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Towards Sustainable Mining: Evaluating Pyrometallurgy as a Green Alternative in Gold Ore Processing

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ABSTRACT: Environmental pollution by mercury in small-scale gold mining in Kulon Progo has occurred. Amalgamation has been carried out since 1997. It caused many impacts to the environment and human health. It contaminated soil and water in Kalirejo, Kulon Progo. Referring to Minamata Convention through Law Number 11 of 2017, Indonesia through Technology Assessment and Application Agency was collaborating with United Nations Development Program for the development of a pilot plant pyrometallurgy in Kulon Progo. This study aimed to evaluate the effectiveness of pyrometallurgy methods. The research method was assessment research. This research used purposive sampling to collect data and the weighting method to process questionnaire data. Based on the research, pyrometallurgy was still not practical due to its high operational costs. On the other hand, it was environmentally friendly. The heavy metals and pH of wastewater from the scrubber of the arc furnace and roasting met the quality standards. It was possible to switch to pyrometallurgy with a society approval level of 64%..

KEYWORDS: amalgamation; effectiveness; gold; pyrometallurgy

I. INTRODUCTION

One of the regencies with substantial mineral reserves is Kulon Progo (Santoso and Gomareuzzaman, 2022). Small-scale Mining Area, which spans approximately 100 hectares, is one of the numerous small-scale gold mining (SSGM) owned by Kulon Progo, for example in Plampang I, Plampang II, Papak, Kalirejo, Kokap. Mercury (amalgamation) tends to be used in the extraction of gold in small-scale gold mining. It results in environmental pollution. It has been in use for an extended period of time due to its ease of acquisition (Kusuma, Budianta and Arifudin, 2017). The concentration of mercury (Hg) in water samples collected from a river in Kokap District was found to be higher than the established quality level. The utilization of mercury in Kalirejo resulted in significant environmental and organismic health consequences (Ernawati, Cahyadi and Rambe, 2021). The nature of Mercury's impact necessitates significant consideration. Accumulate inside intricate ecological systems (Sari, Pertiwi, Ariyani, Ridwan, et al., 2022). Mercury in SGM causing soil contamination (Rachman, Karisma and Trihadiningrum, 2017; Rachman, Mangidi and Trihadiningrum, 2023).

As part of the program to reduce the use of mercury in Small-Scale Gold Mining (SSGM), the Indonesian government, through Technology Assessment and Application Agency (Badan Pengkajian dan Penerapan Teknologi/BPPT), has collaborated with the United Nations Development Programme (UNDP) in the development of a Pilot Plant for Mercury-Free Gold Processing and Waste Treatment in Kalirejo, Kokap (Farisi, Putra and Novianti, 2022). One of these Pilot Plants involves the construction of a gold processing facility using pyrometallurgical methods in Plampang III, Kalirejo, Kokap. Pyrometallurgical gold extraction is a widely used method in the mining industry for recovering gold from various types of ores. The process involves high-temperature treatment of the ore, which results in the separation and extraction of gold from other minerals and impurities (Klaasen, Jones, Durinck, Dewulf, et al., 2010). Pyrometallurgy has been utilized as a conventional approach for the retrieval of valuable metals, including both precious metals and non-ferrous metals (Ojeda, Perino and Ruiz, 2009). For the past thirty years, the pyrometallurgical method has been widely used to extract gold from ores. Pyrometallurgy utilized high temperatures for smelting and refining processes to extract metals from the minerals (Anderson, 2020). This process involves several steps such as incineration, smelting in a plasma arc furnace or blast furnace, dressing, sintering, melting, and conducting reactions at high temperatures (Syed, 2012). Pyrometallurgical methods, particularly selective chlorination processes, have demonstrated higher efficiency and cost-effectiveness in the extraction and refining of metals (Wong, Leong and Mujumdar, 2009; Teschner, Smith, Borrillo-hutter, Quaghe, et al., 2017). The use of pyrometallurgical processes in Kulon Progo provides an opportunity for gold extraction and economic development in the region. The significance of pyrometallurgical gold extraction in Kulon Progo lies in its economic and social implications. Gold extraction contributes to the local economy by generating employment opportunities, stimulating business activities, and supporting the livelihoods of individuals involved in the mining industry. Moreover, gold is a valuable commodity with a wide range of industrial and cultural applications, making it a crucial resource for local and global markets.

However, it is essential to recognize that pyrometallurgical gold extraction is not without challenges. The use of pyrometallurgical methods for gold processing in Kulon Progo is still relatively new, which means that there are not many people who are familiar with the process yet. The process involves the generation of emissions, such as gases and particulate matter, which can have environmental impacts if not properly controlled and managed. Additionally, occupational health and safety considerations must be addressed to ensure the well-being of workers involved in the extraction process. Understanding the process overview of pyrometallurgical gold extraction in Kulon Progo is essential for optimizing extraction practices, ensuring efficient gold recovery, and minimizing environmental impacts. However, the environmental and health risks associated with mercury use have raised concerns, prompting the exploration of alternative techniques. While pyrometallurgical methods have been widely adopted in various industrial sectors, their application specifically in gold ore processing within the Kulon Progo region has received limited attention in existing literature. There have been limited studies concerned with the implementation and effectiveness of pyrometallurgical processes in gold ore processing specific to the Kulon Progo region.

Consequently, there is a gap in understanding the feasibility, challenges, and potential environmental benefits of adopting pyrometallurgy as a sustainable alternative to mercury amalgamation in this particular context. Therefore, this research intends to address this gap by providing a comprehensive process overview of pyrometallurgy in gold ore processing within the Kulon Progo region. By examining the equipment, process flow, challenges, and opportunities associated with pyrometallurgical gold extraction, the paper aims to provide valuable insights for optimizing extraction practices. It seeks to identify the challenges and limitations faced in the current pyrometallurgical gold extraction practices in Kulon Progo. By recognizing these challenges, potential solutions and improvements can be explored. Finally, the paper aims to emphasize the significance of optimizing gold extraction practices in Kulon Progo for improving efficiency and reducing environmental impacts, while considering the socio-economic implications for local communities.

II. METHODS

This study used observation and questionnaire methods. The pH of wastewater in the scrubber was tested using the SNI 06-6989-11-2004 method. Sampling was done by purposive sampling with 30 data. The primary data in this study are pH, the content of arsenic (As), copper (Cu), and lead (Pb) in wastewater from scrubber of arc furnace and roasting , the results of a questionnaire on the possibility of people switching to pyrometallurgy. The secondary data are operational costs and gold recovery in pyrometallurgy. Variables in the questionnaire include the advantages and disadvantages of pyrometallurgy and the public's interest in switching to pyrometallurgy. The questionnaire instrument can be seen in Table 1.

Validity and reliability tests are conducted on the questionnaire responses, and the Likert scale weighting (scoring) method is used. The questionnaire assessment scores are: strongly agree (SA)=5, agree (A)=4, neutral (N)=3, disagree (D)=2, and strongly disagree (SD)=1. The criterion score is obtained by equation (1). The percentage of each statement item is obtained by equation (2). After obtaining the percentage of each item's assessment, the next step is to interpret the calculation score based on the assessment category.

Criterion score = item score x number of respondents………………………………………………………………………..…..(1)

Percentage= ((total score)/(total of highest score)) x 100……………………………………………………………………..(2)

Table 1. Questionnaire instrument

No	Statement	SA	A	N	D	SD
1	The operation of gold processing equipment using the pyrometallurgical method is easy					
2	Training on gold processing with pyrometallurgy needs to be expanded for the surrounding community					
3	The operational cost of processing gold using the pyrometallurgical method is more expensive than processing it with mercury					
4	It is necessary to increase the equipment capacity at the gold processing pilot plant with pyrometallurgy in Plampang III					
5	The pyrometallurgical pilot plant in Plampang III is open to residents					
6	The gold recovery by pyrometallurgical methods is higher than mercury					
7	The high cost of industrial fuel is a barrier to running pyrometallurgical gold processing					
8	Pyrometallurgy is better than amalgamation					
9	Local society still prefers processing gold with mercury					
10	Local society agree to leave amalgamation and switch to pyrometallurgy					

III. RESULTS

3.1 Stages of gold ore processing

The stages of gold ore processing at the pyrometallurgical plant in Kokap Kulon Progo are as follows:

a. Comminution

Comminution is the process of ore size reduction. Prior to mineral separation, the most crucial processes are mineral liberation and size reduction. In this process, the mined ore is crushed using a crusher (primary crushing and secondary crushing), then the crushed material is milled using a ball mill (Chen, Peng and Bradshaw, 2014; Chelgani, Parian, Parapari, Ghorbani, et al., 2019). The jaw crusher is used as the primary crusher to reduce the size of the ore in the first stage. For the past 70 years, size reduction technologies and equipment such as jaw crushers, gyratory crushers, hammer mills, and ball mills have been in utilized (Elisante, 2009). Crushing is used to reduce the ore to small particles (Abdul and Marikar, 2011). The roll crusher is used as the secondary crusher to further reduce the size of the ore. The feed for the roll crusher is the product from the jaw crusher. The ball mill is used for grinding the material obtained from the roll crusher. Within the pyrometallurgical pilot plant, there is a ball mill with a capacity of 90 kg. During a single day of processing operations, it is capable of handling 600 kilograms of ore. However, the target is 1 ton of ore per day. The ore is fed directly into the ball mill from the jaw crusher. This ball mill contains a higher proportion of steel balls, which aid in the grinding process. Ultimately, the grinding operation within the ball mill will reduce the ore to a slurry with a very fine particle size.

b. Concentration

After the ore size is reduced into 200 mesh, the next process is the concentration process by separating the gold minerals from the impurity minerals. The separation technique used is gravity separation. Gravity separation is the process of separating gold from impurities. The process is based on the difference in density between ore particles and impurity particles. The equipment used is a shaking table. The result of this process is a concentrate and tailing consisting of minerals impurities. The shaking table tailings will be discharged into the settling pond. One ton of ore yield 35 kilograms of concentrate.

c. Roasting (oxidation)

Sulfide concentration is now treated with pyrometallurgical flow sheets that combine oxidative roasting in a well-developed approach. The concentrate is roasted to reduce its sulfur and arsenic through evaporation. Roasting is the process of heating an ore or mixture with other minerals or compounds below its melting point (fusion temperature) at a temperature of 600°C. The concentrate is layered over the rice husk during this roasting process, and a blower is used to burn it. At 600–800oC, the roasting process takes around 6 hours. Rosewood is used in the roasting process to help the coal burn.

d. Smelting

Smelting is the process of melting metal at high temperatures. Smelting is done using an arc furnace at a temperature of 2000o C. This process uses lime as flux. The function of lime in the smelting process is to bind disturbing impurities, so the matte (melted metal) will be at the bottom while the top is called slag which is captured by silica in the form of a kind of glass that is easy to break. The amount of flux is 30% of the amount of material to be burned in the arc furnace. However, if the sulfur content of the material is high, the amount of flux is more than 30%. The high sulfur content in the material is indicated by the appearance of a reddish color in the combustion products. Besides active lime, borax can also be used as a flux. However, if borax is used at this stage, the borax will evaporate immediately. Combustion in an arc furnace at 2,000oC requires 15,000 watts (15 KW) of power. The reduction product during the melting process is called bullion (Au-Ag alloy).

e. Parting

Parting is a process to separate gold from silver and base metals from bullion (Au-Ag alloy) with nitric acid solution (HNO3). The result after the last boiling, the sediment color is brown like coffee grounds. This precipitate is gold bullion (High Au Bullion) with a gold content of up to 98%. For better results can be processed with aqua regia in order to obtain levels up to 99.6%. Aqua regia is a mixture of three parts of a volume of concentrated hydrochloric acid (HCl) and one part of a volume of concentrated nitric acid (HNO3).

$Au(s) + 4HCl(aq) + HNO_3(aq) \rightarrow HAuCl_4(aq) + NO(g) + 2H_2O(l)$

3.2 Operating cost

The pyrometallurgical pilot plant processes 600 kilograms of ore/day. The concentration of gold obtained from 600 kilograms of ore is 7 ppm. Operational costs per day can be seen in Table 2. Based on Table 2, the cost that must be prepared daily to process 600 kilograms of ore is 1,191,000 rupiah. The high cost of industrial fuel for heating materials in the arc furnace causes high pyrometallurgical operational costs.

Table 2. Pyrometallurgical operational costs

Operational Cost	Cost (Rupiah)
Transportation of materials	120.000
Industrial diesel	540.000
HNO_3	25.000
HCl	45.000
Borax	5.000
Active Lime	6.000
Labor cost	450.000
Total	1.191.000

3.3 The pH of wastewater

Based on the test results, the wastewater pH from the scrubber arc furnace was 7.3 and 6.6 on the roasting equipment. The pH value still meets the required quality standards (6-9), according to the Decree of the Minister of Environment No. 202 Year 2004 (KEPMEN LH No. 202 Tahun 2004) concerning Quality Standards of Wastewater for Businesses and or Mining Activities for Gold and or Copper Ore. This shows that the wastewater is safe for the environment.

3.4 Heavy Metal in Scrubber Wastewater

In gold processing activities using the pyrometallurgical method, there is wastewater in the scrubber of the arc furnace and roasting equipment. Therefore, a test for heavy metal was carried out on scrubber wastewater. The test was carried out at the Center for Environmental Health Engineering and Disease Control Laboratory in Yogyakarta. Testing for arsenic parameters used the IK/BBTKLPP/3-K/Pj-C.38 test method, copper: SNI 6989.84-2019, lead: SNI 06.6989.46-2005. The test results are shown in Table 3. Table 3 shows that the heavy metal content in wastewater from arc furnaces and roasting on the parameters arsenic (As), copper (Cu), and lead (Pb) still meets the quality standards, so it does not harm the environment.

Table 3. Heavy metals of scrubber wastewater

Parameter	Result (ppm)		
	Furnace	Roasting	Standard
As	0,05	0,005	0,5
Cu	0,2175	<0,0060	2
Pb	< 0,0099	< 0,0099	1

3.5 Pyrrometallurgy Perceptions: Survey Finding

Questionnaires were distributed to 30 respondents from different professions, including members of the general society, active miners, and members of pyrometallurgical pilot plants. The questionnaire that has been distributed was then tabulated to be analyzed. The tabulation of questionnaire results and correlation calculations to determine data validity can be seen in Table 4. Based on Table 4, the r count of statements 1 to 10 is higher than the r table, which is 0.361 (with n=30 and significance level=0.05). Therefore, items 1 to 10 are valid (fulfill the conditions: the r-value is positive and higher than the r-table).

Table 4. Tabulation of questionnaire

Respondent	Statement1	Statement 2	Statement 3	Statement 4	Statement 5	Statement 6	Statement 7	Statement 8	Statement 9	Statement 10	Total
1	3	4	3	2	4	5	5	5	3	3	37
2	3	5	3	3	4	3	3	3	4	3	34
3	3	5	3	3	4	3	3	3	3	3	33
4	2	5	3	3	4	2	3	2	1	3	28
5	3	5	3	3	4	3	3	3	4	4	35
6	3	2	3	3	4	3	3	3	2	3	29
7	2	3	3	3	4	3	3	3	1	3	28
8	2	3	3	3	4	3	3	3	3	3	30
9	2	3	3	3	4	3	3	3	3	3	30
10	1	3	3	3	4	3	3	3	2	3	28
11	1	4	3	3	4	3	3	3	3	3	30
12	3	5	3	3	4	3	3	3	4	3	34
13	3	5	3	3	4	3	3	3	3	3	33
14	3	5	3	3	4	3	3	3	5	4	36
15	3	5	3	3	4	3	3	3	2	3	32
16	2	4	3	3	4	2	3	3	3	3	30
17	4	5	5	5	2	1	5	4	1	3	35
18	2	5	5	5	4	4	5	4	2	4	40
19	4	5	5	5	4	5	5	4	2	5	44
20	2	5	4	5	4	5	5	4	2	5	41
21	1	5	4	5	4	5	5	4	2	5	40
22	1	5	5	5	4	5	5	4	2	5	41
23	4	5	5	5	4	4	4	5	5	5	46
24	2	2	4	4	3	2	3	2	2	2	26
25	1	3	5	3	1	3	3	1	1	1	22
26	2	4	3	3	1	3	3	3	2	2	26
27	2	3	3	3	1	3	3	3	2	2	25
28	2	4	3	3	2	3	3	3	1	2	26
29	2	4	3	3	1	3	3	3	1	2	25
30	2	4	3	3	1	3	3	3	2	3	27
r	0.433	0.666	0.529	0.684	0.588	0.643	0.758	0.799	0.445	0.917	

1= strongly disagree; 2= disagree; 3= neutral; 4= agree; 5 = strongly agree .

Furthermore, the reliability test was carried out: df (degree of freedom) =n-2=28, and a significance level of 0.05. Data reliability can be seen in table 5. From a comparison of the r count value with the r table, the result is that the r count value (0.885) > r table (0.361), so it can be concluded that the variable used is reliable.

Table 5. Correlation value in the reliability test

r-count	0.740
df	28
significance	0.05
t table	2.048
r table	0.361

After obtaining the validity and reliability of the data, then a recapitulation of the frequency of the results of the questionnaires for each statement was carried out based on the number of respondent's responses to the statements "strongly agree", "agree", "neutral", "disagree" and "strongly disagree" as listed in Table 6.

Table 6. Tabulation of frequence

Statement	amount of respondent					N
	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree	
1	0	3	9	13	5	30
2	15	7	6	2	0	30
3	6	3	21	0	0	30
4	7	1	21	1	0	30
5	0	22	1	2	5	30
6	5	2	19	3	1	30
7	7	1	22	0	0	30
8	2	6	19	2	1	30
9	2	3	7	12	6	30
10	5	3	16	5	1	30

Based on the highest percentage value = 100, total Likert score = 5, then the interval = 20 is obtained. So based on the interval value, the score interpretation criteria can be seen in Table 7.

Table 7 Score interpretation criteria

Score	Interpretation
0% - 19,99%	Strongly disagree
20% - 39,99%	Disagree
40% - 59,99%	Neutral
60% - 79,99%	Agree
80% - 100%	Strongly agree

After obtaining the interval on the score interpretation criteria, scoring is carried out by multiplying the number of responses in each statement with the weight of each statement and then calculating the total score in table 8. After scoring, the percentage is calculated (table 8) and interpreted based on the interval of the score interpretation criteria in table 7.

Table 8 Interpretation of results

Statement	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree	Total	Percentage	Interpretation
	5	4	3	2	1		%	
1	0	12	27	26	5	70	46.67	Neutral
2	75	28	18	4	0	125	83.33	Strongly agree
3	30	12	63	0	0	105	70.00	Agree
4	35	4	63	2	0	104	69.33	Agree
5	0	88	3	4	5	100	66.67	Agree
6	25	8	57	6	1	97	64.67	Agree
7	35	4	66	0	0	105	70.00	Agree
8	10	24	57	4	1	96	64.00	Agree
9	10	12	21	24	6	73	48.67	Neutral
10	25	12	48	10	1	96	64.00	Agree

Respondents answered doubtfully regarding statement 1, the easy operation of pyrometallurgical equipment. Respondents from the general society were unsure because they had never operated the equipment. However, respondents who were members of cooperatives or pyrometallurgical operators stated that operating the equipment was difficult. It is proven that only one person is proficient in operating and understanding the equipment.

Although socialization of the equipment operation has been carried out several times, it is indeed tricky and requires much consideration so that gold ore processing activities run smoothly. Therefore, respondents strongly agree with statement 2 that pyrometallurgical gold processing training needs to be extended to the general public. Respondents also agree with statement 5, that the pyrometallurgical pilot plant is open to residents. Respondents from the general public who were still unfamiliar with pyrometallurgy were interested in getting socialization about pyrometallurgy.

Respondents agree with statement 3 that the operational costs of processing gold using the pyrometallurgical method are more expensive than processing gold using mercury. Pyrometallurgical operators stated that pyrometallurgy required high electrical power obtained from generators. The high generator fuel cost (diesel industry) is a major obstacle in running pyrometallurgical operations (according to statement 7). It follows Table 2, which requires at least 30 liters of fuel/day or the equivalent of Rp. 540.000,-/day.

It is necessary to increase the capacity of the existing tools in the pyrometallurgical pilot plant. Respondents agreed with statement 4. The process of processing gold ore at the pyrometallurgical pilot plant is currently running slowly. Currently, it can only process 600 kg of ore/day, even though the target is 1 ton of ore/day. Therefore, it is necessary to increase the capacity of the equipment

Respondents agree that the recovery of gold by pyrometallurgy is higher than amalgamation (statement 6). Pyrometallurgical operators justify this. One ton of ore, when processed using pyrometallurgy, can produce 7 grams of gold, whereas when processed with amalgamation, only 4-5 grams. The recovery of pyrometallurgy is indeed higher than amalgamation, but pyrometallurgy is not profitable due to its high cost and low capacity of the equipment.

Overall, pyrometallurgy is better than amalgamation, and the respondents agreed with statement 8. This is because amalgamation greatly impacts the environment, which can be minimized by pyrometallurgy. Respondents expressed doubts about statement 9, whether they would still choose processing gold with mercury. They accept that pyrometallurgy is environmentally friendly, but on the other hand, they still state that amalgamation is the cheapest and easiest method. However, respondents stated that they agreed to leave gold processing with mercury and switch to pyrometallurgy (statement 10). There is a particular interest for respondents to try to switch to environmentally friendly gold processing. It is a challenge to attract people to switch to pyrometallurgy. It is necessary to increase the capacity of the equipment and divert fuel to reduce operating costs.

IV. CONCLUSSION

Based on the research, can be concluded that Pyrometallurgical methods are still not sufficient for gold processing in current condition. It is due to its high operational costs (especially the fuel), and the capacity of the current equipment is insufficient to achieve the target of 1 ton of ore/day. If the equipment capacity is improved, pyrometallurgy may be an effective method. The advantages of the pyrometallurgical method are environmentally friendly, high gold recovery, silver and platinum are obtained in addition to gold; wastewater fulfills quality standards for As, Cu, Pb, and pH; and refining waste is used as liquid fertilizer. On the other hand, the disadvantages include arc furnace radiation, high operating expenses, huge capital expenditures, and challenging operation of the equipment. The community agree to move to pyrometallurgical methods, with 64% approval level. The community's primary concern with the pyrometallurgical method of processing is the operational expense.

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