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TECHNICAL ARTICLE

Waste Management and the Elimination of Mercury in Tailings from Artisanal and Small-Scale Gold Mining in the Andes Municipality of Antioquia, Colombia

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Abstract
Several artisanal and small-scale gold mining (ASGM) sites in Colombia were located and sampled. At each ASGM site, tailings samples were collected and analyzed. Establishing rapport with mining stakeholders and analyzing the samples allowed our team to draw conclusions about the inefficiency of mercury-use in gold extraction and the superior efficiency of centrifugal and gravimetric methods for reprocessing the mining residues produced by artisanal gold miners.

Keywords Clean technologies · Gravimetric and centrifugal concentration · Sustainability · Mining residues · Informal mining

Introduction

Generally speaking, artisanal and small-scale gold mining (ASCM) involves low levels of technology and organization, and are characterized by very low levels of sustainability. The mining practices that prevail often contaminate the environment and are furthermore unsafe for the miners. Moreover, the scarcity of economic alternatives within the miners' localities and other factors hinder sustainable development in the areas where artisanal gold mining regularly occurs (Cordy et al. 2011; Idrobo et al. 2014; Sarmiento et al. 2013).

ASGM often hinges on the amalgamation process for extracting gold from the rocks that contain it. Miners fashion an amalgam using elemental mercury, which binds to several metals in the ores, including gold. This allows miners to extract gold from the rocky material. Once the mercury-gold amalgam forms, it is heated until the elemental mercury evaporates, leaving behind a mixture of gold and other metals (House and Marsden 2006; Yannopoulos 1991).

The widespread exploitation of gold across a number of regions in Colombia depends on excessive use of mercury, in addition to other chemical agents. Both human health and the environment have suffered as a result. Several studies indicate that Antioquia's municipalities, such as Segovia, Remedios, and Zaragoza, are home to mercury concentrations (in both air and water) a thousand times the international standards (Cordy et al. 2011; Veiga 2010).

The National University of Colombia, via the university's Faculty of Mines and the Institute of Minerals (CIMEX), has been implementing mercury-free technologies to improve the processing and retreatment of ores and mining residues containing gold in several of Antioquia's municipalities. The goal has been to reduce and/or completely eliminate mercury use in all gold mining processes. Our work demonstrates that it is, indeed, possible to process and recover gold without using mercury from tailings that have resulted from informal mining using mercury. Moreover, since this work also encompassed the socialization of the obtained results as well as the implementation and training needed to maintain the equipment installations and other technical issues associated with the extraction of gold, this article shows the importance of performing follow-ups, accompaniment, and monitoring of the ASGM sites where the tailings were produced and stored.

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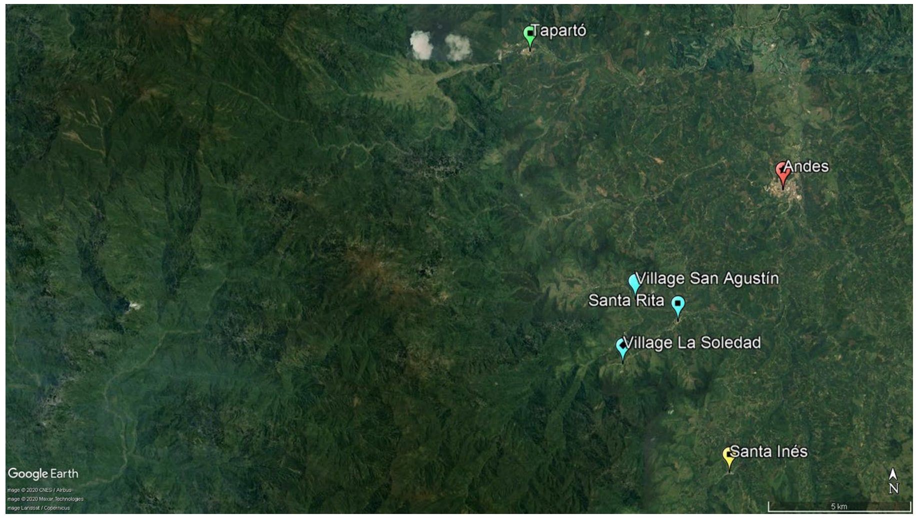

Fig. 1 General map of towns/villages visited in Andes-Antioquia

Recognizing Mining Production Units and Mining Waste Repositories

Our team sought to recognize, identify, and locate various ASGM sites, whether operational or abandoned, where tailings had been produced and stored. The team performed this work in three towns (Santa Ines, Santa Rita, and Tapartó) in the municipality of Andes, within the Antioquia department (Fig. 1).

Santa Rita

The team was able to locate nine ASGM sites in Santa Rita: four in the village San Agustín, of which two were still operating and the other two abandoned; and five south of the village La Soledad. Three of these were found to be operating, one was implementing mercury-free technologies, and another was found completely abandoned. Ultimately, the mine tailings found in Santa Rita amounted to ≈ 9480 t (Fig. 2); samples were collected from the visited ASGM sites.

Fig. 2 Improvised tailings repository in ASGM site in Santa Rita

Santa Inés

In Santa Inés, the team located one operating ASGM site called Virgen del Carmen, where, in addition to poor handing and manipulation of mercury, the team also identified the risk that artisanal and small-scale miners face due to poor practices with explosives, which miners use on the rock faces of their respective mines and mining sites. At this site, the team located various mine waste repositories

Fig. 3 Tailings sacks stacked as tailings repository in Virgen del Carmen ASGM site in Santa Inés

(Fig. 3). Ultimately, the total quantity of tailings found in Santa Inés was ≈ 1,050 t; one sample was obtained from this ASGM site (Fig. 3).

Tapartó

The team located one ASGM site, called Topitos de la Rochela in Tapartó (Fig. 4). It was operating, albeit not constantly so. The owners, or partners, of the ASGM site were willing to collaborate, giving a general tour of the entire area, including the mine, the processing plant, and some tailings repositories. About 200 t of mine tailings were found in Tapartó, and one tailings sample was extracted from this ASGM site.

All of the visited ASGM sites contained at least one processing plant (operating or abandoned) and several tailings repositories. At a few sites, the ASGM sites processed ore brought from other nearby mines, but at most, the processed ore had been mined on site. The processing procedure used by miners to produce gold was virtually the same at all of the visited ASGM sites. First, the miners reduce the size of the ore using a rudimentary crusher. Then, the ore is poured, along with water, lime, and mercury, into artisanal rotatory ball-mills known as ‘cocos’, where it remains for 1–4 h. Once the amalgam is formed, it is separated from the rocky material and burned; the rest of the rocky material is submitted to improvised tailings repositories. The amount of ore processed in most of the visited ASGM sites was ≈ 1–2 ton/day, but some ASGMs had a higher capacity since they processed their own ore as well as some from other mines. In the latter case, miners charge about 1.5 USD per 50 kg of processed ore.

All of the visited ASGM sites had poorly managed their tailings and tailings repositories. In some cases, the mining tailings were dumped into improvised dams (Fig. 2), while at others, the processing residues were stored into sacks and then stacked (Fig. 3). Thus, these stored tailings were environmental liabilities since there was a need to carry out restoration for the environmental damage produced by the ASGM activities (Arango and Olaya 2012).

Fig. 4 ASGM site Topitos de la Rochela in Tapartó

To address this problem, the team executed selective sampling of the processed tailings from each ASGM site to characterize them and test an alternative method of reprocessing those tailings. Two methods were used to sample the tailings repositories. The first method consisted of sampling subsamples from different points on the improvised dams with a hand sampler to a maximum depth of 15 cm; then, all of the subsamples were mixed, and coning and quartering was performed until a final sample was obtained. The second method involved opening several sacks where tailings were stored to obtain a subsample from each of them with a stainless-steel trowel; then, all of the subsamples were mixed, and coning and quartering was once again used to obtain a final sample.

During the site visits, the team also socialized with the artisanal and small-scale mining community of the Municipality of Andes in order to stress the short-term, medium-term, and long-term risks to which miners expose themselves when they make improper or inappropriate, use of mercury as the main means of gold extraction. The main objective of this socialization was to build trust between the mining community in the area and the National University of Colombia, and to let these stakeholders know that the National University of Colombia was willing to help and support mining initiatives that utilize technologies free from mercury-use, within the legal framework.

Characterization of Materials

The samples collected from the field in Andes, Antioquia, were characterized at the National University of Colombia's CIMEX laboratory to learn their chemical and mineralogical composition, and their silver and gold content (g/t). The techniques used and obtained results are described below.

Fire Assay Tests

Several fire assays were performed with tailings samples obtained from the visited ASGM sites to quantify their gold and silver content. In this type of deposits, it is common to find silver accompanying gold due to the origin of the mineralization. Thus, gold extraction is always accompanied by other metals and semi-metals, including silver, copper, zinc, lead, and. in some cases. arsenic. The results (Table 1) vary due the nature (thicknesses and grade) of the different veins and the extractive processes to which the materials were subjected before being placed in the tailings repositories. The gold contents of the samples ranged from 21.4 to 0.2 g/t. Despite this high variability, most of the tailings sampled at

Table 1 Au and Ag contents across ASGM sites in Andes, Antioquia

Zone	Processing site	Au (g/t)	Ag (g/t)
Santa Rita – Village La Soledad	La cubana	21.4	9.2
		5.4	12.1
		8	7.8
		0.2	7
Santa Rita – Village La Soledad	El Chaquiro	1.8	20
		5.5	19.7
Santa Rita – Village La Soledad	Mellizos	2.3	9.4
	San Pablo*	8	10.5
	Asomisura	9.6	10.3
Santa Rita – Village San Agustin	La Cucarrona*	6.8	10
	San Agustín	N.A	N.A
	El Dorado	7	13.2
	La Y*	7	20.2
Santa Inés	Virgen del Carmen	5.3	7.8
Tapartó	Topitos de la Rochela	19.4	18.3

N.A. (not available) Sampling not permitted by the owner(s). * ASGM site abandoned with significant amounts of tailings

Table 2 Chemical compositions of tailings by XRF

Element	Content (% w/w)
Silicon as SiO_2	74.81
Titanium as TiO_2	0.14
Aluminum as Al_2O_3	6.27
Iron as Fe_2O_3	5.86
Manganese as MnO	0.06
Magnesium as MgO	0.69
Calcium as CaO	1.15
Sodium as Na_2O	0.42
Potassium as K_2O	1.43
Phosphorous as P_2O_5	0.19
Sulfur as SO_3	3.72
Arsenic as As_2O_3	2.05
PPI (Loss on ignition 105 to 1000 °C)	3.07

the visited ASGM sites had a high enough gold content to make reprocessing worthwhile.

X-ray Fluorescence (XRF)

X-ray fluorescence (XRF) analysis was performed to learn the general chemical composition of the collected tailings (Table 2). Minerals containing certain chemical elements (e.g. iron and arsenic) can affect the extraction of gold through conventional cyanidation and pose a potential risk to human and ecological health, since tailings exposed to the air could liberate cyanide to the environment and contaminate the surrounding soil and groundwater (Mihee et al. 2009; Ngole-Jeme and Fantke 2017).

X-ray Diffraction (XRD)

X-ray diffraction (XRD) analysis identified the mineralogical composition and approximate mineral content of each sample. For the Santa Rita and Santa Inés samples, the XRD patterns showed that all of the samples were rich in carbonates and sulfates (mainly calcite and gypsum); pyrite (FeS_2) was the main sulfide detected. The mineralogical composition was different for the Tapartó sample; the main phases were quartz (89.0%), clinochlore (4.0%), microcline (3.5%), albite (2.4%), and biotite (1.2%). As no sulfide phase was detected in the Tapartó sample, it appears that most of the gold in the Tapartó sample was present as free gold or associated with sulphides at concentrations too low for XRD to identify it. Although XRD is only semi-quantitative, minerals containing a high level of FeO_3 or As_2O_3 might still be present. Still, this information about the Tapartó sample is valuable since it suggests that these tailings contain little in the way of minerals that could adversely affect cyanidation.

Retreatment of Processing Tailings

For subsequent analyses, only the sample collected in Tapartó was used, as its gold content (and value), was greater than all of the other samples, and the amount of material collected allowed several processes to be carried out: gravimetric concentration, flotation, and conventional cyanidation. Once XRF revealed the chemical composition of the sample and XRD determined its mineralogical composition, it was then possible to process the tailings and carry out beneficiation, as presented in Fig. 5. Through these

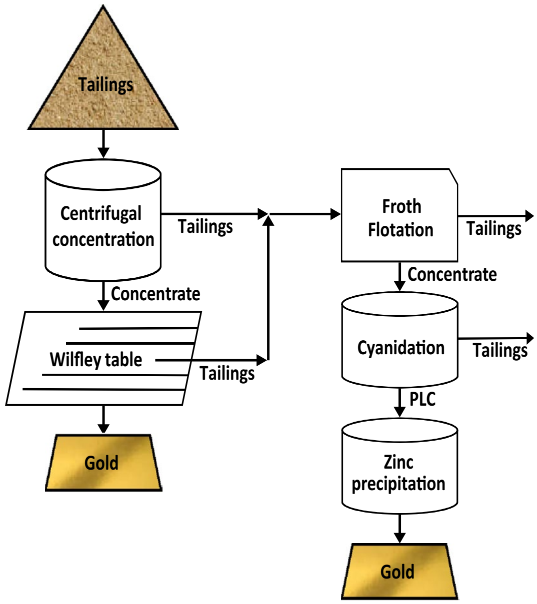

Fig. 5 General schematic of processing and beneficiation of tailings from ASGM sites

Fig. 6 Falcon centrifuge concentrator

Fig. 7 Gravimetric concentrator (Wilfley table)

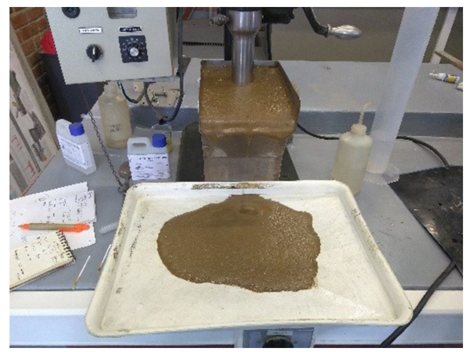

Fig. 8 Laboratory flotation process with Denver D-1 equipment

Table 3 Concentrations (g/ton) of gold across the different extraction processes and their recovery percentages

Processes	Head	Concentrate	Tails	Recuperation (%)
Centrifugal concentration	19.4	51.0	8.9	61.4
Gravimetric concentration	51.0	246.2	7.7	81.4
Flotation	11.4	23.7	3.5	79.8

steps, considerable quantities of gold could be recovered from the mercury-associated tailings.

To recover the free gold present in the sample, the team subjected the tailings to centrifugal concentration using a Falcon Concentrator (Fig. 6) at a force of 70 G (at 2 psi). Then, the concentrate was conditioned to 30% solids to allow gravimetric concentration using a Wilfley table at operating parameters of 4.8 L/min, a lateral angle of 1°, a transverse angle of 5°, and a speed of 180 rpm (Fig. 7).

The tailings were then mixed and conditioned to a pulp of 30% solids. This material was added into a 5 L DENVER D-1 flotation cell (Fig. 8) to concentrate the gold associated with sulfides. The pulp temperature was maintained at room temperature (≈ 25 °C), the conditioning time of the collector was 10 min, the flotation time was 160 s, and the stirring speed was kept constant at 130 rpm.

The recovery concentration percentages were considerable, indicating the inefficient use of mercury as a gold-extraction material (Table 3). A cyanidation test (Fig. 9) was performed with the flotation concentrate to recover any gold associated with the sulfides. The test was performed in a mechanically stirred reactor with a capacity of 2 L, using 500 g of dry sample. The pH of the 50% solids pulp was brought to 11 by adding 1 g of lime. The cyanide concentration measured 3 kg/t, and the treatment time was carried out for up to 24 h. The cyanidation solutions were sampled at hours 2, 4, 7, 20, and 24, and then analyzed on a Thermo Scientific iCE 3300 reference atomic

Fig. 9 Conventional cyanidation processes in the laboratory

absorption spectrophotometer to determine the amount of gold extracted and control the cyanide level.

Table 4 shows the consumption of cyanide and percentages of gold extraction from zero to 24 h, the total duration of the time in which the leaching process was carried out. Clearly, the highest percentage of gold extraction occurred from the seventh hour when the recovery percentage was more than 89%. The drop in the percentage of dissolved gold after hour 7 may be associated with gold reprecipitation or by adsorption of the metal by some mineral present in the ore, and suggests that a shorter leaching time can be used.

Table 4 Amount of cyanide consumed, and percentage of gold extracted

Time (h)	Cumulative Consumed Cyanide (kg/t)	Au Extracted (%)
0.0	0.00	0.0
2.0	0.65	45.9
4.0	0.65	77.1
7.0	0.63	89.5
20.0	0.65	81.0
24.0	0.27	80.6

Waste Management and the Elimination of Mercury in Tailings from Artisanal and Small-Scale Gold Mining in the Andes Municipality of Antioquia, Colombia

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The Artisanal Miners

To create rapport between the mining stakeholders in Andes and the National University of Colombia, the team leading this project carried out a series of workshops to identify the main concerns of the artisanal and small-scale miners regarding the elimination of mercury in ASGM (Fig. 10). The main challenges identified in the workshops were: mistrust towards the State and the organizations that represent it at the regional level; inability to pay for the engineering studies required by the mining authority; lack of education and training; and lack of association among small-scale miners.

Conclusion

Many ASGM sites (whether operating or abandoned) were located and sampled, as well as many of the tailings repositories in Santa Rita, Santa Inés, and Tapartó, all of which are contained in Antioquia's municipality of Andes. Poor tailings management was found at all of the visited ASGM sites.

The fire assay results revealed a high gold content in most of the tailings sampled from the ASGM sites, showing the inefficiency of mercury use, and the possibility of reprocessing those mine tailings. Then gold was recovered, demonstrating the efficiency of centrifugal and gravimetric concentrations for gold extraction. Further studies should be conducted to optimize the concentration and cyanidation stages with tailings from each of the ASGM sites.

A good relationship of mutual collaboration was established between the miners, the owners of the ASGM, and the National University of Colombia, Medellín. The trust generated among the project participants facilitated the dissemination of the results within the ASGM community, which showed its willingness to apply better technologies to eliminate the use of mercury.

Fig. 10 Workshop with mining leaders of the municipality of Andes

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References

Arango M, Olaya Y (2012) The problem of mining environmental liabilities in Colombia. Gestión Ambiente J 15(3):125–133 [in Spanish]. https://www.redalyc.org/articulo.oa?id=1694/169424893009

Cordy P, Veiga M, Salih I, Al-Saadi S, Console S, Garcia O, Mesa LA, Velásquez-López CP, Roeser M (2011) Mercury contamination from artisanal gold mining in Antioquia, Colombia: the world's highest per capita mercury pollution. Sci Total Environ 410–411:154–160. https://doi.org/10.1016/j.scitotenv.2011.09.006

House I, Marsden J (2006) Chemistry of Gold Extraction. Society for Mining, Metallurgy, and Exploration, Littleton, CO, USA

Idrobo N, Mejía D, Tribin AM (2014) Illegal gold mining and violence in Colombia. Peace Econ Peace Sci Public Policy 20(1):83–111. https://doi.org/10.1515/peps-2013-0053

Mihee L, Gi-Chun H, Ji-Whan A, Kwang-SY H-S (2009) Leachability of arsenic and heavy metals from mine tailings of abandoned metal mines. Int J Environ Res Public Health 6(11):2865–2879. https://doi.org/10.3390/ijerph6112865

Ngole-Jeme VM, Fantke P (2017) Ecological and human health risks associated with abandoned gold mine tailings contaminated soil. PLoS ONE 12(2):e0172517. https://doi.org/10.1371/journal.pone.0172517

Sarmiento M., Giraldo BH, Ayala H, Uran A, Soto AC, Martinez L (2013) Characteristics and challenges of small-scale gold mining in Colombia. In: Cremers L, Kole J, de Theije M (eds), Small-Scale Gold Mining in the Amazon. The Cases of Bolivia, Brazil, Colombia, Peru and Suriname. Serie: Cuadernos del CEDLA #26, Centre for Latin American Studies and Documentation, Amsterdam p 46–67

Veiga M (2010) Antioquia, Colombia: The world's most polluted place by mercury: impressions of two field trip. Report to the UNIDO-United Nations Industrial Development Organization. https://redjusticiaambientalcolombia.files.wordpress.com/2011/05/final_revised_feb_2010_veiga_antioquia_field_trip_report.pdf

Yannopoulos JC (1991) The extractive metallurgy of gold. Springer, New York City