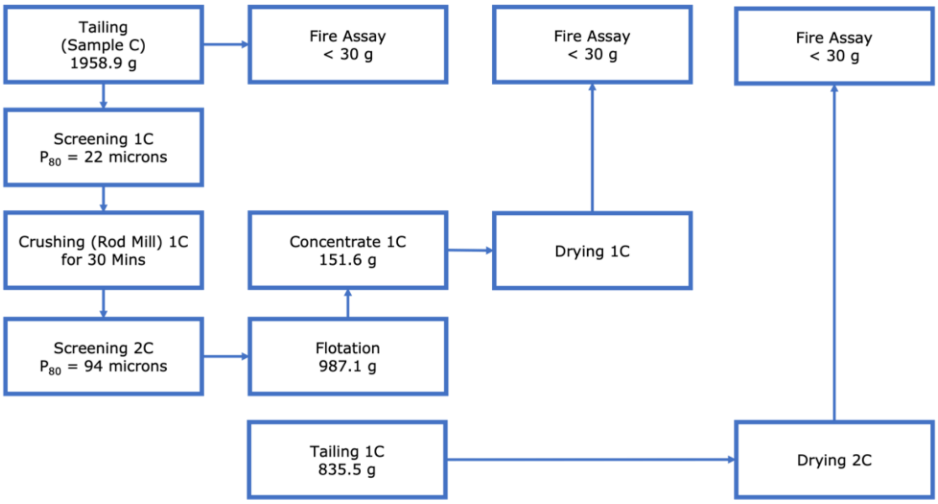

Figure 4. Sample C procedure.

This additional procedure has made Sample B's treatment different from the other two samples (A and C), (Figure 2 and Figure 4).

2.5. Drying

The moisture content of the testing product was filtered using Peterson Filters. To further reduce the moisture content as preparation for fire assay, Micropack Drying Oven was used to dry the materials.

2.6. Assaying & Metallurgical Balancing

During the project, 13 products were sent for fire assays. Fire assay is still a widely accepted method for analyzing Platinum Group Metal (PGE) and gold elements from low to medium grades. The fire assay procedure generally consists of fluxing and fusion, slag separation, cupellation, and complex analyses, which usually include gravimetric and instrumental analysis. In this study, the result obtained from the fire assay was used to calculate the recovery in the metallurgical balancing of every test conducted.

3. Results and Discussion

3.1. Testing Result for Sample A

As previously explained, there were two gravity concentration processes followed with flotation conducted for sample A. The gravity concentration tests used the Knelson Concentrator and the panning method. The combined metallurgical balancing result of gravity concentration and flotation tests for sample A is summarized in Table 6.

After carrying out the metallurgical balance of sample A as shown in Table 6, it was found that the recovery for the gravity concentration concentrate was 71.72%, concerning the highest amount of concentrate grade. This number was considered amenable as using the Knelson Concentrator combined with panning should at least recover 57% of gold (Chen et al., 2020).

Table 6. Metallurgical balance for samples A and B.

Sample	Process	Stream	Weight (g)	Grade (g/t)	Yield (%)	Recovery (%)	Total Recovery (%)
A	Gravity Concentration	Feed	2124.70	54.43	100.00	100.00	
		Concentrate	14.40	5759.57	0.68	71.72	71.72
		Tailing	2110.30	15.50	99.32	28.28	
	Flotation	Concentrate	151.30	87.11	15.05	23.93	95.64
		Tailing	854.10	2.81	84.95	4.36	4.36
B	Gravity Concentration	Feed	2379.80	13.54	100.00	100.00	
		Concentrate	24.10	1227.56	1.01	91.81	91.81
		Tailing	2335.70	1.12	98.99	8.19	
	Flotation	Concentrate	21.30	18.84	2.13	2.94	94.76
		Tailing	979.30	0.73	97.87	5.24	5.24
	Leaching	Concentrate	28.80	9.60	8.91	6.93	98.74
		Tailing	294.40	0.17	91.09	1.26	1.26

This number was considered amenable as using the Knelson Concentrator combined with panning should at least recover 57% of gold (Chen et al., 2020).

In terms of fire, the assay result compared with the initial assay before the sample was received, as shown in Table 6 anda Table 2, the gravity concentration feed had almost similar percentages, 54.43 and 51.35 g/t. This grade increased as there were more minerals liberated after the comminution process conducted before the gravity concentration process. In this case, the total recovery of the gravity concentration produced from the metallurgical balance for sample A above could be accepted.

Meanwhile, the recovery for only the flotation test obtained for sample A was 23.93% and 4.36% for flotation concentrate and tailings, respectively. This produced the final recovery for the whole stages, including the gravity separation of sample A, which was 95.64%. It can be inferred from this result that panning as the second treatment of the gravity separation could not give a significant result as there was only a 4.35% of recovery improvement from the tailing of both gravity separations to the concentration of the flotation process.

3.2. Testing Result for Sample B

The result of the metallurgical balance for sample B is also shown in Table 6. According to Table 6, the recovery for only the gravity concentration concentrate obtained was 91.81%. However, after being passed to the flotation test, the results for sample B were only 2.94 and 5.24% for concentrate and tailing, respectively.

The overall result for gravity concentration and flotation obtained for sample B was 94.76%. When leaching was conducted, the improvement for the recovery only increased by almost 4%. In this case, it can be said that sample B contains more free gold, which was already liberated since the gravity separation process and is quite difficult to be recovered during flotation and leaching.

3.3. Testing Result for Sample C

The result for sample C was only obtained from the flotation process as this was thought as the only process appropriate due to the least grade of the sample (< 2 g/t). From the flotation test, it was obtained that the overall recovery achieved was 82.74% (see Table 7). It is interesting to see in sample C that the sample grade increases dramatically from 3.43% to 18.49%. This proves that the tailing still contains many valuable products, and it is unfortunate if the miners do not process the tailing and only discharge it as waste.

3.4. Comparison between Samples

Comparison made between the three samples shows interesting findings. First, sample A seems less liberated or less free gold than sample B. This is proved by the result obtained for sample B that the recovery for only the gravity concentration concentrate obtained was 91.81%, which is significantly higher than sample A of 71.72%. It is important to note that before the treatment, the initial grade for sample B before the test was conducted was roughly 10 – 17% lower than sample B (see e and Table 3).

When the flotation tests between sample A and B were compared, the results obtained were in line with the result of gravity separation. This recovery for sample B was far lower than for sample A. Even though the Particle Size Distribution (PSD) shows an insignificant difference in size, sample B was finer than sample A. The flotation result achieved for the concentrate of sample B was only 2.94% compared to 23.94% of sample A. Even if the leaching was conducted, the recovery only improved by 3.1%.

Additionally, for the three sample categories, the pH for the flotation process was maintained between 9.1 to 9.6, and the limes added for samples A, B, and C were 0.7, 0.5, and 0.8, respectively. For sample A, due to the high grade of silver (>10 g/t) indicating the presence of electrum, the greater reactivity of silver may affect flotation (Marsden and House, 2006). Hence, the flotation had to be controlled very well. Meanwhile, a comparison between sample C and the other sample could not be made as the initial grade for sample C was far lower than both other samples.

Table 7. Metallurgical balance for sample C.

	Weight (g)	Grade (g/t)	Yield (%)	Recovery (%)
Feed	987.10	3.43	100.00	100
Conc.*	151.60	18.49	15.36	82.74
Tail*	835.50	0.70	84.64	17.26

*Conc. = Concentrate, Tail = Tailing

3.5. Selecting the Best Processes

From the discussion made in the previous sections, some suggestions can be proposed for the Kenyan artisanal miners. Firstly, no processes can be chosen as a single permanent solution. Every process depends on the characteristic of the sample itself. Thus, to achieve the best mineral processing routes, involvement, and cooperation of both the artisanal miners and the processing center are needed.

Secondly, gravity concentration is more effective in processing medium to high-grade samples. If the miners could crush the sample into the average size, e.g., over 100 microns, their recovery will be significantly improved. However, this seems impossible as crushing and concentrating the ore can only be handled by the processing center, highly mechanized equipment. In this case, the artisanal miners still choose the panning process even though it is less effective.

The third suggestion that can be made is that the processing center should also have flotation equipment. The processing center can gain more gold by installing flotation devices, particularly for more disseminated gold or tailing. In the fair mechanism, as it is quite costly to obtain a flotation device for the artisanal miners, the processing center should be in charge more.

The ideal scenario proposed for Kenyan artisanal mining is that the government as the regulator should act as a mediator and clear the roles between the artisanal miners and the processing center. At this point, artisanal miners can only process the ore through panning and/or sell the unprocessed material (i.e., medium grade) and the tailing from the panning to the processing center in the medium to high price range.

From this scenario, the artisanal miners can double their incomes. At the same time, the processing center can gain more from the medium-grade and tailing using the flotation, particularly as they own more capital and resources (i.e., cost, supporting equipment). Even though deeper economic analysis is needed, from the results presented in the previous section, it is believed that the processing center will not lose.

With the scenario, the use of mercury for the artisanal miners can be eliminated, and the cyanide usage (only for the processing center) can be minimized due to the insignificant improvement after being leached. This is in line with the statement that the flotation process could improve the process and reduce the use of cyanide for the leaching process (Chen et al., 2020). As a result, the damage to the environment can be reduced significantly.

3.5. Lesson Learned for Acehnese Miners

Regarding the deposit characteristic, the gold samples used in this study originated from Nyanza, Kenya. The deposit is predominantly from quartz veins and a few impregnations with a high proportion of alluvial gold (Pulfrey, 1969). The gold is present in the electrum that contains silver, as shown in e and Table 3.

The Nyanza site is located very close to Lake Victoria in Kisumu. The area near Lake Victoria is a productive greenstones area, which lies along the Migori Belt as part of a gold-enriched Archaean Tanzanian craton (Mshiu et al., 2015). A study conducted showed that most gold attachment is sulfide minerals in the form of iron-sulfide also bounded with pyrrhotite, molybdenite, sphalerite, and a small amount of arsenopyrite (Baris and Mutua, 2019; Mshiu et al., 2015).

This mineralization proves why more gold can be recovered just only with gravity concentration and leaching. The existence of most quartz, a harder rock, correlates with the PSD analysis of high-grade and tailing samples. It took almost 25 – 30 minutes to grind the material to liberate the ore.

In the case of Aceh, Indonesia, there is not much literature discussing the Acehnese gold deposits. Some types of deposits mined traditionally, which the researchers highlighted, are epithermal, breccia, and placer deposits, as stated by Maryono et al. (2014), Mulja et al. (2003), dan Van Leeuwen (2014). In these cases, it is fair to say that the Acehnese artisanal mining activities and management should learn from the Kenyan case. This can be at least by implementing a centralized processing site (Processing Center) to accommodate the miners.

Suppose both optimizations on processing and implementation of centralized processing sites are successfully applied in the future. Cyanide consumption is reduced, and even zero mercury can be achieved, as in the UN International Guidelines on Mercury Management in Small-Scale Gold Mining (Spiegel and Veiga, 2010). However, those suggestions indeed depend on the good intentions of the policymakers, miners, and civil society to continue giving their best solutions in tackling the artisanal mining issue (Putra, 2018).

4. Conclusion

From the study conducted, it can be learned that gravity concentration, particularly panning, still shows very promising results if the scenario proposed is performed. Meanwhile, the combination of a highly mechanized Knelson concentrator and flotation is considered suitable to be applied by the Processing Centers due to the high capital cost and more complex equipment. This also becomes the best solution to partially replace the cyanidation process as the process can still recover some gold. The Processing Center can also recover more gold from the tailing (sample C). Although the similarity between the Acehnese and Kenyan artisanal mining cannot be made, mainly because there is not much information related to the deposit characteristic, the Acehnese artisanal mining should learn from the scenario proposed by Kenyan artisanal mining. In this case, if the government can maximize their roles, the artisanal gold mining activities, in both cases, will lead to the economic welfare of the miners as well as a safe and healthy living environment around the mine site.

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