minerals

Article

Investigation of Gold Recovery and Mercury Losses in Whole Ore Amalgamation: Artisanal Gold Mining in Nambija, Ecuador

Richard González-Vásquez, María Jesús García-Martínez * and David Bolonio

Energy and Fuels Department, Escuela Técnica Superior de Ingenieros de Minas y Energía, Universidad Politécnica de Madrid, C. de Ríos Rosas 21, 28003 Madrid, Spain; r.gonzalezv@alumnos.upm.es (R.G.-V.); david.bolonio@upm.es (D.B.)
* Correspondence: mj.garcia@upm.es

Abstract: Mercury is a highly toxic pollutant that can negatively affect human health and the environment; informal mining is one of the main sources of anthropogenic mercury release due to the separation or concentration by amalgamation that is still used to recover gold directly from ore. In the Nambija mining district, there is still informal mining based on practically no technical knowledge, which uses amalgamation as a processing technique for gold recovery. The production tasks that directly affect the handling of mercury during the in situ grinding–amalgamation process are monitored here. Experimental grinding tests were initially carried out in a "chancha" bar mill for a range of ore sizes and as a function of time; then, experimental tests were performed at the macro-level on grinding cycles in Chilean mills. Considering the characteristics of the ore mineral and the operation of the Chilean mills, it was determined that it is possible to reduce the Hg input to mill by up to 20% (at source). Experimental grinding–amalgamation tests were carried out at different times along with a grain size analysis of the ore; the recovery establishes the grinding time and the fraction in which the gold is extracted in a greater proportion, which affects the control of the amalgamation times. The mercury dosage used by the miners in the amalgamation process should be reduced, considering trials where there is better gold recovery and with the purpose of also reducing mercury losses; eventually, it is possible to jointly achieve an increase in gold recovery.

Keywords: artisanal mining; mercury; grinding; amalgamation; grain size tests; optimization; Nambija mining district

check for updates

Citation: González-Vásquez, R.; García-Martínez, M.J.; Bolonio, D. Investigation of Gold Recovery and Mercury Losses in Whole Ore Amalgamation: Artisanal Gold Mining in Nambija, Ecuador. *Minerals* **2023**, *13*, 1396. https://doi.org/10.3390/min13111396

Academic Editor: Carlos Hoffmann Sampaio

Received: 26 July 2023
Revised: 23 October 2023
Accepted: 23 October 2023
Published: 31 October 2023

1. Introduction

Artisanal gold mining is an important extractive activity in several countries of the world [1], where it is considered as important an economic sector as large-scale mining [2]. It is estimated that more than 10 million people, including women and children, are directly involved in this activity. In addition, it produces about 10%–15% of the world's total gold (Au) [3,4], making it one of the most important sources of metallic minerals on the planet [5]. Studies have shown that this activity is economically important for rural communities and reducing poverty [6]. The informal mining practice of amalgamation, as determined by Ecuadorian legislation [7,8], is the predominant method of extracting Au [9]. Amalgamation is one of the oldest processes used in gold recovery [10]. Mercury is a nonessential and toxic element that occurs in nature in three forms: inorganic compounds, organic compounds, and elemental mercury, the latter being used in artisanal mining [11,12]. During the last decade, an increase in the use of Hg in informal mining has been reported [13].

In order to make artisanal and small-scale mining mercury-free, many measures must be implemented, which must be adapted to the characteristics of the ore [14]. This, added to inadequate working conditions, the use of deficient and polluting technologies [15], and the application of rudimentary procedures [16], has caused not only a decrease in mineral recovery, but also an increase in the use of Hg in mineral processing, mainly in informal mining activities [17]. This is of concern in Ecuador, where, despite the use of Hg having been banned since 2015, it continues to be released into the environment via the process of gold extraction in artisanal mining, harming human health and ecosystems [18,19]. In certain mining operations, some progress has been made on the ground as Hg, which was previously extracted in the open air, can now be recovered using simple and economical retorts [7]. Retorts are devices that capture Hg vapor before it is emitted to the atmosphere during amalgamation and decomposition [20]. Although this process is of great help to recover Hg, losses during amalgamation and in tailings in more than 70 artisanal mining countries amount to 2000 t/a of Hg [21,22].

However, the negative effects of informal mining are not always attributable to poor technical practices, but sometimes to the socioeconomic circumstances of the miners [23]. Therefore, a very important aspect that even large-scale mining companies take into consideration is the degree of mineral liberation. Mineral liberation is one of the most important objectives of the grinding process [24]. Inefficient grinding can result in poor gold liberation. When mercury is added to the grinding circuit, mercury is pulverized (floured), losing its capacity to amalgamate free particles of gold. Most artisanal miners do not take this into consideration and add mercury into ball mills for whole-ore amalgamation, making this the most significant source of mercury pollution globally.

The Nambija mining district is, together with Portovelo and Ponce Enriquez, one of the three areas where subway gold mining is centered [25]. Most of the Au is extracted by the amalgamation method [26]. Currently, several Au deposits continue to be exploited by informal mining operations [27].

The method primarily used for gold extraction in the mining area of Nambija is amalgamation. The equipment generally used are: (1) bar mills (amalgamation), or "chanchas", that work in an open circuit and can process up to 55 kg of ore per grinding–amalgamation cycle (usually 2 h depending on the ore fed); and (2) Chilean mills or "trapiche" that work in an open circuit. The processing starts with the crushing of the ore up to ø 2 cm, then this is fed to the Chilean mills manually. At the beginning of the milling, 454 g (1 lb) of Hg is added, and it is fed 454 g of Hg/day until the completion of the milling cycle, which is generally 8 days. In some cases, the choices of mills, grinding times, and Hg feeding are made arbitrarily and/or depending on the miller's experience.

The objective of this article is the reduction of Hg use and the consequent reduction of Hg losses in the amalgamation process as a mitigation measure to limit its use and consumption; it is clear that the ideal is to not use mercury at all, but while this happens, it should be used responsibly. However, it should be taken into consideration how inefficient and polluting the amalgamation process is and the senselessness of amalgamating all the ore in an open circuit, as well as the low mineral recovery (Au) even if grinding times are adjusted. In conclusion, more efficient and environmentally friendly alternatives for gold recovery should be sought and implemented.

The results of this research are viable and can have a positive impact on the reduction of mercury release in the mining area, so they could be replicated in other settlements where this type of mining is carried out.

2. Materials and Methods

2.1. Study Area

The Nambija mining district is located in the southeastern region of Ecuador, 25 km from the city of Zamora, in the parish of San Carlos de las Minas on the western flank of the Nanguipa mountain range (Figure 1). It comprises the northern and southern condominiums of a 69-hectare mining concession legally granted by the Ecuadorian state. The terrain is rugged, with altitudes varying between 1500 and 2100 m above sea level. The climate is typical of the inter-Andean region, with temperatures ranging between 18 and 24 °C and annual rainfall between 200 and 300 mm. The main economic activity in Nambija is mining [28]. However, informal mining activities, a lack of technical guidance in operations [27], and the rudimentary processes used for Au extraction [29] have resulted in large amounts of waste and tailings throughout the surrounding sector. Mining wastewater laden with a high content of heavy metals and the emission of mercury into the environment have altered the quality and physicochemical properties of the soil and water.

Nambija is geologically constituted by marine sedimentary formations of the Mesozoic age intruded by the Zamora batholith; it is considered a Skarn-type deposit. The gold-bearing mineral contains almost exclusively native gold with granulometries ranging between 60 and 120 mesh; it is mineralogically associated with quartz, is quite pure, and can reach a grade of 94%.

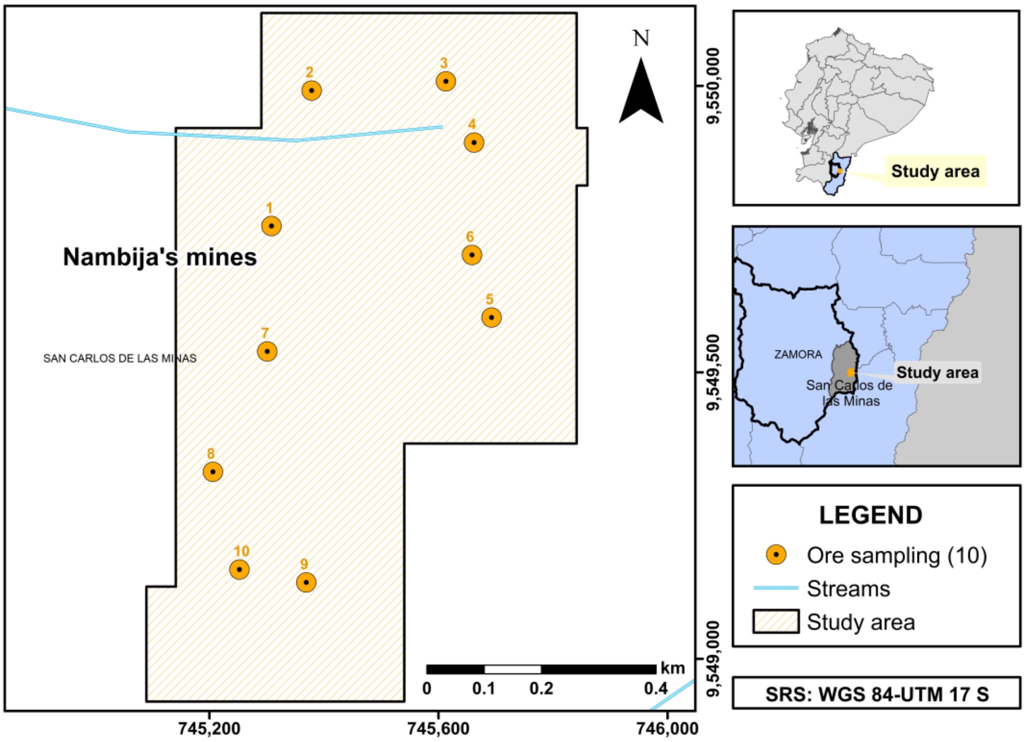

Figure 1. Location of the study area and location of the sampling sites in the mining district of Nambija.

2.2. Sampling and Data Analysis

Ten sampling points were established in the study area to collect ore (Figure 1). The ore sample consisted of 10 subsamples of approximately 45 kg each.

The objective of the sampling was to achieve homogeneity of the ore processed in the mining area. For the tests, sampling was carried out at 8 mining fronts and in 2 old rock dumps (ore with lower grades) that were being worked by the miners in the area at the time. A total of 450 kg of samples were collected. The subsamples collected at the mining faces, which were used to obtain the representative sample, were taken from the accumulated crushed mineral stock from the hoppers (stockpile). Likewise, the subsamples collected in the dumps were crushed until a fraction of Ø $\pm$ 1 cm was obtained. The sampling method used was Chip Sampling, which is commonly used for ore-grade control in productive mines [30]. The representative sample was disaggregated, homogenized, and quartered before analysis, resulting in eight samples of 55 kg each (S#1, S#2, S#3, S#4, S#5, S#6, S#7, and S#8). The samples were analyzed at the Chemical Metallurgical Laboratory JV Metals, located in El Pache, Portovelo, Ecuador. The method used to determine the head grade (feet) of the mineral sample was the Fire Assay [31]. This method consists of melting the sample with reagents and fluxes to detect metals such as gold and silver. It is one of the most widely used techniques in Au prospecting worldwide [32–34].

2.3. Determination of the Adequate Grinding Mesh Size

The characterization of the degree of liberation of the mineral of interest as a function of particle size is a key variable [35] that helps to determine the adequate grinding size to obtain higher gold recovery [36]. The amalgamation tests were conducted in a 1.30 m long octagonal (metal) rod mill with a total capacity of 0.297 m^3 and a speed of 70 rpm. This mill, commonly called a "chancha" or amalgamating cylinder because it is used to perform the amalgamation process, is a device that uses steel bars to reduce the size of the minerals [37]. It works by the impact and friction that occurs between the bars against the particles of the material to be fractionated. The standard and constant technical parameters during the tests to ensure the proper operation of the mill were a circulating load of 55 kg of sample, a grinding load of 120 kg of bars, a pulp solid-to-liquid ratio of 1/1, a mercury addition of 1 lb (454 g), and a bar of brown sugar. Brown sugar is an additive used to improve amalgam formation by keeping Hg coalescence, avoiding the formation of fine droplets. Once the amalgamation process was completed, the amalgam was separated from the pulp by washing. The adequate particle size was determined through the grinding/amalgamation process for samples S#1, S#2, S#3, S#4, and S#5. Samples S#1, S#2, S#3, and S#4 were subjected to 80, 100, 120, and 140 min of grinding, respectively. Subsequently, test 5 was replicated and subjected to the grinding time where the highest Au recovery of the first 4 tests was obtained (sample S#3), in order to validate the results. Next, 250 g samples were taken from the tailings after the mineral concentration of each grinding test to perform dry and wet particle size tests using the Chip Sampling method. This method consists of taking material from geometrically distributed points in the mineral mass, either linearly or forming a regular mesh in two dimensions [38]. The particle size curve was performed using the Gates–Gaudin–Schuhmann (G–G–S) distribution function, taking into account the total weight and the retained weight. This function describes the particle size distributions by comparing the values of the cumulative passing percentage with the mesh opening [39]. The mesh sizes used for the particle size curve were #10 (2000 µm), #18 (1000 µm), #35 (500 µm), #60 (250 µm), #120 (125 µm), #230 (63 µm), #325 (45 µm), and #400 (37 µm). The particle size distribution curve made it possible to visualize the homogeneous or heterogeneous tendency of the grain sizes (diameters) of the particles. Based on the results obtained in each test, the ore grade of each test was calculated. Finally, the head grade and tailings grade were balanced and analyzed. The valid head grade (grade of the ore coming from the mine and entering the plant) of the ore sample was 7.34 g Au/t.

2.4. Reducing Mercury Inputs

To determine the adequate mercury input, the amount of Hg used by the miners was taken as an initial reference. Thus, samples S#3 and S#5 (samples with better Au recovery) were fed with 454 g of mercury (100%), while samples S#6 and S#7 were tested to reduce the Hg fed and received 340.5 g (75%) and 227 g (50%), respectively. The standard operating conditions considered in the previous section were kept constant, with a grinding time of 120 min (more efficient) and the mercury input as a variable parameter. Then, the amount of Au recovered in the process and the Au present in the tailings were determined in order to establish the efficiency and to reduce the mercury input for the mineral beneficiation of the mining area. Finally, S#8 was tested with the input that gave the best results to verify and validate the results obtained.

2.5. Monitoring the Efficiency of the Gold Amalgamation

As a complementary step, and based on results obtained from previous tests on the amalgamation mill, a macro-level follow-up of the grinding–amalgamation operations of the MiningAndos S.A. mineral beneficiation plant, located in the Mapasingue sector within the Condominio Minero Sur de Nambija, was carried out. The plant consists of two sections, each with two open-circuit Chilean-type wheel mills. Initially, two mills were built to process the ore from the sector, which was of high grade at the time. However, due to the change in mining conditions, the rise in the price of gold, and the variation in grade, it was decided to double production by building two more mills to compensate and work lower-grade ores. A Chilean mill consists of a main shaft with arms that move the wheels in circles to grind the ore. They apply three effects in their operation: friction, pressure, and shear. Initially, an 8-day grinding cycle was monitored to observe the processes and phases of amalgam recovery and the methods and techniques used for mercury recovery. In addition, the feeding of material (ore) to the mills is performed arbitrarily, when the mills are unloaded and/or relying on the expertise of the miller. Miners typically add 454 g of mercury to each mill at the start of the operation and continue to add 454 g of Hg/day until the grinding cycle is complete. Subsequently, tests 2, 3, and 4 were conducted, based on the initial standard procedure and reducing the daily mercury feed in order. The constant parameters considered in these tests were: ore feed, constant water flow to the circuit (solid–liquid ratio), initial Hg input, and daily mercury feed. Amalgam and mercury recovery processes and techniques were identified to optimize and/or reduce losses. The main procedures identified for the handling and recovery of mercury were concentration after the grinding–amalgamation process; during the burning of amalgam in retorts; and in tailings (panning) and sedimentation tanks.

3. Results and Discussion

3.1. Adequate Grinding Mesh

The grinding size reduction ratio is determined empirically, evaluating at what size a higher percentage of gold recovery is obtained [40]. The results obtained in the particle size tests determine the adequate grinding mesh based on the calculated standard deviations (see Table 1).

Table 1. Results of the particle size distribution tests.

Test	Grinding Time (min)	d80 (µm)
S#1	80	465
S#2	100	240
S#3	120	180
S#4	140	120
S#5	120	180

Tables S1–S4 (see the Supplementary Materials) show the results of the grain size analysis with grinding times of 80, 100, 120, and 140 min for samples S#1, S#2, S#3, and S#4, respectively. The particle size distribution curves resulting from the four tests (80, 100, 120, and 140 min) are defined in a semi-logarithmic log-normal graph, where the x-axis shows the particle size in µm and the y-axis shows the accumulated % of mass retained in each screen size (%Ac(+)); see Figure 2.

The ore sample with a grinding time of 120 min (S#3) has 83.43% of the mass retained in 400 mesh (37 µm) and 99.90% passing 10 mesh (2000 µm). The most adequate gold liberation to allow mercury trapping in the amalgamation process seems to be around 120 mesh (125 µm), whereas the % mass accumulated at this grain size is 62.18%, (Table S3 and Figure 2). The grain size analysis resulting from this test indicates that 80% of the particles (d80) are below 180 µm. With this milling time, a higher proportion of gold is recovered; as can be seen, the yield in this test was 54.25%.

A simple control test of the amalgamation times and the proportion of mercury used can also reduce losses, together with an increase in gold recovery [41].

For verification and validation of the results obtained, test #5 was carried out, reproducing the test with the parameters with which the best performance was obtained (test #3), with the same standard operating conditions. The results of the verification test showed great similarity to those obtained in test #3.

Once the grinding mesh was defined for the Nambija ore, a metallurgical balance test was performed to determine the gold recovery for each test.

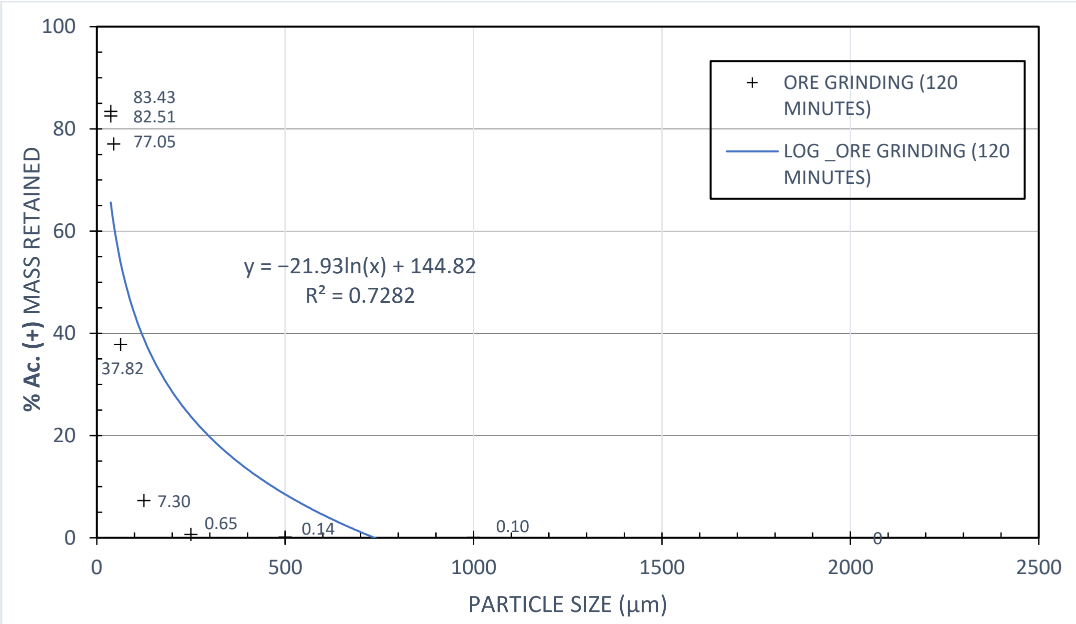

Figure 2. Grain size analysis of Nambija ore grinding for 120 min (mineral liberation).

Table 2 shows the results of the tests and the balance of the grinding–amalgamation operation for each test.

Table 2. Gold recovery by amalgamation as a function of grinding time.

Test	Grinding Time (min)	Gold Recovered (g)	Gold Recovered (g/t)	Au Lost with Tailings (g/t)	Gold Extracted (%)
S#1	80	0.067	1.22	6.12	16.60
S#2	100	0.153	2.78	4.56	37.90
S#3	120	0.219	3.98	3.36	54.25
S#4	140	0.124	2.25	5.09	30.72
S#5	120	0.221	4.02	3.32	54.74

This determines that there is a mineral particle size that liberates gold in a greater proportion when the grinding time is 120 min (tests S#3 and S#5); with respect to the mineral grain size d80 = 180 μm, the average yield for tests S#3 and S#5 is 54.49%.

In conclusion, the adequate grain size for improving gold amalgamation is 120 mesh, which corresponds to an accumulated passing Ac (-) % of 62.12% (average of S#3 and S#5 tests), with a 120-min grinding time (Tables S3 and S5).

3.2. Mercury Dosing in the Rod Mill

It is necessary to determine the ratio of mercury/mineral to be used in an adequate amalgamation time to achieve the least possible contamination [11]. In relation to mercury input, a balance was established to estimate losses; this consisted of measuring (weighing) the amount of mercury introduced in the amalgamation process [42]; two additional tests were conducted to test reducing the amount of mercury used by the miners (S#6 and S#7). In tests S#3 and S#5, where 454 g (100%) of Hg was fed, the % Au extracted achieved was 54.74%; in test S#6, where 340.5 g (−25%) of Hg was added, this increased to 56.48%; in the case of test S#7, in which 227 g (−50%) of Hg was added, the yield dropped to 45.33%. Undoubtedly, it is possible to achieve better performance and reduce the amount of Hg added by the miners by up to 25%. To corroborate the results obtained, a verification test (S#8) was performed using the input of the most successful test (S#6), feeding 340.5 g of

Hg to the cycle. The results in this test showed a % of Au extracted of 57.47%, which is consistent with that obtained in test S#6 (see Table 3).

Table 3. Mercury (Hg) input and performance.

Test	Grinding Time (min)	Hg Imput (g)	Au Recovered (g)	Gold Grade (g/t)	Lost with Tailings (g/t)	Efficiency (%)
S#3	120	454.0	0.219	3.98	3.36	54.25
S#5	120	454.0	0.221	4.02	3.32	54.74
S#6	**120**	**340.5**	**0.228**	**4.15**	**3.19**	**56.48**
S#7	120	227.0	0.183	3.33	4.01	45.33
S#8	**120**	**340.5**	**0.232**	**4.22**	**3.12**	**57.47**

In principle, the results of tests S#6 and S#8 define the mercury (Hg) input that allows for achieving a better recovery of gold (Au) from the ore; to process the ore in the mill/amalgamator, 340.5 g of Hg must be fed to each grinding cycle (see Table 2).

3.3. Monitoring and Optimization of the Use of Mercury in the Plant

In relation to the amalgamation grinding process at the beneficiation plant (Miningandos SA), the following parameters were considered: (1) the grinding time required for processing, (2) the volume of ore processed, and (3) the total mercury fed and recovered at the end of each operation in the two sections. Initially, the amount of mercury added by the miners for ore beneficiation in Chilean mills (test 1) was taken as a base; in the same way, it was tested to replicate three grinding cycles (tests 2, 3, and 4), reducing the mercury addition by 20%.

Once the grinding–amalgamation cycle is finished, miners remove the amalgam and excess mercury from the Chilean mills (see Figure 3).

Figure 3. Settlement of the grinding–amalgamation cycle: (**a**) mineral concentration (mill washing), (**b**) traditional amalgam and mercury recovery from tailings.

In order to improve the management of mining activity, and with the objective of reducing mercury losses while trying to improve gold recovery, actions were implemented. The strategy was to introduce measures to reduce mercury use without significant changes in infrastructure and then introduce new equipment to concentrate gold [43]. The following complementary actions were carried out: (1) A change in the discharge grain size in the mills, due to the use of an inadequate mesh (#60 mesh); due to the fact that the grain size with which the best gold recovery is obtained for the ore in the sector is the #120 mesh, a #100 mesh was used to avoid clogging problems. (2) The ore feed to the mill was regularized every 20 min in order to avoid overgrinding (excess of fine mineral), with consequent pulverization of the Hg. In the tests, the water flow was kept constant.

The results obtained show that it is possible to reduce the mercury addition to a Chilean mill by up to 20.00%, which is positive since it allows for reducing mercury consumption at the source. Likewise, it is evident that, with the implemented actions, the amount of mercury recovered at the end of the concentration process increased from 24.20% to 35.63% (test 2) in Section 1 and from 29.08% (test 1) to 36.48% (test 3) in Section 2 (see Table 4).

Table 4. Mercury recovery from the grinding–amalgamation process.

	Section 1			
Test	**Grinding Time (h)**	**Ore Processed (Tn)**	**Hg Fed (g)**	**Hg Recovered (%)**
1	157	226	3372.97	24.20
2	160	250	2800.20	35.63
3	154	250	2800.09	35.11
4	157	250	2800.05	33.61
	Section 2			
1	150	215	3455.38	29.08
2	161	250	2800.15	34.81
3	156	250	2800.07	36.48
4	153	250	2800.13	35.52

Finally, after reducing the mercury addition and consequent loss, the gold extraction was not affected. This is consistent with what was observed in the bar mill tests. This means an economic benefit for miners, considering that 1 lb (454 g) of Hg in the mining area costs around USD 40.

3.3.1. Mercury Distillation in Retort

Mercury distillation using a retort to condense the Hg vapor is widely recommended to recover mercury from amalgam and thus avoid its dispersion into the environment. That said, the burning time in the retort used by the miners to evaporate mercury from the amalgam is 45 min (Test 1).

To improve the process, we tried increasing the retort burn time by 25% (tests 2, 3, and 4); consequently, the tests were followed with a retort burning time of 60 min.

Table 5 shows the results of the percentage of mercury recovered from the amalgam and the Hg lost and/or not recovered at the end of the distillation process. The variations in amalgam weights and mercury content are dependent on the amount and type of gold amalgamated (coarse or fine gold).

Table 5. Mercury recovered from the amalgam.

	Section 1			
Test	**Amalgam (g)**	**Au Recovered (%)**	**Hg Recovered (%)**	**Hg Lost (%)**
1	1342.36	21.57	88.03	11.97
2	1411.02	28.91	89.23	10.77
3	1274.37	27.85	93.98	6.02
4	1357.94	29.34	93.09	6.91
	Section 2			
1	1257.21	32.05	93.65	6.35
2	1309.5	29.61	97.5	2.5
3	1475.64	29.59	97.92	2.08
4	1339.24	31.78	97.34	2.66

The results obtained show that there was an increase in the amount of mercury recovered when the burning time in the retort was increased to 60 min; the percentage of unrecovered mercury was reduced from 11.97% (test 1) to 6.02% (test 3) in the best case in Section 1 and from 6.35% (test 1) to 2.08% (test 3) in the best case in Section 2. The increase in mercury recovery with retorts during its decomposition has a positive impact on the environment and, mainly, on the health of the operators and surrounding people. In addition, the mercury recovered can also be recycled, saving money for miners.

3.3.2. Recovery of Gold from the Amalgamation and Sedimentation Boxes

In addition, the amalgam and mercury present in the stored tailings from the primary concentration process are recovered in the sluices and the amalgamation tailings in the sedimentation box; these processes are carried out to recover the gold that escapes from the amalgamation process and leaves the mill in the tailings.

To recover gold from the tailings collected in the sluices and sedimentation boxes, miners rework the tailings in a trough (Figure 4) and then concentrate it with pan or batea. The panning is one of the processes used to obtain the gold–mercury amalgam. It consists of separating the amalgam from the finer material by making circular movements in a convex pot-shaped container [44].

The concentrates retained in fiberglass and/or carpets on the sluices are washed off in a batea to be panned, concentrating the gold even more. This is performed by miners with a washing frequency of every 3 h for the first two carpets and every 8 h for all the carpets (test 1).

Test 1 was analyzed as performed by the miners; likewise, in order to improve recovery and improve this process, the panning time was readjusted to 0.5 h for the first two carpets and every 6 h for all the carpets, regularizing the panning (test 2), with the objective of concentrating more tailings. The implemented measure evidenced, as foreseen, an increase in the volume of accumulated sand with respect to test 1; similarly, it was performed with other tests (3 and 4) under the same conditions. However, for the recovery we tested reworking the accumulated tailings in a generic concentrator (a mini centrifugal concentrator), where the concentrate was panned to obtain the amalgam and mercury. This was evident from the increase in the recovery of gold and mercury from the panning tailings in the two sections (see Table 6).

Table 6. Recovery of amalgam and mercury product from sluices and sedimentation tanks, sections 1 and 2.

	Section 1			
Test	**Gold Recovery (Sluice) (g)**	**Hg Recovery (Sluice) (%)**	**Gold Recovery (Sand Tank) (g)**	**Hg Recovery (Sand Tank) (%)**
1	8.76	10.08	3.17	8.74
2	10.28	12.78	4.53	10.2
3	14.51	11.95	5.21	10.59
4	13.96	13.01	5.38	10.75
	Section 2			
1	6.41	10.46	4.09	8.53
2	8.59	15.75	5.26	9.13
3	9.16	12.83	6.07	8.57
4	11.87	13.22	7.52	12.18

Likewise, regarding the treatment and recovery of gold and mercury from the primary concentration tailings (each section has a storage tank), we proceeded in a similar way as with the tailings from the amalgamation tailings. The tailing storage tanks are used as a last alternative to recover the gold not trapped by the mercury. As in the previous case, these tailings were processed in the mini centrifugal concentrator, and the concentrate was panned.

Similarly, the results are consistent with what was observed when processing the tailings from the panning, since there was an increase in the recovery of gold (already amalgamated) and mercury when processing the sand from the sedimentation tanks, ranging from 8.74% recovered in test 1 to 10.75% in the best case (test 4) in Section 1 and from 8.53% (test 1) to 12.18% in the best case (test 4) in Section 2. This increase can be attributed to the use of the centrifugal concentrator that replaces the manual tilling of the tailings in a chute.

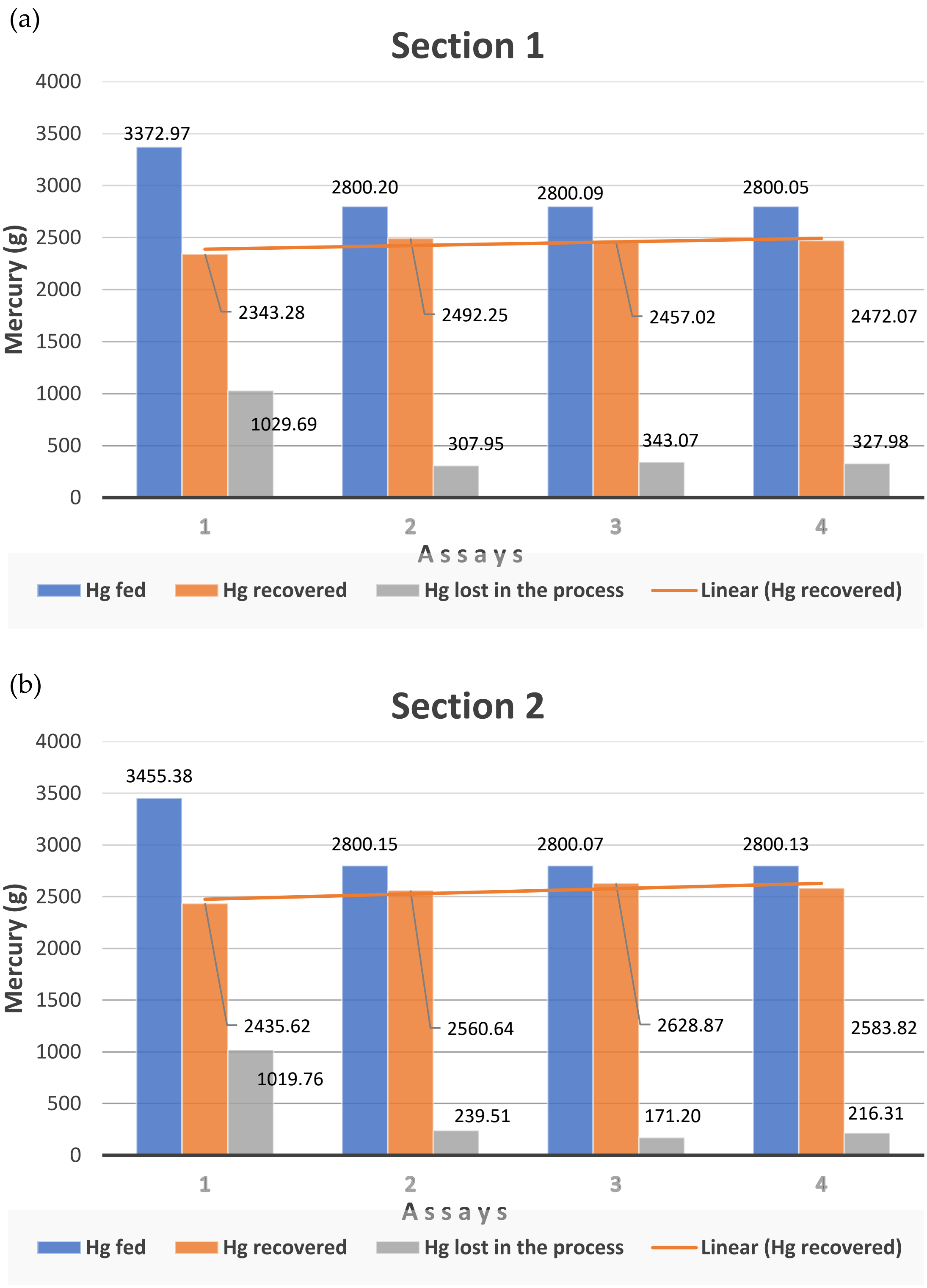

Figure 4. Mercury balances for tests 1, 2, 3, and 4: (**a**) Section 1; (**b**) Section 2.

The balances made to the grinding, amalgamation, and concentration cycle in tests 2, 3, and 4 determine a significant increase in amalgam and mercury recovered; it is evident that mercury losses are reduced with respect to the initial tests in each section, which has a positive impact on the optimization of concentration and mineral use.

In general, Table 7 summarizes the total percentage of mercury recovered and lost; mercury losses were reduced from the initial test (test 1) in the two sections.

Table 7. Balance of recovery and mercury losses of the grinding-amalgamation tests.

Test	Total Hg Recovered from the Process (g)	Hg Recovered (%)	Total Hg Lost in the Process (g)	Hg Lost %
	Section 1			
1	2343.28	69.47	1029.69	30.53
2	2492.25	89.00	307.95	11.00
3	2457.02	87.75	343.07	12.25
4	2472.07	88.29	327.98	11.71
	Section 2			
1	2435.62	70.49	1019.76	29.51
2	2560.64	91.45	239.51	8.55
3	2628.87	93.89	171.20	6.11
4	2583.82	92.28	216.31	7.72

In summary, the results obtained indicate that there was a significant increase in the mercury recovered in the amalgamation process compared to that recovered in test 1 (input used by the miners), ranging from 87.75% to 89.00% in Section 1 and from 91.45% to 93.89% in Section 2 (Figure 4). The differences and fluctuations in the results of tests 2, 3, and 4 are a possible consequence of the operation and/or ore feed of each mill (involving stoppages for maintenance, which explains why some process more mineral than others).

4. Conclusions

The results of the grain size tests and mineral recovery show that the mineral fraction that liberates Au in greater proportion occurs when 62.12% of the material passes the #120 mesh (125 µm), achieved with a grinding time of 120 min in an amalgamating mill ("chancha"). Regarding the mercury input for the ore processed, it was determined that the adequate input to feed a mill/amalgamator is 340.5 g, which allows for a 25% reduction of the Hg usually fed by the miners in each work cycle, with a gold recovery of 57 $\pm$ 0.5%. Likewise, considering the characteristics of the ore mineral and the operation of the Chilean mills, it was determined that it is possible to reduce the Hg input to each mill by up to 20% (Hg reduction at the source). When applying this reduction, it was observed that neither the mineral concentration nor the mill performance was affected, and it is possible to apply simple and viable alternatives that can improve the operating performance, increase gold recovery up to 4.68%, and reduce Hg losses in the process by up to 20.36% on average.

The control of amalgamation times and proportion of mercury used can also reduce losses, together with an increase in gold recovery [43], which implies a greater economic benefit for miners. However, the inefficiency of the process, the senselessness of amalgamating all the ore in an open circuit, the low mineral recovery (Au), and the harmfulness of amalgamation to the surrounding environment and population should be considered; therefore, more economical and environmentally friendly alternatives for recovery should be sought and implemented: grinding the ore, concentrating and amalgamating only a little at a time (concentrate), or selling it to a cyanidation plant.

Undoubtedly, the efficient use of mining resources can reduce and, to some degree, control the use of mercury in the concentration and gold beneficiation processes. The proposal indicated in this study is feasible and can have a positive impact on the reduction of anthropogenic mercury emissions as a mitigation measure within the mining sector of Nambija so that it can be replicated in other gold deposits where this type of mining is carried out.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/min13111396/s1, Table S1: Grain size analysis, grinding time (80 min), Table S2: Grain size analysis, grinding time (100 min), Table S3: Grain size analysis, grinding time (120 min); Table S4: Grain size analysis, grinding time (140 min), Table S5: Verification test, grinding time (120 min).

Author Contributions: R.G.-V.: Conceptualization, Investigation, Methodology, writing-original draft. M.J.G.-M.: Supervision, Methodology, Writing—review & editing. D.B.: Supervision, Validation, Writing—review & editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: All data are contained within the article or supplementary materials.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Sana, A.; Christophe, D.B.; Hien, H. Knowledge and perceptions of health and environmental risks related to artisanal gold mining by the artisanal miners in Burkina Faso: A cross-sectional survey. *Pan Afr. Med. J.* **2017**, *27*, 280. [CrossRef] [PubMed]
2. Mwandiringana, E.; Ye, J. Mining what is not mine: Artisanal gold mining in Gwanda, Zimbabwe. *Extr. Ind. Soc.* **2023**, *13*, 101217. [CrossRef]
3. Vergara-Murillo, F.; González-Ospino, S.; Cepeda-Ortega, N.; Pomares-Herrera, F.; Johnson-Restrepo, B. Adverse Health Effects and Mercury Exposure in a Colombian Artisanal and Small-Scale Gold Mining Community. *Toxics* **2022**, *10*, 723. [CrossRef] [PubMed]
4. Jiménez, A.D.; Smith, N.M.; Holley, E.A. Capitals in artisanal and small-scale mining in Marmato, Colombia: Using the sustainable livelihoods framework to inform formalization. *Extr. Ind. Soc.* **2022**, *12*, 101157. [CrossRef]
5. Jiménez-Oyola, S.; Chavez, E.; García-Martínez, M.-J.; Ortega, M.F.; Bolonio, D.; Guzmán-Martínez, F.; García-Garizabal, I.; Romero, P. Probabilistic multi-pathway human health risk assessment due to heavy metal(loid)s in a traditional gold mining area in Ecuador. *Ecotoxicol. Environ. Saf.* **2021**, *224*, 112629. [CrossRef]
6. Bester, V. Towards a sustainable artisanal gold mining sector in South Africa: Proposed developmental initiatives. *J. Rural Stud.* **2023**, *97*, 375–384. [CrossRef]
7. Veiga, M.M.; Gunson, A.J. Gravity Concentration in Artisanal Gold Mining. *Minerals* **2020**, *10*, 1026. [CrossRef]
8. Manzila, A.N.; Moyo, T.; Petersen, J. A Study on the Applicability of Agitated Cyanide Leaching and Thiosulphate Leaching for Gold Extraction in Artisanal and Small-Scale Gold Mining. *Minerals* **2022**, *12*, 1291. [CrossRef]
9. Jonkman, J.; de Theije, M. Amalgamation: Social, technological, and legal entanglements in small-scale gold-mining regions in Colombia and Suriname. *Geoforum* **2022**, *128*, 202–212. [CrossRef]
10. Rodrigues, P.d.A.; Ferrari, R.G.; dos Santos, L.N.; Junior, C.A.C. Mercury in aquatic fauna contamination: A systematic review on its dynamics and potential health risks. *J. Environ. Sci.* **2019**, *84*, 205–218. [CrossRef]
11. Jiménez-Oyola, S.; García-Martínez, M.-J.; Ortega, M.F.; Bolonio, D.; Rodríguez, C.; Esbrí, J.-M.; Llamas, J.F.; Higueras, P. Multi-pathway human exposure risk assessment using Bayesian modeling at the historically largest mercury mining district. *Ecotoxicol. Environ. Saf.* **2020**, *201*, 110833. [CrossRef]
12. Torkaman, P.; Veiga, M.; Lima, L.d.A.; Oliveira, L.; Motta, J.; Jesus, J.; Lavkulich, L. Leaching gold with cassava: An option to eliminate mercury use in artisanal gold mining. *J. Clean. Prod.* **2021**, *311*, 127531. [CrossRef]
13. Alfonso, P.; Anticoi, H.; Yubero, T.; Bascompta, M.; Henao, L.; Garcia-Valles, M.; Palacios, S.; Yáñez, J. The importance of mineralogical knowledge in the sustainability of artisanal gold mining: A Mid-South Peru case. *Minerals* **2019**, *9*, 345. [CrossRef]
14. Lydia, O.; Godwin, A.; Isaac, L. "We have done nothing wrong": Youth miners' perceptions of the environmental consequences of artisanal and small-scale mining (ASM) in Ghana. *Extr. Ind. Soc.* **2022**, *12*, 101179. [CrossRef]
15. Sánchez-Vázquez, L.; Espinosa-Quezada, M.G.; Eguiguren-Riofrío, M.B. "Golden reality" or the "reality of gold": Artisanal mining and socio-environmental conflict in Chinapintza, Ecuador. *Extr. Ind. Soc.* **2016**, *3*, 124–128. [CrossRef]
16. Kosai, S.; Nakajima, K.; Yamasue, E. Mercury mitigation and unintended consequences in artisanal and small-scale gold mining. *Resour. Conserv. Recycl.* **2023**, *188*, 106708. [CrossRef]
17. Mestanza-Ramón, C.; Mora-Silva, D.; D'orio, G.; Tapia-Segarra, E.; Gaibor, I.D.; Parra, J.F.E.; Velásquez, C.R.C.; Straface, S. Artisanal and Small-Scale Gold Mining (ASGM): Management and Socioenvironmental Impacts in the Northern Amazon of Ecuador. *Sustainability* **2022**, *14*, 6854. [CrossRef]
18. Gonçalves, A.O.; Marshall, B.G.; Kaplan, R.J.; Moreno-Chavez, J.; Veiga, M.M. Evidence of reduced mercury loss and increased use of cyanidation at gold processing centers in southern Ecuador. *J. Clean. Prod.* **2017**, *165*, 836–845. [CrossRef]
19. Morgan, V.L.; McLamore, E.S.; Correll, M.; Kiker, G.A. Emerging mercury mitigation solutions for artisanal small-scale gold mining communities evaluated through a multicriteria decision analysis approach. *Environ. Syst. Decis.* **2021**, *41*, 413–424. [CrossRef]

20. Cruz, U.; Vega, E. Characterization of Environmental Pollution Associated with the Amalgamation Process Based on the Loss of Mercury. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *835*, 012010. [CrossRef]
21. Torkaman, P.; Veiga, M. Comparing cyanidation with amalgamation of a Colombian artisanal gold mining sample: Suggestion of a simplified zinc precipitation process. *Extr. Ind. Soc.* **2023**, *13*, 101208. [CrossRef]
22. Hinton, J.J.; Veiga, M.M.; Veiga, A.T.C. Clean artisanal gold mining: A utopian approach? *J. Clean. Prod.* **2003**, *11*, 99–115. [CrossRef]
23. Parapari, P.S.; Parian, M.; Rosenkranz, J. Quantitative analysis of ore texture breakage characteristics affected by loading mechanism: Fragmentation and mineral liberation. *Miner. Eng.* **2022**, *182*, 107561. [CrossRef]
24. Carling, G.T.; Diaz, X.; Ponce, M.; Perez, L.; Nasimba, L.; Pazmino, E.; Rudd, A.; Merugu, S.; Fernandez, D.P.; Gale, B.K.; et al. Particulate and dissolved trace element concentrations in three southern ecuador rivers impacted by artisanal gold mining. *Water Air Soil Pollut.* **2013**, *224*, 1415. [CrossRef]
25. Appleton, J.D.; Williams, T.M.; Orbea, H.; Carrasco, M. Fluvial Contamination Associated with Artisanal Gold Mining in the Ponce Enríquez, Portovelo-Zaruma and Nambija Areas, Ecuador. *Water Air Soil Pollut.* **2001**, *131*, 19–39. [CrossRef]
26. Requelme, M.R.; Ramos, J.; Angélica, R.; Brabo, E. Assessment of Hg-contamination in soils and stream sediments in the mineral district of Nambija, Ecuadorian Amazon (example of an impacted area affected by artisanal gold mining). *Appl. Geochem.* **2003**, *18*, 371–381. [CrossRef]
27. MAE-PRAS Ministerio del Ambiente de Ecuador. *Programa de Reparación Ambiental y Social—Diagnóstico Socioambiental de la Zona Minera Nambija*; MAE-PRAS Ministerio del Ambiente de Ecuador: Quito, Ecuador, 2015.
28. Ministerio de Energía y Minas. Reporte de Minería. 2016. Available online: https://www.mem.gob.do/index.php/consultas-publicas (accessed on 12 January 2020).
29. *Guía de Buenas Prácticas de la Esmeralda Colombiana*; Comisión Colombiana de Recursos y Reservas Minerales: Bogotá, Colombia, 2020.
30. Diana Buitrón, O.; Diego Barona, D.; Francisco Iturra, M.; Johana León, F. Validación del método para la determinación de oro por ensayo al fuego combinado con espectrometría de absorción atómica en muestras geológicas mineras metalúrgicas. *InfoAnalítica* **2021**, *9*, 119–136. [CrossRef]
31. Magalhães, F.B.; Carvalho, C.d.F.; Carvalho, E.L.C.N.; Yoshida, M.I.; Dos-Santos, C.G. Rendering wastes obtained from gold analysis by the lead-fusion fire-assay method non-hazardous. *J. Environ. Manag.* **2012**, *110*, 110–115. [CrossRef]
32. Hajinia, A.; Heidari, T. Sensitive fluorometric determination of gold in geological samples using fire assay pre-concentration coupled with microfluidic paper-based analytical device. *Microchem. J.* **2021**, *164*, 105923. [CrossRef]
33. Baena, O.J.R.; Aristizábal, G.; Pimentel, M.S.; Flórez, C.A.; Argumedo, C.E. Waste Management and the Elimination of Mercury in Tailings from Artisanal and Small-Scale Gold Mining in the Andes Municipality of Antioquia, Colombia. *Mine Water Environ.* **2021**, *40*, 250–256. [CrossRef]
34. INEN-Instituto Ecuatoriano de Normalización. Norma Técnica Ecuatoriana-INEN 2169: 2013 Agua, Calidad del Agua, Muestreo, Manejo y Conservación de Muestras. 2013, p. 26. Available online: http://www.trabajo.gob.ec/wp-content/uploads/2012/10/nte-inen-2169-agua.-calidad-del-agua.-muestreo.-manejo-y-conservación-de-muestras.pdf (accessed on 12 January 2020).
35. Pérez-García, E.; Bouchard, J.; Poulin, É. Integrating online mineral liberation data into process control and optimisation systems for grinding–separation plants. *J. Process Control* **2021**, *105*, 169–178. [CrossRef]
36. Altun, O.; Altun, D. Estimation of mineral liberation distribution functions to be used in modelling of impact and attrition milling. *Miner. Eng.* **2021**, *173*, 107236. [CrossRef]
37. Ministerio de Energía y Minas del Perú. Guía de Orientación del Uso Eficiente de la Energía y de Diagnóstico Energético. 2022, p. 112. Available online: https://www.sonami.cl/v2/informacion-de-la-mineria/mineria-metalica/ (accessed on 12 January 2020).
38. Jackson, C.F.; Hedges, J.H. *Metal-Mining Practice*; U.S. Bureau of Mines: Washington, DC, USA, 1939.
39. García, L.P.; Llópiz, Y.C.; Puyáns, L.R.G. Modelo Matemático Para Describir la Distribución Granulométrica de la Fase Dispersa de las Suspensiones de Laterita. *Tecnología Química* **2009**, *XXIX*, 83–91. Available online: https://www.redalyc.org/articulo.oa?id=445543761010 (accessed on 4 May 2023).
40. Pantoja-Barrios, G.K.; Molina-Ramírez, E.K.; Fuentes-Torres, S.N.; Ramírez, F.A.; Mojica, J.; Londoño-Escobar, J.I. Metodología geometalúrgica para mejorar el proceso de extracción de oro en pequeña escala de la mina Gualconda en Nariño—Colombia. *Revista UIS Ingenierías* **2020**, *20*, 143–152. [CrossRef]
41. García, O.; Veiga, M.M.; Cordy, P.; Suescún, O.E.; Molina, J.M.; Roeser, M. Artisanal gold mining in Antioquia, Colombia: A successful case of mercury reduction. *J. Clean. Prod.* **2015**, *90*, 244–252. [CrossRef]
42. Pantoja, T.F.; Álvarez, R.R.; Rodríguez, A.A.S. Methods to reduce mercury pollution in small gold mining operations. *Rev. Metal.* **2005**, 194–203. [CrossRef]
43. FMAM-Fondo para el Medio Ambiente Mundial; ONUDI; AGC-Artisanal Gold Council. *Línea de Base Nacional Para la Minería Artesanal y en Pequeña Escala de Oro en Ecuador, Conforme la Convención de Minamata Sobre Mercurio*; Ministerio del Ambiente, Agua y Transición Ecológica: Pichincha, Ecuador, 2020; pp. 8–89.
44. del Ambiente, M.-M. Norma de calidad ambiental y de descarga de efluentes: Recurso agua. *Quito* **2015**, *131*, 35–40.