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Mapping the Reality of Hg-Free Artisanal Small-Scale Gold Mining

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Abstract: Artisanal gold mining (AGM) is a very important topic, of which the environmental and social impact has been widely studied. However, there are few studies on operational efficiency, financial analysis, and the lack of mine planning. The purpose of this work was to investigate whether AGM operation without mercury is sustainable. The following parameters were analyzed in the case study: the general situation, interaction with the company that owns the area, production, drilling and blasting, loading and transport, freight to the centralized plant, workforce, materials and supplies, geological control planning and the relationship with the processing plant. Even without the mercury variable, AGM was found to be unsustainable. The lack of planning and operational inefficiency did not allow for continuous operation. The results of this research provide guidance on the future steps the current government and society should take to achieve sustainable AGM.

Keywords: mining sustainability; artisanal small-scale gold mining; Hg-free

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1. Introduction

The concept of "sustainable mining operations" is based on the efficiency of operations and rigorous mine planning and adherence to the plan to ensure maximum efficiency.

In most cases, small-scale mining (SSM) fails to employ proper mine planning. The core of mine planning lies in the knowledge of the mineral body that depends on geological research, which is in turn based on expensive exploratory drilling campaigns. The lack of capital access within SSM constrains the implementation of the aforementioned procedure.

The main subjects addressed by scholars regarding artisanal and small-scale mining encompass the formalization of operation, followed by assessing environmental and health impacts, the relationship between small mining and communities, conflict between small and large mining, and case studies in different countries [1–13].

Projects that analyze technical aspects of operations integrated with the environmental impacts are novel and scarce [14–16].

In the last two years, a recurring theme in studies has been the impact of the pandemic on the mineral economy and its social impact [17–20].

Formalization is still a very important topic worldwide, especially in places far from urban centers that are difficult to control, such as the Amazon [21–23].

Each country in Latin America has different bottlenecks. For example, in Colombia, although mining is seen as an economic growth import, small-scale mining is controlled by violent national groups [24].

Many Latin American governments believe that the centralization of purchasing minerals and constructing more efficient processing plants is the solution for increasing the formalization of activities. With these new mechanisms, small-scale miners have obtained a greater revenue from the production and sale of minerals [25,26].

This research was conducted in a mercury-free AGM region, in order to determine whether Hg-free AGM operation is sustainable.

1.1. Artisanal Mining in Chile

In Chile, most operations are formalized; therefore, the topics addressed differ from those of other countries. ENAMI, a government mining company founded in 1960, focuses on small- and medium-scale mining, encouraging the formalization of and reduction in environmental impacts.

The Atacama region still faces problems of formalization and environmental impacts due to mercury use. Nevertheless, this is not a scientific issue, because the solutions are already well defined. The regional government declared its intention to invest CLP 792 million in the construction of three Hg-free concentration plants in the provinces of Chañaral, Copiapó and Huasco in northern Chile [27].

Environmental impact has been the subject of a few recent peer-reviewed publications on small-scale mining in Chile. However, in the last three years, only four articles were published relating to technical aspects [28–31].

As established earlier, SSM is affected by a lack of planning, but also by high operating costs (OPEX, due to scale effects) and a high variability in income [32].

Operational health and safety are also one of the most critical issues in small mining. It is common to read news of accidents related to a lack of technical knowledge and the non-application of good practices, which are consolidated in the mining sector in medium and large companies. The main causes are related to landslides, a lack of geo-mechanical studies and the improper handling of explosives [33–35].

Veiga and Fadina [36] analyzed the relationship between miners and mineral processors. According to them, a successful system for eliminating mercury use is having a central plant, and the miners sell their ore to processing plants instead of processing it themselves: they make more profit than when they use mercury for amalgamation.

1.2. The Support of Public Agencies for Small-Scale Mining in Chile

Figure 1 shows the complex network of public agencies and their contribution to the small-scale mining sector in Chile (for any substance, not only Au). In Chile, artisanal mining is considered a subset of small-scale mining. Such support includes financial help, access to loans and technical assistance. The most important contribution, in terms of environmental protection, is the fact that the ores (or ore concentrates) are bought and processed in centralized plants that operate with industrial standards and do not involve pollutants such as cyanide or Hg. This was the same condition observed by Veiga and Fadina [36], but with the distinction of the processing plants belonging to a public company instead of a private one.

ENAMI

Of the public agencies indicated in Figure 1, the only one dedicated to small- and medium-sized companies is ENAMI, which promotes and sustains small- and medium-sized mining companies [37].

i. ENAMI buys the minerals from miners

ENAMI buys both run-of-mine (ROM) ores and concentrated minerals, with the minerals of interest being copper, gold and silver, whether major or minor. The material is processed in controlled and clean plants (therefore, no Hg or other pollutants are involved) and sold by ENAMI itself. In 2020, 1557 small miners were registered to sell their minerals to this agency [38].

The purchase value at which ENAMI buys from the mines is a function of (a) the main mineral grade; (b) the type of processing ENAMI executes; (c) the international value of the mineral being processed; (d) the dollar exchange rate with the Chilean Peso; (e) penalties for contaminants and moisture content; and (f) added value for secondary minerals. A table of all the values mentioned above is published monthly on the ENAMI website.

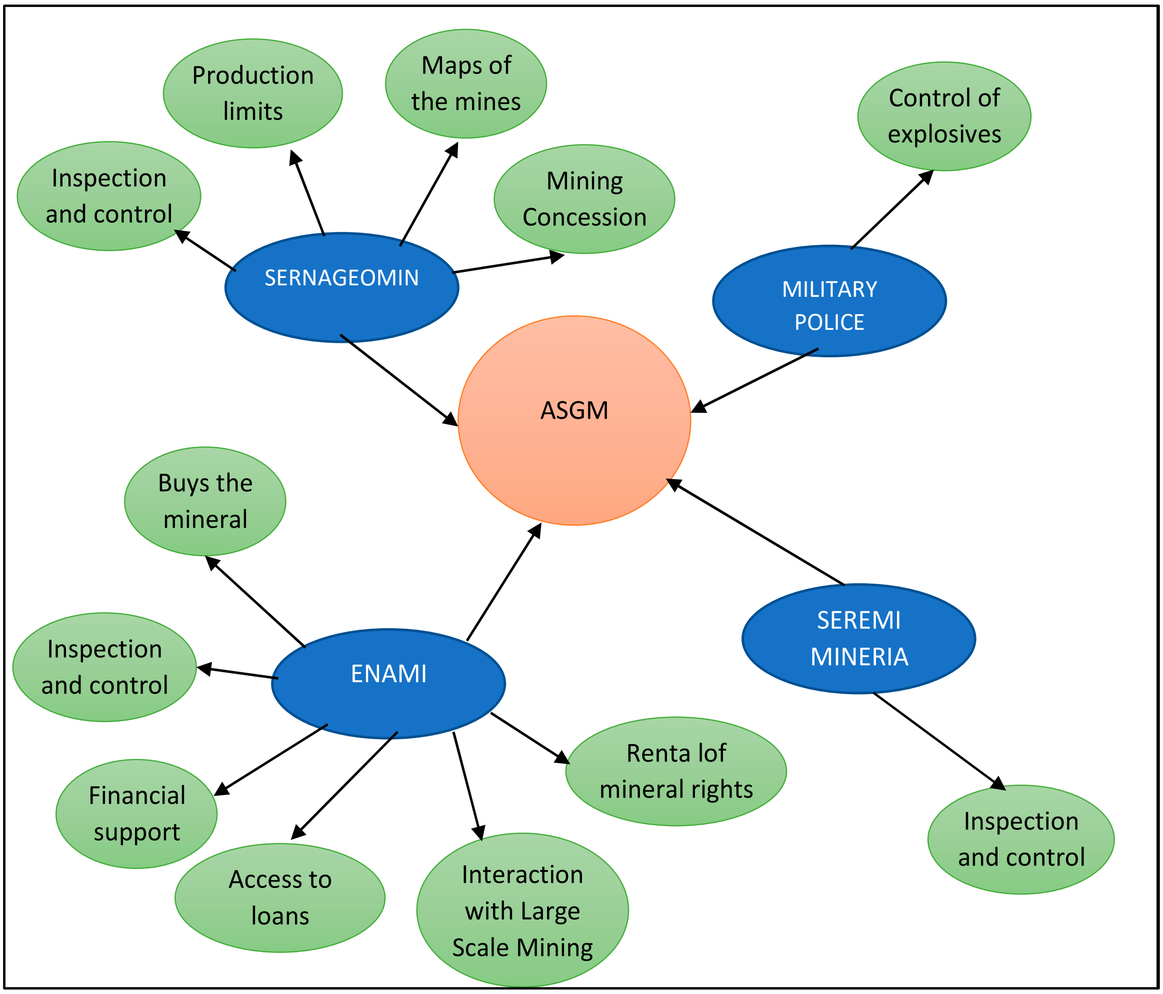

Figure 1. Map of the role of government agencies in small-scale mining in Chile.

ii. Non-refundable financial support

The types of financial support mechanisms are:

- Development of the Competitive Capacities Program: The objective of the program is to incorporate and develop technical and business management capacities. The maximum amount is USD 2500 for individual projects and USD 20,000 for projects of associated miners. The nomination options are fostering innovation, technological transfer and training.
- Recognition of resources and/or reserves and mine planning: This involves financing exploratory drilling or reconnaissance tunnels for the preparation of a mining project. To apply for this financing mechanism, it is necessary to wait for a national competition managed by ENAMI.
- Technical assistance: This is specialized consultancy for the development of mining projects, including the study of the entire mineral production chain, from topographic surveys to the sale of ores.
- District Studies Program: This involves bidding for geological studies of areas predefined by ENAMI. The maximum annual amount is USD 150,000 per mining district. In this case, the benefit to small-scale miners is having access to maps to help postulate other development instruments.

- Production Support Program: This attends to the specific technical requirements of the miners, such as equipment repair, mining works or the purchase of materials. The maximum amount is USD 5000 per project.

iii. Loans

The value of loans is deducted from the sale of material to ENAMI. The grace period, discount rate and payment period vary according to the program.

- Support for safe production: This is a loan to adapt the mine closure plan, ground support, ventilation, emergency exits, and other works related to occupational hygiene and safety; payment for consultancy in management and risk prevention; quality; and the environment. The maximum amount is USD 30,000 per project. The payment period is 5 years, with a grace period of up to 1 year. The method of payment sales discounts at the rate of 1 USD/ton of mineral sold to ENAMI. There is no warranty, and the interest rate is fixed by ENAMI.
- Mine Reactivation Program: This is a program for putting an inactive mine back into production. The amount per project is USD 35,000. The return period is up to 2 years.
- Credits for the operation: This is a loan to stabilize cash flow and finance the purchase of minor equipment and other materials. The maximum amount is USD 50,000, with a payment term of up to one year and a grace period of three months. The interest rate is set semi-annually, and the commission is 2.5%.
- Credit for mine development: This is funding for open-pit or underground development to access the orebody. The maximum amount is USD 300,000, with a term of up to 5 years and a grace period of 1 year. The interest rate is set semi-annually. In this case, it is necessary to present real guarantees. The loan is released gradually as the progress of the project is monitored.
- Credit for investments: This is a loan for the purchase and renovation of equipment, innovations, the construction of access roads, environmental care and working capital, among other activities related to mining work. There is a term of up to 5 years with a grace period of 1 year. The interest rate is defined every six months and the commission is 2.5%. In this case, it is necessary to present real guarantees. The project will determine the value and the loan is released gradually as the progress of the project is monitored.
- Emergency credit: This is a loan to solve unforeseen situations caused by natural catastrophes. There are limits of USD 25,000 if raw minerals are sold and USD 50,000 if mineral products are sold. There are terms of up to 1 year, with a grace period of 3 months. The interest rate is set semi-annually, and the commission is 2.5%.

Other roles of ENAMI are:

- Supervising miners who have some type of promotion or active credit.
- Interaction with big-scale mining companies: the rental of areas belonging to large companies.
- Leasing properties: the lease of mining prospects from ENAMI to small-scale miners.

2. Materials and Methodology

2.1. Study Population

This field study collected sample data from the mining area of Chancón (see Figure 2). This area has already been the focus of previous small-scale mining studies [30,38].

Mines in the Chancón sector (see their distribution in Figure 3) are all underground, in hard rock and operate utilizing drilling and blasting methods.

When cataloging the mines for census purposes, public agencies cited a previously encountered difficulty in identifying the mines due to the local custom of changing the tunnel name whenever a new mine owner assumes the mine. In order to minimize this problem, the local government agency for mining (called “SEREMI Mineria”) created a project to identify the tunnels with standardized plaques at the entrance to each mine (Figure 4) and location signs along the way (Figure 5).

Figure 2. Location of the field study area in Chile. The blue star indicates the location of the Chancón district.

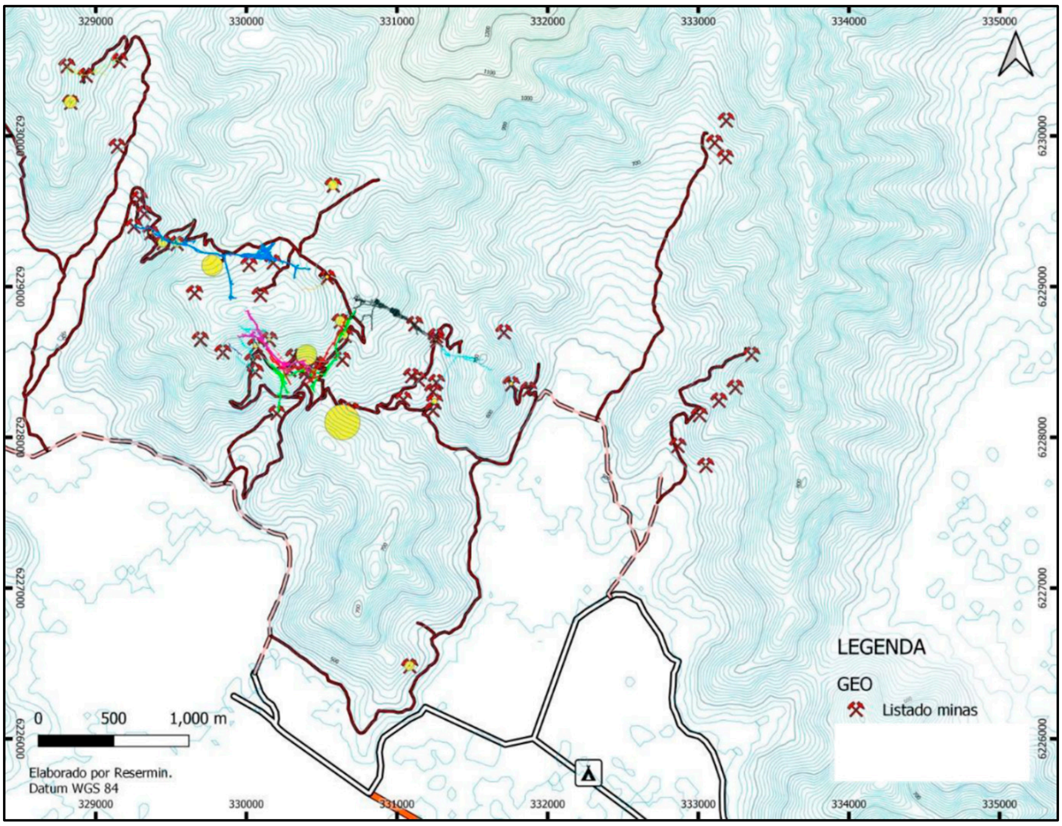

Figure 3. Distribution of the mines in the Chancón district. The legend is in Spanish. "Listado minas" = list of mines.

Figure 4. A currently abandoned mine with its identification plate (upper right).

Figure 5. Sign along the road indicating the paths toward the mines.

2.2. Methodology

The first phase of the study was to catalog the mines currently in operation in the Chancón sector. The indicators were collected in situ, starting with a visit to the tunnel and an interview with the miner in charge of the operation. The questions were adapted for the area from the general questionnaire previously developed by Seccatore et al. [39].

The number of mines operating in the area varied significantly over time, mainly as a function of the gold price and the organization of the company. In 2012, the regional government cataloged 158 tunnels, of which 129 were classified as irregular (active or not), 24 were abandoned, and only 5 were active [40]. In 2014, ENAMI identified 40 active mines [41]. At the time of the field survey (2019–2023), approximately 30 mines were in operation, and it was possible to visit 23 of them, of which only 19 fed our database, as four of the miners failed to answer many of the questions or did so in an untrustworthy way. None of the visits made it possible to complete the questionnaire, especially the questions about cost per item, such as explosives, diesel, water, maintenance, labor, etc. In the area, costs were associated with the cost per meter of the tunnel advanced. By disregarding the section of the tunnel, which is irregular and varied from time to time, it was impossible to calculate the cost per ton of mineral, the stripping ratio or mineral dilution.

3. Results

The area of Chancón is peculiar with regard to the organizational models among small-scale miners. The legal concessions in the region only belonged to three different companies, which will be referred to as Company A, Company B and Company C, for confidentiality. Company C owned approximately 80% of the concessions, land and property.

In the case of negotiations with Company C, the area was divided into three-dimensional "cubes", and each cube was leased to an "owner". These owners paid a fee to Company C, depending on the mineral grade sold to ENAMI, as shown in Table 1.

Table 1. Discount rates paid to Company C as a function of the mineral grade of the ROM.

Mineral Grade	Discount
0.00–5.00 g/t	22%
5.01–6.00 g/t	27%
6.01–7.00 g/t	33%
>7.01 g/t	38%

Daily production varied significantly, from 2 to 40 tons per day. Figure 6 shows the production distribution of the 19 mines visited.

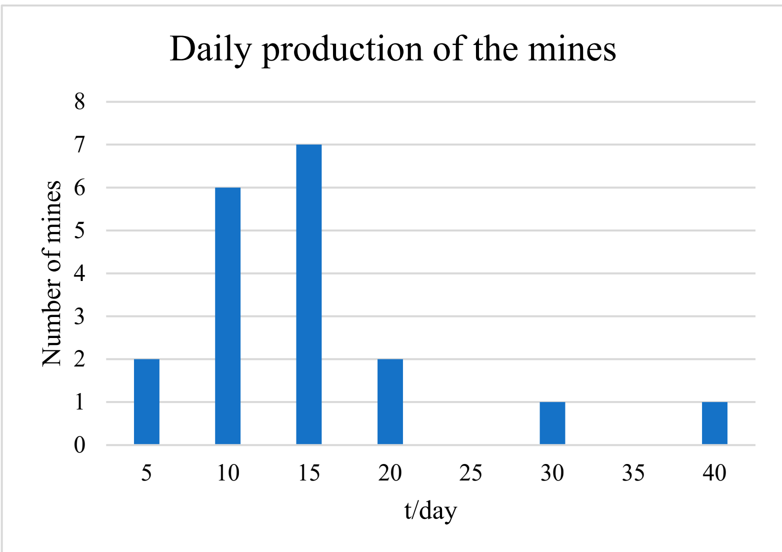

Figure 6. Number of mines associated with their daily production.

The mineral ROM grades of the mines were between 1.8 g/t and 5.0 g/t, with an average of 3.7 g/t. As discussed before, the sections of the tunnels were irregular, and so the dilution and stripping ratio influenced the inconsistencies of the grade sampled in the whole ROM. A common practice was to blend the material to keep it at about 5 g/t, to avoid the higher discounts imposed by Company C.

Mine operations were composed of drilling and blasting, loading and transport to the mine stockpile and then transport from the stockpile to the ENAMI plant. The miners did not see potential value for the waste rock, so this was randomly deposited on the mountain slopes of that region. The workforce, inputs, geological control, planning and other observations are detailed below.

3.1. Drilling and Blasting

This was an operation that can be considered as the standard for the whole of the Chancón area. It consisted of an emulsion 1″ per 8″ cartridge as a primer for a column charge of ANFO (ammonium nitrate/fuel oil). The emulsion is initiated by a fire cap and safety fuse. Hole distributions on the tunnel face and their 3D inclination depend purely on the sentiment of the driller. Figure 7 (manual drilling) and Figure 8 (explosives ignited by the fuse and fire cap) show examples of the drilling and blasting activity.

Figure 7. Rock drilling.

Figure 8. Explosives handling (incorrect and dangerous).

The mines visited were being operated by a drilling team with a manual jackleg drill and one set of air compressors with a diesel generator per drill. Even in mines with only one drilling crew, the number of drills was 2–3 for maintenance backup purposes.

The advance per blast was between 1.0 and 1.8 m, with an average of 1.5 m. The efficiency of advancing after a tunnel blast was a key indicator in tunneling science; it is the ratio between the drilled length (pull) and the actual pull obtained. It is commonly lower than 100%, and only excellent blasting in very competent rock achieves the full efficiency. This indicates how much work (drilling) and material (explosives) were wasted in the incomplete advance of the drilled length. In economic terms, this was loss in the investment: drilling and charging 1.0 m and obtaining a 0.9 m advance meant that 10% of the investment to advance the 1.0 m was lost. In previous studies on rock blasting in a mine within the region [31], actual measurements of the pull efficiency were performed. In the case of the present work, for practical reasons, it was impossible to perform measurements in all the mines. Therefore, miners were directly asked for their average efficiency. Due to lack of technical knowledge, the miners had some confusion regarding this aspect; therefore, our interviews obtained "perceived" pull efficiency (see Figure 9). This shows that the miners did not consider the pull efficiency to be an important concept, as they did not understand it. Most miners thought that they obtained all that they drilled, which was hardly the case using the rudimentary techniques of fire fuse and manual ignition. Some even considered their efficiency to be superior to 100%, a clear physical impossibility.

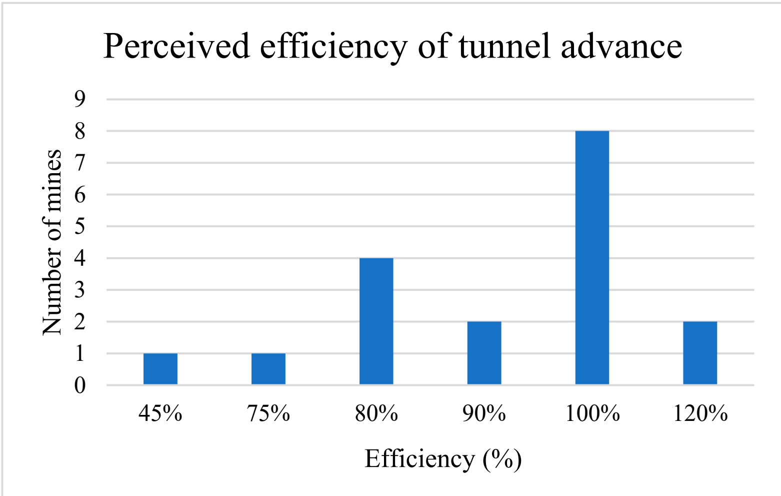

Figure 9. The efficiency of tunnel advance according to miners' perceptions.

An indicator of the operation inefficiency was the frequent use of secondary breaking, whether manual (with a sledgehammer) or with explosives and/or hydraulic hammers, as shown in Figure 10.

Figure 10. Secondary breaking of fragments.

3.2. Loading and Hauling to the Mine Stockpile

This operation was extremely variable: from 100% manual operations, up to the use of 3 ton capacity transport equipment.

In most of the mines visited, the equipment was owned, but cases of equipment being rented or shared by more than one mine were also registered. Figures 11 and 12 show examples of the hauling equipment used in the area.

Figure 11. Manual hauling equipment.

Figure 12. Hauling equipment.

3.3. Transport from the Mine Stockpile to the Plant

To deliver the material from the mine to the ENAMI processing plant, the miners needed to pay for transporting the ore on large trucks to the plant (Figure 13). The transport fee ranged between 2 and 4 USD per ton, depending on the distance from each specific mine to the plant. The closest plant was within the area of Chancón. There was another ENAMI plant about 250 km to the north; the transport fee was USD 18 per ton, and miners sent their ore there only when the mineral grade was very high.

Figure 13. Hauling truck from the mine to the plant.

3.4. Workforce

This was different to other areas of artisanal mining, where the work was remunerated by participation in production (as documented in [42]); the remuneration in Chancón was a monthly salary. There were also day labor contracts for occasional jobs or to increase production when extracting high-grade ores.

Across the region, there was still the antique figure of the "chanqueiro". A chanqueiro is a skilled miner who can visually appreciate fragments of the ROM and assess which of them are rich in ore. The chanqueiro manually selects the rocks in the ore pile that will be sent to the processing plant. Whoever transports the ROM also performs this visual separation of the mineral.

Work shifts varied for each mine: the most common was from Monday to Friday, with a 7–8 h shift and occasionally part-time on Saturday. Only one of the mines visited adopted the 5 × 5-day shift system employed in large-scale mining. This shift system comprises 5 days of work and 5 days off. In large-scale mining, the production never stops, as the size of the workforce allows for alternating teams to cover any days off. In this case, the workforce of these mines is limited; hence, for the 5 days off, the mine does not operate. The owner declared that he prefers not to have two teams taking alternate turns, as he believes that it is better for each operator to be responsible for the equipment that they use.

In general, a team of miners consisted of one driller, one drilling assistant and a hauling machine operator. The driller and the machine operator were trained and, generally, did not take turns.

The presence of female operatives was almost non-existent in the operation and management of the mines. Only one woman was observed as an active miner, specializing in the use of loading–hauling equipment. In addition to her, another woman worked as a prospector. Generally speaking, female presence was associated with being caregivers or cooks, whose husbands are mine managers or mine watchmen.

3.5. Materials and Supplies

In the case of materials and supplies, the owners knew their consumption over a period but did not document cost control or expenses.

- The operation consumed around 200 L of water per day. The sources were local spring water, mine drainage water, water brought in from the city or water from a reservoir.

- Potable water for human consumption was about 20 L per operator per day.
- Diesel consumption varied between 250 and 3000 L per month. This wide range was due to the fact that some mines employed used equipment bought from large-scale mines.
- Oil consumption for equipment lubrication was not registered by the miners, as equipment maintenance was only carried out inconsistently.
- There was no electricity beamline. Two mines had solar-powered systems for their office and cafeteria.

3.6. Geological Control and Mine Planning

Geological control was performed visually at the tunnel face, by color or the presence of accessory minerals that the miners generally associated with the presence of gold. A common practice was to use the drill bar to drill up to 12 m and observe the color of the flush water. The miners called this "exploratory drilling".

Regarding the identification of the veins at the surface, the miners observed veins on the outcrops and attempted to visually project the visible veins to the location of the veins in the other mines. This operation was extremely imprecise. In the field, cases were observed in which a tunnel had to drastically detour from its axis because the vein was 5 to 10 m away from the estimated location. In other cases, advances of between 30 and 50 m have been observed without "reaching" the vein. The associated costs of advances per meter are documented by Seccatore et al. [30], and the chances of finding a vein and the associated economical risk of losing the investment for tunnel advance in the case of "missing" the vein are extensively documented, calculated and discussed by Espinoza et al. [38].

Without geological knowledge, it is impossible to perform mine planning. The miners relied on a general idea of the direction of the next tunnel advance depending on the visually determined direction of the vein. A monthly limit of ores that can be sold to ENAMI exists, which is determined by SERNAGEOMIN, depending on the available equipment in the mine.

3.7. Economic Analyses

As described in the methodology section, despite the detailed questionnaire, miners could not define every separated item of cost. Instead, they considered the cost per meter of tunnel advanced. The cost reported was 350,000 CPL/m for a tunnel with a section of 2.5 m × 2.5 m. The actual tunnel contour was irregular, but, for the sake of simplicity in the calculation, it was considered a square. The average rock density was 2.7 t/m^3. The cost per mass of ROM was calculated using Equation (1), and the result was 20,741 CLP/t.

$$Cost/mass = \frac{Cost/meters}{\rho \times A} \tag{1}$$

Cost/mass: cost per mass of ROM (CLP/t).
Cost/meters: cost by extraction meters (CLP/m).
ρ: density (t/m^3).
The income was calculated using the following equations:

$$INC = ROM \times P \tag{2}$$

INC: income (CLP).
ROM: run-of-mine (t).
P: ROM price at the mine (USD/t).
The price of the mineral is what ENAMI pays, minus the transportation cost of the mineral from the mine to the plant and the fee that the miners must pay to the actual owner of the mine.

$$P = V_E - f - t_o \tag{3}$$

V_E: amount paid by ENAMI.
F: mine-to-plant freight.
t_o: mine owner's fee (Table 1).

ENAMI payments are subjected to different reductions, varying from taxes to penalties related to the quality of the mineral sent to the plant.

$$V_E = P_R - reductions \quad (4)$$

V_E: amount paid by ENAMI.
P_R: reference price for calculating fees.
Reductions: taxes, fees, moisture and contaminant penalty and loan payment.

$$V_E = P_R - t_{SM} \times P_R - f_{RM} \times P_R \quad (5)$$

$$V_E = P_R \times (1 - (t_{SM} + f_{RM})) \quad (6)$$

t_{SM}: taxes for small-scale mining in Chile.
f_{RM}: Rancagua miners association fee (ASOMIN).

$$P_R = g_R \times (V_B + (g_R - g_B) \times V_S) - d_{con} \times V_S \quad (7)$$

P_R: reference price for calculating fees.
g_R: ROM grade.
V_B: mineral base value of ENAMI.
g_B: base grade of ENAMI.
V_S: mineral **scale value** of ENAMI (discount based on the base grade).
d_{Con}: **fee** for minerals to be concentrated on ENAMI.

$$P = ((g_R \times (V_B + (g_R - g_B) \times V_S) - d_{con} \times V_S) \times (1 - (t_{SM} + f_{RM} + f_{ower})) - f) \quad (8)$$

g_R: variable g/t.
V_B: CLP 119,342.
g_B: 5 g/t.
V_S: CLP 31,957.
d_{Con}: 15%.
t_{SM}: 4%.
f_{RM}: 0.2%.
f_{ower}: 22%.

The results for differences in grades, costs and production rates are presented in Tables 2 and 3. The production rates considered here are the most frequent rates indicated in Figure 6. The costs indicated here do not consider the investments necessary for waste excavation nor equipment purchase, maintenance or rental.

Table 2. Net cash provided by the grade and cost for 200 t/month.

Scenario 1—Net Cash Provided by Operating Activities for: 200 t/Month (CLP/Month)							
Grade (g/t)	INCOME (CLP)	Cost CLP/t 10,000	15,000	20,000	25,000	30,000	35,000
2	18,664	1,732,712	732,712	(267,288)	(1,267,288)	(2,267,288)	(3,267,288)
3	42,248	6,449,602	5,449,602	4,449,602	3,449,602	2,449,602	1,449,602
4	65,832	11,166,492	10,166,492	9,166,492	8,166,492	7,166,492	6,166,492
5	89,417	15,883,383	14,883,383	13,883,383	12,883,383	11,883,383	10,883,383

Table 3. Net cash provided by the grade and cost for 300 t/month.

Scenario 2—Net Cash Provided by Operating Activities: 300 t/Month (CLP/Month)							
Grade (g/t)	**INCOME (CLP)**	**Cost/t**					
		10,000	**15,000**	**20,000**	**25,000**	**30,000**	**35,000**
2	18,664	2,599,068	1,099,068	(400,932)	(1,900,932)	(3,400,932)	(4,900,932)
3	42,248	9,674,404	8,174,404	6,674,404	5,174,404	3,674,404	2,174,404
4	65,832	16,749,739	15,249,739	13,749,739	12,249,739	10,749,739	9,249,739
5	89,417	23,825,074	22,325,074	20,825,074	19,325,074	17,825,074	16,325,074

It was reported by the miners that it is necessary to develop up to 100 m in waste rock until the mineral vein is reached. The cost of mere development in waste to encounter the vein can reach CLP 35,000,000. Realistically, for Chancón, a reserve of about 193k oz Au was plausible. This corresponds to 10 months of production for scenario 1 and 7 months for scenario 2. These values are shown in Tables 2 and 3; conditions with a mineral grade below 3 g/t and OPEX above 25,000 CLP/t are unfeasible. We show these values in Tables 2 and 3 with a lighter tone for didactic purposes.

3.8. Accidents

Table 4 summarizes the accidents in Chancón documented by the public media. It is plausible that the number of accidents that were not fatal is higher, as they may not have been communicated outside the mine, therefore not having mediatic coverage.

Table 4. Accidents in Chancón reported by the public media.

Year	Type of Accident	Number of Miners Involved	Fatal	Source
2022	Fall from height	1	Yes	2022 [42]
2022	Rockfall	1	No	2022 [43]
2020	Rockfall	1	Yes	2020 [44]
2016	Premature detonation of explosives	3	No	2016 [45]

Figure 14 and Table 5 summarize the fatal accidents in the whole mining industry in Chile as reported by Sernageomin [46]. Table 5 details the accidents in the mining industry over the last few months, before the redaction of this article.

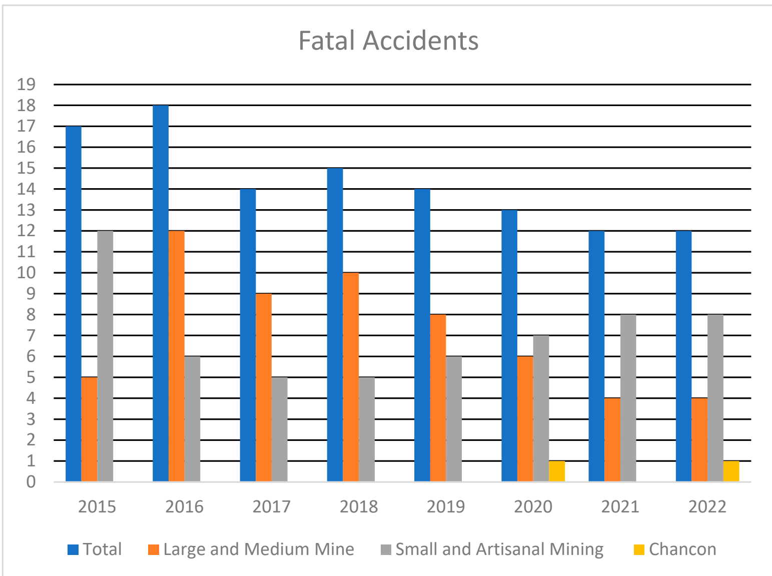

Figure 14. Mining fatal accidents, 2015–2022.

Table 5. Fatal accidents during mining operations in the second quartile of 2023 (Sernageomin).

Month	Type of Accident	Mine Type	Number of Miners Involved	Number of Deaths
January	Getting crushed	Large	1	1
February	Fall from height	Small-Scale	1	1
February	Rockfall	Artisanal	2	1
March	Vehicle out of control	Exploration	1	1
April	Fall from height	Medium	3	1

Figure 15 shows the total number of accidents, both fatal and non-fatal, in the Chilean mining industry between 2019 and 2022.

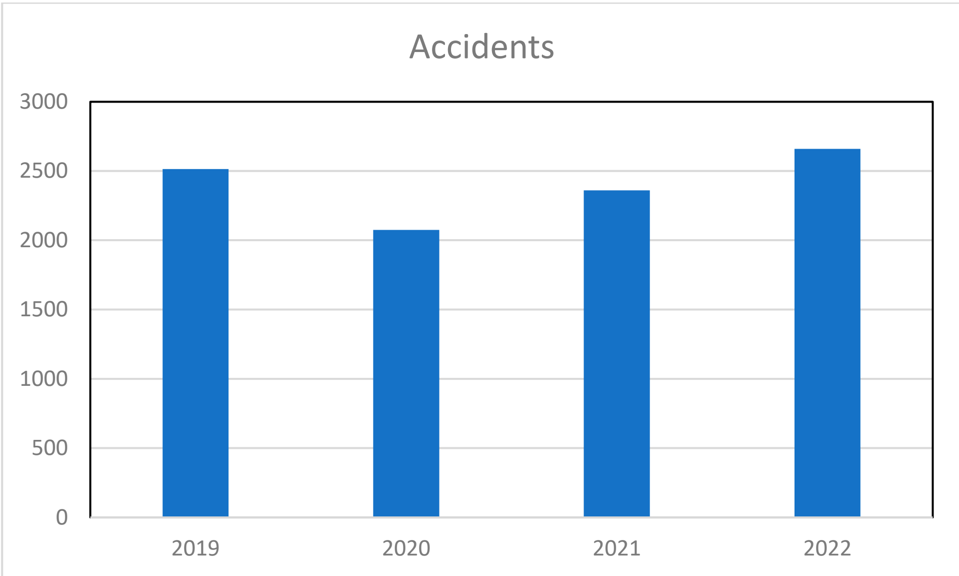

Figure 15. Total mining accidents, 2019–2022.

3.9. Further Observations

- Of the mines, 60% had some type of funding from ENAMI. The range of funding was between CLP 5,000,000 and CLP 75,000,000.
- The government is present in the region: at least every six months, an agency visits each mine. In the case of mines with active financing, visits from the funding agency may take place on a monthly basis.
- In general, miners had only one work front available, which did not allow for operational flexibility and generated periods of pure cost, extracting only waste rock.

The main problems that miners identified were:

- The time taken to analyze the samples of the material sent to ENAMI. The miners used these results as a control tool to know what mineral grade was present in the ore they extracted. Therefore, they would know if they were excavating in the right direction or not. The average time to obtain the grade was 30 days; therefore, when the result arrived, the area had already been mined.
- There is a systematic positive difference between the grade of the sample collected by the miners and sent for analysis and the grade of the lot sent to the processing plant and estimated by ENAMI. This is because the miners sampled the vein and, as mentioned, did not contemplate the concept of excavation dilution due to the size of the tunnel.
- The monthly production limit established by SERNAGEOMIN "strangled" cashflow, which was already compromised by all the other reductions documented above.

3.10. Issues with the Processing Plant

The biggest challenge observed was the reconciliation between the grades of the samples collected by the grades of the lot delivered to the plant. Miners sampled the "richest area" samples and did not consider the operational dilution, so the lot grade was systematically lower than that of the samples. The difference between the analyses, reported by the miners, was 100–400%.

Furthermore, if the grade of the lot was lower than the cut-off grade, miners lost the amount they paid for freight. The current cut-off grade at Chancón is 2 g/t. There is a rule according to which lots between 1 and 2 g/t are stored for 1 month: if the miner manages to deliver a lot that is sufficient to be blended to a grade greater than 2 g/t, then the miner receives the value of the low-grade lot. Otherwise, the material stays within the plant.

An alternative solution which was encountered was to send the material to a gravitational pre-concentration plant, located about 300 km to the north of Chancón. This is a private plant which carries out a pre-concentration, from the mill to the flotation cells, and sells the concentrate to ENAMI (Figures 16–19). This reduced the grade variability. Miners could follow the lot processing, and the amount of transported material was reduced by at least 80%, which can be visually observed by the difference between the lots in Figures 16 and 19. The advantage was that the plant was completely mercury- and cyanide-free. The disadvantage was that it generated flotation waste which, despite being an inert material, needed to be deposited in a tailings dam.

Figure 16. Stockpiles of the initial lot that would be processed. Each pile belonged to a different miner.

Figure 17. Crusher and mill at the plant.

Figure 18. Flotation cells.

Figure 19. End-of-process material that would be sold to ENAMI. Each stack belonged to a different miner.

4. Discussion

The area of study is unique to South American artisanal mining sites. Even within Chile, many artisanal miners still process their own ore, amalgamating it with mercury, especially in the north. They are called "pirquineros", and the common process is milling the ore in what are known as "Chilean mills" or "trapiches", which consist of a stone basin in which the material is deposited and two stone wheels, which rotate around an axis to mill the material. Mercury is usually added directly into the trapiche. This is well documented in many works, such as [47–54]. As such, artisanal gold mining (AGM) is generally associated with Hg pollution, as stated in the introduction, within studies across the world. Therefore, previous initiatives have focused on the elimination of Hg in Au processing. Table 6 reports a selected list of initiatives aimed at the reduction in or elimination of Hg pollution.

Over time, initiatives moved from purely technological approaches to a more heuristic approach, including a broader vision of the framework.

Regarding the attempts made in Table 6 (and as mentioned in the introduction), one of the most prolific authors working and publishing in this field eventually came to an unfortunate conclusion: "those approaches have not resulted in mercury reduction or elimination" [36]. It is in that study that the authors came to the proposed solution from the experience of "over 40 years of intensive research and field projects across 35 countries":

centralized, clean and modern processing plants where the miners' ores are processed for them. "The miners mine while the processors process".

Table 6. A selected list of initiatives which attempted to reduce or eliminate Hg from Au processing.

Source	Place	Solution Proposed	Type of Solution
[55]	Latin America	Gravity concentration Flotation Electro-leaching Cyanidation NaCl electrolytic process Retort for Hg recovery Law enforcement Technical assistance Training artisanal miners	Technological Policy Strategic
[6]	Transversal	Construction of a training center for miners	Policy
[55]	Indonesia, Ecuador, Colombia	Mill leaching	Technological
[56]	Mozambique	Adopt clean technologies that obey the criteria of being economically beneficial, simple and expedient	Technological
[12]	Transversal	Mercury removal technology, miner education on mercury hazards, economic gains and policy	Policy
[57]	Colombia	Capacity building, education and the presence of trainers prior to introducing a new approach	Strategic
[58]	Ecuador–Peru	Gold isolation via centrifugal and magnetic removal of gangue materials	Strategic
[59]	Transversal	Incentivize gravity concentration	Technological–Policy

This conclusion formed the basis of this study: a clean centralized processing plant with no Hg involved. Having eliminated Hg, is it currently a sustainable operation?

The authors' findings indicated that no, it is not.

Albeit simplified, the general perception of sustainability or sustainable development is based on three concepts, or "pillars": social, economic and environmental factors (see the discussion by Purvis et al. [60]). Considering these three concepts, the following considerations can be made for the Chancón district:

- Economic point of view: The miners did not have a constant income; they had only one producing front and advances in the hope of finding ores. The system was to work as much as possible on the mineral with all the equipment and people available and, when operating in waste rock, work gradually, according to how much was possible to invest. Generally, the earnings from ore extraction were spent or saved and not used as working capital to invest in waste rock extraction. There was no planning for managing the sterile–mineral ratio (stripping ratio). If it were not for the support of ENAMI, many miners would not be able to sustain their operating costs.
- Social point of view: Even though the operation produced a small economy and socially impacted miners' families and the surroundings (e.g., maintaining the presence of a school), this impact was not constant. There was no real development in the region, as there was no increase in or development of new schools, good medical care, clean water, sanitation, etc. This was due to the precarious income described above.

- Environmental point of view: As stated, Hg was not used in the area. Nevertheless, Hg is not the only environmental externality of a mining operation. Waste rock was simply deposited on the slopes of surrounding hills, creating a geotechnical hazard in the form of slope instability (also considering Chilean seismicity) and the potential for acid drainage. The mines were not closed, but simply abandoned, leaving a panorama of empty holes on hillsides, with many dangers associated with abandoned tunnels. There was no concern for material and equipment management. Machinery which did not work was set aside to rust or be used as a source of scrap materials. Used tires, diesel and motor oil were thrown away (one of the authors of this study needed some used tires for another project and found four at the side of the first bend of the road).
- To parallel the list in Table 6 (of proposed solutions for the Hg issue adopted in the past), the authors prepared a list of issues encountered, proposed solutions and classifications of solution types for this Hg-free alternative (Table 7).

Table 7. Issues versus solutions for Chancón artisanal and small-scale Hg-free mining.

Issue Encountered	Solution Proposed	Type of Solution
High discount rates paid to Company C (the company that owned 80% of the concessions). The discounts are determined according to a rigid table with pre-fixed ranges of values of mineral grades (0.1 g/t above the limit value of the range, and the discount rate rises to the upper range).	Negotiate new rates with the company. Negotiate a continuous discount curve based on the grade and not a discrete set of values.	Economic Note: The government could help in the negotiation.
Waste rock: currently, it is dumped with no criterion or control on the slopes of hills.	Adopt a circular economy concept to give economical value to waste rock, e.g., for road pavement or construction material. Transform an environmental passive externality into an economic asset. Within the concept of the zero-waste operation.	Technological Market Note: The government could create projects for material use and valorization, together with entities such as universities.
Drilling and blasting. The drilling mesh, selection of the number of holes and their distribution is aleatorial. Hole ignition is still made by a safety fuse.	Create rules for a blasting plan (drill plan, charge per hole, initiation sequence) for each type of rock, and train miners in its implementation and realization. Adopt modern techniques (such as shock-tube initiation and employ delays). These solutions were discussed by Seccatore et al. [30,39]	Technological Training
Lack of geological control and mine planning.	Carry out studies for small-scale geological characterization (with auditable samples). Create auditable geological models. Implement a mine planning cycle for small-scale mining (thoroughly discussed in [14,61]).	Technology Transfer Economic Policies Note: Central and local governments and local agencies play a central role in helping public or private financing of these initiatives
Issues with the ENAMI processing plant: its technological efficiency and real recovery rate.	Public investment for upgrading the ENAMI plant. Promotion of investment to build competitive private plants with state-of-the-art technology and higher recovery. Build gravimetric concentration plants close to the mines to transport concentrate only.	Policy Technological Economic

From the list of proposed solutions, only a few are purely technological; they go hand-in-hand with policy making and economic investment.

5. Conclusions

Most academic studies on AGM are focused on mercury use and its environmental and social impacts. They are mainly focused on people's health, including both the miners and the people around mines. Another much-studied aspect is the formalization of operations: as anyone would agree, it is necessary to be familiar with the operations in order to do something about them. Little is discussed about operational efficiency and mine planning, which was the focus of this study.

This work was carried out in a Hg-free AGM region to answer the following question: Are Hg-free AGM operations sustainable? The focus was to analyze sustainability in the context of the following main pillars: social, economic, and environmental factors.

It can be concluded that, for an AGM operation to be sustainable, there are many other requirements besides eliminating mercury. It is necessary to act on the three pillars of sustainability simultaneously and implement a mine planning cycle with geological knowledge, constant improvement, and operational efficiency.

With mining planning, it will be possible to respect the sterile–mineral relation (stripping ratio). The waste rock can be extracted at the necessary pace to make mineralized fronts available. The operation could continue steadily, in a similar manner to a standard medium or large mining company.

In this study, we performed a transversal diagnosis of mining operations. Based on the results exposed here, it is possible to implement simple operational improvements, plan mineral exploration and, by employing a geological model, create a mining plan, thus achieving sustainable operations.

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References

1. Cano, Á.; Kunz, N.C. Large-scale and small-scale mining in Peru: Exploring the interface. *Resour. Policy* **2022**, *76*, 102530. [CrossRef]
2. CASM. Map of Artisanal and Small-Scale Miners around the World, Communities and Small-Scale Mining (CASM). 2012. Available online: http://www.artisanalmining.org/casm/minersmap (accessed on 20 August 2019).
3. Cossa, H.; Scheidegger, R.; Leuenberger, A.; Ammann, P.; Munguambe, K.; Utzinger, J.; Macete, E.; Winkler, M.S. Health studies in the context of artisanal and small-scale mining: A scoping review. *Int. J. Environ. Res. Public Health* **2021**, *18*, 1555.
4. Estrela, A.M.; Hilson, M.H. Cooperatives as a Centre Piece for Formalizing Small-Scale Mining in Sub-Saharan Africa: Rationale, Benefits and Limitations. In *Routledge Handbook of the Extractive Industries and Sustainable Development*; Routledge: London, UK, 2022.
5. Hilson, G. 'Formalization bubbles': A blueprint for sustainable artisanal and small-scale mining (ASM) in sub-Saharan Africa. *Extr. Ind. Soc.* **2020**, *7*, 1624–1638. [CrossRef]
6. Hinton, J.J.; Veiga, M.M.; Veiga, A.T.C. Clean artisanal gold mining: A utopian approach? *J. Clean. Prod.* **2003**, *11*, 99–115.
7. McDaniels, J.; Chouinard, R.; Veiga, M.M. Appraising the Global Mercury Project: An adaptive management approach to combating mercury pollution in small-scale gold mining. *Int. J. Environ. Pollut.* **2010**, *41*, 242. [CrossRef]
8. MMSD. Artisanal and Small-Scale Mining. In *Final Report on Mining, Minerals and Sustainable Development*; International Institute for Environment and Development and World Business Council for Sustainable Development: London, UK, 2002; Chapter 13.

9. Purnomo, M.; Utomo, M.R.; Pertiwi, V.A.; Laili, F.; Pariasa, I.I.; Riyanto, S.; Andriatmoko, N.D.; Handono, S.Y. Resistance to mining and adaptation of Indonesia farmer's household to economic vulnerability of small scale sand mining activities. *Local Environ.* **2021**, *26*, 1498–1511.
10. Sousa, R.N.; Veiga, M.M.; Meech, J.; Jokinen, J.; Sousa, A.J. A simplified matrix of environmental impacts to support an intervention program in a small-scale mining site. *J. Clean. Prod.* **2011**, *19*, 580–587. [CrossRef]
11. Urkidi, L. A local environmental movement against gold mining: Pascua–Lama in Chile. *Ecol. Econ.* **2010**, *70*, 219–227.
12. Veiga, M.M.; Angeloci-Santos, G.; Meech, J.A. Review of barriers to reduce mercury use in artisanal gold mining. *Extr. Ind. Soc.* **2014**, *1*, 351–361. [CrossRef]
13. Velásquez, J.R.; Schwartz, M.; Phipps, L.M.; Restrepo-Baena, O.J.; Lucena, J.; Smits, K.M. A review of the environmental and health implications of recycling mine tailings for construction purposes in artisanal and small-scale mining communities. *Extr. Ind. Soc.* **2022**, *9*, 101019. [CrossRef]
14. Marin, T.; Seccatore, J.; De Tomi, G.; Veiga, M. Economic feasibility of responsible small-scale gold mining. *J. Clean. Prod.* **2016**, *129*, 531–536. [CrossRef]
15. Massaro, L.; de Theije, M. Understanding small-scale gold mining practices: An anthropological study on technological innovation in the Vale do Rio Peixoto (Mato Grosso, Brazil). *J. Clean. Prod.* **2018**, *204*, 618–635.
16. Teschner, B.; Smith, N.M.; Borrillo-Hutter, T.; John, Z.Q.; Wong, T.E. How efficient are they really? A simple testing method of small-scale gold miners' gravity separation systems. *Miner. Eng.* **2017**, *105*, 44–51. [CrossRef]
17. Calvimontes, J.; Massaro, L.; Araujo, C.; Moraes, R.; Mello, J.; Ferreira, L.; de Theije, M. Small-scale gold mining and the COVID-19 pandemic: Conflict and cooperation in the Brazilian Amazon. *Extr. Ind. Soc.* **2020**, *7*, 1347–1350. [CrossRef]
18. Hilson, G.; Van Bockstael, S.; Sauerwein, T.; Hilson, A.; McQuilken, J. Artisanal and small-scale mining, and COVID-19 in sub-Saharan Africa: A preliminary analysis. *World Dev.* **2021**, *139*, 105315. [CrossRef]
19. Perks, R.; Schneck, N. COVID-19 in artisanal and small-scale mining communities: Preliminary results from a global rapid data collection exercise. *Environ. Sci. Policy* **2021**, *121*, 37–41. [CrossRef]
20. Pijpers, R.J.; Luning, S. We have so many challenges: Small-scale mining, COVID-19 and constant interruptions in West Africa. *Anthropol. Today* **2021**, *37*, 10–14.
21. Springer, S.K.; Peregovich, B.G.; Schmidt, M. Capability of social life cycle assessment for analyzing the artisanal small-scale gold mining sector—Case study in the Amazonian rainforest in Brazil. *Int. J. Life Cycle Assess.* **2020**, *25*, 2274–2289. [CrossRef]
22. Ulmer, G. The Earth Is Hungry: Amerindian Worlds and the Perils of Gold Mining in the Peruvian Amazon. *J. Lat. Am. Caribb. Anthropol.* **2020**, *25*, 324–339. [CrossRef]
23. Siqueira-Gay, J.; Sánchez, L.E. The outbreak of illegal gold mining in the Brazilian Amazon boosts deforestation. *Reg. Environ. Chang.* **2021**, *21*, 28. [CrossRef]
24. Kaufmann, C.; Côte, M. Frames of extractivism: Small-scale goldmining formalization and state violence in Colombia. *Political Geogr.* **2021**, *91*, 102496. [CrossRef]
25. IIMP—El Instituto de Ingenieros de Minas del Perú. Colombia y Peru Buscan Centralizar Compra de Oro Para Combatir Crime e Informalidad. 2021. Available online: https://iimp.org.pe/raiz/colombia-y-peru-buscan-centralizar-compra-de-oro-para-combatir-crimen-e-informalidad (accessed on 17 January 2022). (In Spanish).
26. DW; El Oro De Los Latinoamericanos: ¿Qué Tanto Se Conserva En Los Bancos Centrales? 2022. Available online: https://www.dw.com/es/el-oro-de-los-latinoamericanos-qu%C3%A9-tanto-se-conserva-en-los-bancos-centrales/a-56776949 (accessed on 15 July 2022). (In Spanish).
27. MCH. Invertirán $792 Millones Para Modernizar Plantas de Procesamiento de Oro Libre de Mercurio en Atacama. 2021. Available online: https://www.mch.cl/2021/02/15/invertiran-792-millones-para-modernizar-plantas-de-procesamiento-de-oro-libre-de-mercurio-en-atacama/# (accessed on 10 May 2022). (In Spanish).
28. Faúndez, P.I.; Marquardt, C.; Jara, J.J.; Guzmán, J.I. Valuation and Prioritization of Early-Stage Exploration Projects: A Case Study of Cu–Ag and Au-Mineralized Systems in the Tiltil Mining District, Chile. *Nat. Resour. Res.* **2020**, *29*, 2989–3014. [CrossRef]
29. Poveda-Bautista, R.; Gonzalez-Urango, H.; Ramírez-Olivares, E.; Diego-Mas, J.-A. Engaging Stakeholders in Extraction Problems of the Chilean Mining Industry through a Combined Social Network Analysis-Analytic Network Process Approach. *Complexity* **2022**, *2022*, 9096744. [CrossRef]
30. Seccatore, J.; Gonzalez, P.; Herrera, M. Peculiarities of drilling and blasting in underground small-scale mines. *REM-Int. Eng. J.* **2020**, *73*, 387–394. [CrossRef]
31. Tripodi, E.E.M.; Rueda, J.A.G.; Céspedes, C.A.; Vega, J.D.; Gómez, C.C. Characterization and geostatistical modelling of contaminants and added value metals from an abandoned Cu–Au tailing dam in Taltal (Chile). *J. South Am. Earth Sci.* **2019**, *93*, 183–202. [CrossRef]
32. Reinoso, F.; Rodrigo, P. Formulación de Instrumentos de Fomento a la Innovación em Pequeña Minería. Tesis Para Optar al Grado de Magíster em Gestión Políticas Públicas. Ph.D. Thesis, Universidade de Chile, Facultad de Ciencias Físicas y Matemáticas, Departamento de Ingeniería Industrial, Santiago, Chile, 2013. (In Spanish).
33. BBCL—BioBio Chile. 2022. Available online: https://www.biobiochile.cl/noticias/nacional/region-de-ohiggins/2022/03/24/rescatan-a-minero-que-quedo-atrapado-tras-derrumbe-en-el-maiten-de-chacon-de-rancagua.shtml (accessed on 7 October 2022). (In Spanish).

34. MIREME. Ministério dos Recursos Minerais e Energia, Republica de Mocambique. 2022. Available online: https://www.mireme.gov.mz/index.php?option=com_content&view=article&id=2:ministra-dos-recursos-minerais-inteira-se-do-acidente-na-mina-de-ouro-em-nampula&catid=9:comunicados&Itemid=101 (accessed on 10 May 2022). (In Portuguese)
35. NYTIMES. Mining Disasters. 2022. Available online: https://www.nytimes.com/topic/subject/mining-disasters (accessed on 2 May 2022).
36. Veiga, M.M.; Fadina, O. A review of the failed attempts to curb mercury use at artisanal gold mines and a proposed solution. *Extr. Ind. Soc.* **2020**, *7*, 1135–1146. [CrossRef]
37. ENAMI—Empresa Nacional de Mineria. 2023. Available online: www.enami.cl (accessed on 8 February 2023). (In Spanish).
38. Espinoza, C.; Seccatore, J.; Herrera, M. Chilean artisanal mining: A gambling scenario. *REM-Int. Eng. J.* **2020**, *73*, 241–246. [CrossRef]
39. Seccatore, J.; Magny, L.; De Tomi, G. Technical and operational aspects of tunnel rounds in artisanal underground mining. *REM Rev. Esc. Minas* **2014**, *67*, 303–310. [CrossRef]
40. SERNAGEOMIN. *Atlas de Faenas Mineras, Regiones de Valparaíso, del Libertador General Bernardo O ´Higgins y Metropolitana de Santiago (Versión Actualizada)*; Servicio Nacional de Geología y Minería, Mapas y Estadísticas de Faenas Mineras de Chile: Santiago, Chile, 2012; No 9; 177p. (In Spanish)
41. ENAMI. *Estudio Geológico Distrital Enami Chancon*; Propriedade ENAMI: Santiago, Chile, 2014; 112p. (In Spanish)
42. El Rancaguino. Fallece Trabajador en Mina don Hector Ubicada en Chancon. 2022. Available online: https://www.elrancaguino.cl/2022/10/28/fallece-trabajador-en-mina-don-hector-ubicada-en-chancon/ (accessed on 11 July 2023). (In Spanish).
43. Portal Minero. Tras Estar Atrapado Por Mas de Seis Horas Fue Rescatado Minero En Chancon. 2022. Available online: https://www.portalminero.com/wp/tras-estar-atrapado-por-mas-de-seis-horas-fue-rescatado-minero-en-chancon/ (accessed on 11 July 2023). (In Spanish).
44. El Tipografo. Trabajador Minero Fallece en Chan-Con. 2020. Available online: https://eltipografo.cl/2020/05/trabajador-minero-fallece-en-chancon (accessed on 11 July 2023). (In Spanish).
45. Revista Tecnicos Mineros. Trabajadores Resultan Lesionados en Faenas Mineras de Chan-Con. 2016. Available online: https://www.revistatecnicosmineros.com/2016/12/trabajadores-resultan-lesionados-en-faenas-mineras-de-chancon/ (accessed on 11 July 2023). (In Spanish).
46. Sernageomin. Estadísticas de Accidentabilidad. Industria Extractiva Minera. Servicio Nacional de Geología y Minería. 2023. Available online: https://www.sernageomin.cl/accidentabilidad-minera/ (accessed on 11 July 2023). (In Spanish).
47. Castro, S.H.; Sánchez, M. Environmental viewpoint on small-scale copper, gold and silver mining in Chile. *J. Clean. Prod.* **2003**, *11*, 207–213. [CrossRef]
48. Ghorbani, Y.; Kuan, S.H. A review of sustainable development in the Chilean mining sector: Past, present and future. *Int. J. Min. Reclam. Environ.* **2017**, *31*, 137–165. [CrossRef]
49. Higueras, P.; Oyarzun, R.; Oyarzún, J.; Maturana, H.; Lillo, J.; Morata, D. Environmental assessment of copper–gold–mercury mining in the Andacollo and Punitaqui districts, northern Chile. *Appl. Geochem.* **2004**, *19*, 1855–1864. [CrossRef]
50. Higueras, P.; Oyarzun, R.; Lillo, J.; Oyarzún, J.; Maturana, H. Atmospheric mercury data for the Coquimbo region, Chile: Influence of mineral deposits and metal recovery practices. *Atmos. Environ.* **2005**, *39*, 7587–7596. [CrossRef]
51. Higueras, P.; Oyarzun, R.; Kotnik, J.; Esbrí, J.M.; Martínez-Coronado, A.; Horvat, M.; López-Berdonces, M.A.; Llanos, W.; Vaselli, O.; Nisi, B.; et al. A compilation of field surveys on gaseous elemental mercury (GEM) from contrasting environmental settings in Europe, South America, South Africa and China: Separating fads from facts. *Environ. Geochem. Health* **2014**, *36*, 713–734. [CrossRef] [PubMed]
52. Oyarzún, J.; Castillo, D.; Maturana, H.; Kretschmer, N.; Soto, G.; Amezaga, J.M.; Rötting, T.S.; Younger, P.L.; Oyarzún, R. Abandoned tailings deposits, acid drainage and alluvial sediments geochemistry, in the arid Elqui River Basin, North-Central Chile. *J. Geochem. Explor.* **2012**, *115*, 47–58. [CrossRef]
53. Rector, J.L. *The History of Chile*, 2nd ed.; Greenwood: Santa Barbara, CA, USA, 2019; ISBN 9781440863738.
54. Veiga, M.M.; Nunes, D.; Klein, B.; Shandro, J.A.; Velasquez, P.C.; Sousa, R.N. Mill leaching: A viable substitute for mercury amalgamation in the artisanal gold mining sector? *J. Clean. Prod.* **2009**, *17*, 1373–1381. [CrossRef]
55. Veiga, M.M. *Introducing New Technologies for Abatement of Global Mercury Pollution in Latin America*; CETEM/CNPq: Rio de Janeiro, Brazil, 1997; p. 94.
56. Drace, K.; Kiefer, A.M.; Veiga, M.M.; Williams, M.K.; Ascari, B.; Knapper, K.A.; Logan, K.M.; Breslin, V.M.; Skidmore, A.; Bolt, D.A.; et al. Mercury-free, small-scale artisanal gold mining in Mozambique: Utilization of magnets to isolate gold at clean tech mine. *J. Clean. Prod.* **2012**, *32*, 88–95. [CrossRef]
57. 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]
58. Veiga, M.M.; Angeloci, G.; Ñiquen, W.; Seccatore, J. Reducing mercury pollution by training Peruvian artisanal gold miners. *J. Clean. Prod.* **2015**, *94*, 268–277. [CrossRef]
59. Zolnikov, T.R.; Ortiz, D.R. A systematic review on the management and treatment of mercury in artisanal gold mining. *Sci. Total Environ.* **2018**, *633*, 816–824. [CrossRef]

60. Purvis, B.; Mao, Y.; Robinson, D. Three pillars of sustainability: In search of conceptual origins. *Sustain. Sci.* **2019**, *14*, 681–695. [CrossRef]
61. Seccatore, J.; Marin, T.; De Tomi, G.; Veiga, M. A practical approach for the management of resources and reserves in Small-Scale Mining. *J. Clean. Prod.* **2014**, *84*, 803–808. [CrossRef]