The Impact of the Use of Mercury in Mining in Colombia

Johan Martinez

Follow this and additional works at: https://scholarship.claremont.edu/cmc_theses

Part of the Environmental Health and Protection Commons, and the Environmental Monitoring Commons

Recommended Citation
Martinez, Johan, "The Impact of the Use of Mercury in Mining in Colombia" (2024). CMC Senior Theses. 3406.
https://scholarship.claremont.edu/cmc_theses/3406

This Open Access Senior Thesis is brought to you by Scholarship@Claremont. It has been accepted for inclusion in this collection by an authorized administrator. For more information, please contact scholarship@claremont.edu.
The Impact of the Use of Mercury in Mining in Colombia

A Thesis Presented By

Johan Martinez

To the Keck Science Department
Of Claremont McKenna, Pitzer, and Scripps Colleges
in partial fulfillment of
The Degree of Bachelor of Arts

Senior Thesis in Chemistry
13th December 2023
Table of Contents

Abstract .......................................................................................................................... 2
1. Introduction .............................................................................................................. 3
  1.1. Brief Contextualization of Colombia ............................................................... 3
  1.2. Mercury in Mining ............................................................................................ 5
  1.3. Effects of Mercury ............................................................................................ 7
  1.4. Impacts of Mercury on Human Health ............................................................. 9
  1.5. World Issue ...................................................................................................... 11
  1.6. Mercury Use in Colombia ............................................................................... 12
  1.7. Aims .................................................................................................................. 14
2. Material and Methods .............................................................................................. 16
  2.1. Mercury in Water ............................................................................................ 16
  2.2. Mercury in Air .................................................................................................. 22
  2.3. Data Analysis ................................................................................................... 24
3. Results and Discussions .......................................................................................... 25
  3.1. Mercury in Water ............................................................................................ 25
  3.2. Mercury in Air .................................................................................................. 26
  3.3. Decreasing Mercury Emissions ....................................................................... 27
  3.4. Policy ............................................................................................................... 32
4. Conclusion ................................................................................................................. 35
5. Acknowledgments ..................................................................................................... 36
6. Literature Cited ......................................................................................................... 37
Abstract

Artisanal and small-scale gold mining is a practice that is common all around the world, especially in Latin America, Africa, and Asia. It is also one of the leading consumers of mercury and leading sources of emissions. Governments have banned the use of mercury completely, including Colombia, but it continues to be used and emitted into the environment. This issue is exacerbated because there is a lack of standards, a lack of research done regarding mercury use in mining, and a complex socio-political history in Colombia. For this reason, this paper seeks to provide a proposed pathway for research to be conducted. These methods can be applied to any part of Colombia, but the focus is the National Natural Park the Farallones, which as a park should not have any mining in its vicinity. However, we expect there to be mercury concentrations that could negatively impact the health of people and the environment both in air and in water sources, specifically in areas close to emission sites. There are numerous alternatives to reduce and eradicate mercury use, including Gemini Tables, the Borax method, and education around mercury use. Several policy suggestions could be implemented as well, including a provision of materials, including borax which is an alternative to mercury and Gemini Tables which has found success in French Guinea, and education, such as introduction to concentrate amalgamation and information on proper ventilation practices, to reduce mercury and exposure. Our main goal is to provide research to secure the health and livelihood of people who work in the artisanal and small-scale gold mining industry, as well as secure environmental health.
1. Introduction

1.1 Contextualizing Colombia

Colombia is a country with one of the highest numbers of displaced people, an internal armed conflict that has lasted decades, one of the leading exporters of cocaine, and has plenty of natural resources at its disposal. Many blame the narcos, the rural “backwardness,” the paramilitary, and the guerillas for the lack of social and economic improvement. However, there is one actor that stands above all others when it comes to the armed conflict in Colombia and that is the Colombian government. They have failed to protect the lands of the people, whether it be from drugs, monocrop, guerillas, paramilitaries, or from big resource draining foreign corporations. In this paper I will explore one of the industries that has caused harm to Colombian communities, the informal mining industry. To begin I will lay out a historical understanding of Colombia, as it has a long history of internal conflict. It is imperative to understand Colombia’s guerilla movements, specifically the Colombian Revolutionary Armed Forces (FARC) and how they formed due to the government's inability to keep the peace and create agrarian reform (Wickham-Crowley 1993). Next, we must talk about the mining sector and where Colombia stands currently with their gold mining industry. This industry has long been tied with armed actors including the FARC and has been important for the economic growth of the country, and integral to the drug industry. It was believed that if a peace treaty could be struck with the FARC that the informal mining industry would diminish, but the government has failed to move forward with the peace treaty. The peace treaty would have failed at diminishing informal mining from the start, as there are other actors besides the FARC in the industry (Massé and Le Billon 2020). The damages have been great.
FARC began as a military campaign in 1964 and 1965 to retake areas that had been taken away by the government from peasants (Wickham-Crowley 1993). The peasants had been autonomous both defensively and economically up to this point. When land is taken away from a peasant, this takes away their livelihood and their way of life. In the present day, money is what allows people to live in the absence of land. The government created the FARC by not allowing its people to live on lands they had owned. This has led to the current problem where the government fails to tackle the root of the issue, which is that people need money or land to survive. The Colombian government has yet to create ways to help its citizens make wages that support themselves or their families, which is why many are forced to participate in informal and dangerous industries, such as being a part of the mining industry. The brunt of the violence then falls on the most vulnerable populations, such as people who live in the rural areas of Colombia, which is where the violent armed actors reside.

This armed conflict has lasted decades and has become more complex as more actors emerged. Two actors that we have not discussed are paramilitary groups and drug cartels, both of which have played major roles in Colombian history. Paramilitary groups arose from the guerilla movement, and was the right-wings attempt to protect themselves. Oftentimes these groups claimed self defense, but they eventually moved towards other motives, such as social cleansing and moral killing among others (PBS 2008). Then we have the cartels, which arose from the marijuana trade, which eventually turned to the cocaine industry. As cartels grew, so did their influence in government, politics, and the environment around them. Cartels started intertwining themselves with both guerilla movements and paramilitary groups due to the money that could be made (PBS 2008). The armed actors are complex and numerous, which cannot be captured in a couple of sentences.
The government, in an attempt to make peace with one of the many armed actors, FARC, created a 2016 peace treaty. However, this peace treaty failed on multiple levels because the government thought that once the peace treaty was signed that everything the FARC was involved in, such as informal gold mining, would cease to occur. However, the government failed to understand that there are numerous actors in the informal gold mining industry. At the end of the day, policy and change will only go as far as the government decides to go in terms of measures and implementation of agreements. So, there are people who do not think that a peace agreement with the FARC or another guerilla group such as the National Liberation Army (ELN) would solve or translate to the end of informal mining or the relationship between armed actors and extractive sectors in Colombia (Massé and Le Billon 2020). The peace treaty did not solve the problems in the gold mining industry. Moreover, the government was not able to implement its policy and agreements in a way that would have made the 2016 peace treaty effective. Again, the government has failed to create real change in the country and to create ways for people to make a wage that does not require people to be in informal and dangerous jobs.

1.2 Mercury in Mining

Unfortunately, mining with mercury is common all over the world, specifically when it comes to artisanal and small-scale gold mining, the focus of this thesis. Mercury is often used in mining because it is cheaper than other alternatives and the process can be conducted by a single person (UNEP 2012). In general, there is one main process for how the mining takes place and it is shown in Figure 1. First the rocks or sediments containing gold are collected. The ore is then concentrated to reduce mass. The process of concentration is done using gravity, but there are many ways to concentrate the gold. One way is sluicing, where a sluice box is used, and heavy gold particles are trapped within the carpet as a mixture of ore and water, slurry. This concentrate
is then collected by washing the carpet (Balzino et al. 2015). After this, mercury is added to the ore to create an amalgamation. Finally, the amalgamation is collected and heated to evaporate out the mercury and isolate the gold. This process usually takes place in one of two ways, whole ore amalgamation (WOA) and concentrate amalgamation. WOA is considered a bad practice, as it is inefficient and releases the most amount of mercury. Mercury is brought into contact with the “whole ore” rather than concentrated ore, which means that there is not as much ore being collected, and there is more mercury used. However, in concentrate amalgamation, the rocks and sediments are concentrated to have as much gold as possible. Then mercury is added to the concentrate, which leads to higher effectiveness and less mercury use, but it does not take away from the human exposure that is faced (UNEP 2012). The exposure is faced usually because there are no regulations for the mercury use. Therefore, workers wear no protective gear, and there is often poor ventilation at the evaporation sites, so they inhale the mercury vapor when it is evaporated.

Figure 1. Flowchart of mining with mercury.
1.3 Effects of Mercury

Mercury is extremely destructive to both humans and the environment. The effects of mercury exposure on humans have been studied extensively. It is reported that the inhalation of mercury vapor can result in harmful effects on several systems including nervous, digestive, and immune systems. Moreover, the mercury vapor can affect lungs and kidneys, and could be fatal. The effects of mercury exposure can vary, and the United States Environmental Protection Agency (U.S. EPA) mentions different factors that can lead to the severity of health issues, which includes exposure time and amount, form of mercury, age, and method of exposure (US EPA 2015). Elemental mercury is the form of mercury that is used for mining, however it changes as it goes into the environment and begins to interact with other substances. In the environment, mercury can disrupt food chains by damaging the development of different living organisms. For example mercury has been found to affect algal growth; crustacean health; fish growth, brain function, and reproduction; and amphibian larval health and survival (Esdaile and Chalker 2018). Moreover, mercury can accumulate within fish and aquatic plants, which poses a threat to any living organism that consumes it. Communities, who mine for gold using mercury, are also fishing and eating the animals around the area. This also leads to danger for humans, who can be exposed to mercury through the food chain. The World Health Organization (WHO) has developed international standards for mercury concentrations both in the air and in water. WHO’s guidelines for air are that concentrations should not exceed 1 mg/m³ and water should not exceed 6 µm/L. The recommended level of mercury in soil of residential areas should not exceed 1 mg/kg of soil according to the United Kingdom (Bose-O’Reilly et al. 2016). Tables 1. and 2. Demonstrates different standards in water and in air that should be followed. The standards vary a lot, so it is key to note which standard to use at different times.
Table 1. Standards for the concentration of mercury that can be in water (US EPA 2023) (British Columbia 2020).

<table>
<thead>
<tr>
<th>Organization</th>
<th>Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>U.S. EPA (in drinking water for inorganic mercury)</td>
<td>.002 mg/L or 2 ppb</td>
</tr>
<tr>
<td>U.S. EPA (methyl mercury acceptable for daily exposure)</td>
<td>0.1 micrograms per kilogram of body weight per day.</td>
</tr>
<tr>
<td>Health Canada</td>
<td>0.001mg/L</td>
</tr>
</tbody>
</table>

Table 2. Standards of the concentration of mercury that can be found in the air (US EPA 2021)(Ye et al. 2016).

<table>
<thead>
<tr>
<th>Organization</th>
<th>Standard ( (mg/m^3) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Korean Ministry of Employment and Labor (Time Weighted Average (TWA), Aryl)</td>
<td>0.1</td>
</tr>
<tr>
<td>Korean Ministry of Employment and Labor (TWA, Alkyl)</td>
<td>0.01</td>
</tr>
<tr>
<td>American Conference of Governmental and Industrial Hygienists (TWA)</td>
<td>0.025</td>
</tr>
<tr>
<td>American Conference of Governmental and Industrial Hygienists (Short term exposure limit, 15 minutes)</td>
<td>0.03</td>
</tr>
<tr>
<td>California Environmental Protection Agency Office of Environmental Health Hazard Assessment(1 hour exposure)</td>
<td>0.0006</td>
</tr>
<tr>
<td>California Environmental Protection Agency Office of Environmental Health Hazard Assessment (8-hour exposure)</td>
<td>0.00006</td>
</tr>
<tr>
<td>California Environmental Protection Agency Office of Environmental Health Hazard Assessment (Lifetime exposure)</td>
<td>0.00003</td>
</tr>
<tr>
<td>U.S. EPA (Lowest observed adverse effect level)</td>
<td>0.009</td>
</tr>
</tbody>
</table>
1.4 Impacts of Mercury on Human Health

The amount and duration of mercury exposure are the major factors in terms of health impacts. Many studies have been conducted about the effects of mercury on human health. There have been numerous studies on the effects of mercury on artisanal and small-scale gold miners as well.

A study conducted in Peru surveyed 103 residents from a mining town, 35 of which had direct contact with mercury at least once a month. To assess the levels of mercury in the residents, they used biomarkers such as blood and urine, including a questionnaire that assessed their perceived level of mercury exposure. They found that more than 50% of residents reported headaches, mood swings, or muscle weakness. Prior medical diagnoses found that 20 residents had digestive system disorder, 9 had kidney dysfunction, and 4 had nervous system disorder. The study found that the participants that had reported kidney dysfunction had higher concentrations of mercury in urine (Yard et al. 2012). This data is useful because it describes the effects that mercury exposure can have on people who are not directly exposed to mercury, while also showing us what direct exposure to mercury can lead to. Many people suffer from mercury exposure, not only the people who work in the mining industry.
A different study was conducted in Brazil that focused on gold mining exclusively. They surveyed 93 gold workers and 779 workers related to gold mining activities. In order to test the effects of mercury exposure on the 93 gold workers, they conducted urine tests. This was coupled with a medical exam to correlate exposure to side effects. They found that almost half of the 93 workers, who were considered most susceptible to exposure, reported 5 or more symptoms related to mercury exposure, which includes sleep disorders, frequent headaches, fatigue, cough, trembling, irritation of mouth, dizziness, fits of giddiness, difficulty walking, vision disorders, tingling sensation at hands or feet, thoracic pain, and rhinitis. When they tried to correlate the symptoms to the concentration of mercury in urine, they only found positive correlations for two symptoms, thoracic pain and difficulty grabbing. The article talks about several reasons why this might be possible, including the variability of mercury concentrations in urine, as well as the “healthy worker effect,” where the sickest workers were not present (Tomicic et al. 2011). Several factors could lead to the lack of correlation, but the fact remains that many reported symptoms that can be attributed to mercury exposure.

These effects are already being studied in Colombia. A study conducted in San Martin de Loba, Colombia surveyed 124 participants. Most of the people were miners. Demographics and health surveys were done, as well as blood samples to study the concentration of mercury in the blood. They found that 60% of miners from the area had neurotoxic abnormalities, which is one of the side effects from mercury exposure. Moreover, they found that the miners were 8.9 more likely to have neurotoxic abnormalities than non-miners. This shows that miners are more likely to have mercury exposure symptoms, which makes sense since they have the immediate exposure in rooms that are often not ventilated (Vergara-Murillo et al. 2022). From this paper we can understand the effects that mercury exposure has in Colombia.
The effects of mercury on the communities that deal with them need to be further studied, but studies have shown that exposure can lead to several issues, specifically neurological issues, and organ issues (Gibb and O’Leary 2014). The effects of mercury depend on exposure and type of exposure, but the dangers of mercury are ever present and can range from non-life-threatening effects, such as headaches, to kidney dysfunction, which could be life threatening. Moreover, studies need to take in consideration children and pregnant women, since they are often vulnerable populations that can be susceptible to mercury.

1.5 World Issue

Human mercury exposure and environmental contamination is an issue around the world. According to information from the United Nations Environment Programme (UNEP), artisanal and small-scale gold mining is the leading consumer for mercury, estimated at 1400 tonnes of mercury during 2011, which makes up about a fourth of all consumption. To add to this, UNEP estimates that it is second, at about 327 tons, only to coal combustion in terms of mercury emissions to the atmosphere (UNEP 2012). However, these sources are dated, recent data from shows that mercury emissions have risen since 2011. Data for a 2018 UNEP report found around 838 tons of mercury was emitted through artisanal and small-scale gold mining (UNEP 2018). This shows an increasing amount of mercury use. Figure 2 shows the different parts of the world where mercury emissions are prevalent. High mercury emissions in the air (orange zones) are found in Africa, Asia, and Latin America (US EPA 2023). One of the highest emission rates (orange/red section) is Colombia, which is the area of focus. However, not all emissions are from artisanal and small-scale mining, global annual mercury emissions from anthropogenic sources are estimated at around 2220 tons per year. Although mining is the lead cause of mercury emissions, it does not account for all emissions. Coal combustion is also a major source of
mercury emissions. It was the main contributor to mercury emissions in 2011, but since then, it has been overtaken by artisanal and small-scale gold mining. Other major contributors of mercury emissions are nonferrous metals productions, cement production, and waste from products (US EPA 2023).

![Figure 2. Mercury air emissions separated geospatially from the year 2015. (US EPA 2023)](image)

1.6 Mercury use in Colombia

Although alternatives to the utilization of mercury for mining have been developed and the use of mercury prohibited, mercury is still used in Colombia. However, the extent and total mass of mercury use are not known, which makes it difficult to ascertain the gravity of the situation. Questions remain about the practice of using mercury for gold mining. Has the ban on mercury worked? Have the alternative practices been implemented enough? Prior to the ban and the new technologies, a study was conducted in the Andean region of Colombia, which found
that Colombia had the most mercury pollution emissions per capita in the world (Cordy et al. 2011). It is hard to believe that a country that held the highest mercury pollution per capita could liberate itself completely from mercury. Although mercury has been banned in Colombia, there is a black market that allows for the trade of mercury (Sasse 2019). This is a major reason why the socio-political state of Colombia is important, as it plays a role in how the government can regulate mercury. The Colombian government has been “absent” in various parts of the country, and there is no regulation. Therefore, the illicit economy of mercury trade can flourish, as well as the other illicit economies found in Colombia. There is plenty of data that suggest that there is plenty of gold mining happening in Colombia with no regulation.

For the past few years, the United Nations Office on Drugs and Crime (UNODC) has released evidence about the “Alluvial Gold Exploitation in Colombia,” where they note how much land is being used to mine gold. The findings released in the latest report in 2022 based on 2021 data, showed that 13 of the 32 departments, which are similar to states in the United States, in Colombia have evidence of alluvial gold exploitation (EVOA). From UNODC evaluations, a total of 98,567 ha of land were used for gold mining. This is further complicated because most of gold mining is done illicitly, 65% (UNODC 2022). This means that there is no regulation for that mining, and anything can be used, including and most often mercury. This lack of regulation makes way for entables, processing centers for the gold amalgam, that do not have proper ventilation, nor have fume hoods with condensers and filters to limit the release of emissions to the open air (US EPA 2023). So, the miners and gold shop workers are exposed to the mercury vapor, which is the primary form of exposure.

Finally, it is imperative to note that half of all EVOA is done on land that is excluded from mining areas, this is land that should not have mining, which includes National Natural
Parks, Regional Natural Parks, Ramsar Sites, Paramo Zones, and Forest Reserve Zones. Gold mining is extremely popular, not just in Colombia, but all over the world because of the demand for gold and its rising prices. The pandemic serves as an obvious point of analysis, as many try to invest money in gold due to its safety within the market. This then drives the price of gold up, which also drives production up (UNODC 2022).

1.7 Aims

The purpose of this project is to shed light on the issue of mercury use in artisanal gold mining in Columbia. However, this issue is not black and white. This is a socio-political issue and the Colombian context matters. Mercury is cheap and can provide a source of income for families that have none. Alternatives are expensive or require technical skill. Mercury can be used, but it must be done in a safe and controlled manner, as to not impact human health or the environment. Several studies have already been conducted about the effects of the use of mercury in mining. Usually, the studies focus on how much mercury is being released into the environment, both in the air and water. My proposed project is to see where Colombia currently stands with its mercury use. I will seek to develop experiments that will survey and measure mercury levels in the Pacific Region of Colombia, specifically in the Parque Natural Nacional Los Farallones (National Natural Park the Farallones), where there is a substantial amount of illicit mining, due to the inability to regulate the forest. About 6 ha of land is used in gold mining in the park (UNDOC 2022). This land and the land around it will be the points of reference for the experiment. However, for both safety reasons and practical reasons, it might not be possible to measure mercury pollution at the emission sites. The amount of land used for gold mining has diminished over the years, however, mercury does not degrade so it is noteworthy to see where
the mercury levels stand both in the air and the water due to both historic and current mining activities (UNDOC 2022). I hypothesize that the air where the amalgam is being heated will have the highest amount of mercury in the air, and that it will be higher than the international recommendations. Moreover, concentrations will be affected based on the distance from the evaporation sites. I expect there to be larger concentrations of mercury in the water, as mercury in the air usually settles in the water or land (US EPA 2023). I have chosen to focus on water instead of land because water from the park is used by a community that lives in the park, so it is imperative that the water is clean. Again, the concentrations in water will depend on the distance from the evaporation site.
2. Materials and Methods

2.1 Mercury in Water

As mentioned before, although there is satellite imagery that shows where the mining is occurring. It might not be possible to run an experiment near the emission sites. Therefore, the sampling for water and air will serve as a survey to check what the mercury pollution is for. These sites were chosen because mining should not be happening in this nature park, so miners would mine in sites that are harder to reach and are farther from the city in order to maintain secrecy. Moreover, these rivers are large, so they play a larger role in the ecosystem around them.

![Map of Parque Nacional Natural los Farallones](image)

**Figure 3.** Map of Parque Nacional Natural los Farallones (Natural National Parks in the Farrallones). The six black marks are the sites where the water samples will be collected.

Water sampling is a rigorous process and requires a lot of steps. Three water samples of 100-2000 mL will be collected from the six different rivers, as shown by Figure 3. The analysis will take place in a lab elsewhere, the hope is that it will be somewhere nearby so that analysis
can happen promptly (US EPA 1996). From this lab, all sampling equipment and sample containers will be cleaned using detergent mineral acids, and reagent water. Borosilicate glass bottles will be pre-cleaned by heating it for 1 h in a furnace at 500°C and cleaned as mentioned before too (US EPA 2002). At the laboratory, it will be imperative to create an acceptable equipment blank to demonstrate that the equipment and containers are free from contamination before they are shipped to the sampling sites. A blank is defined as one that is free from contamination below the minimum level, which in the case of mercury is 0.0005 μg/L. After cleaning, the sample containers are each filled with weak acid solution, double bagged, and shipped to the sampling site. Moreover, the laboratory oversees preparing a large container filled with reagent water, so that it can be used for the collection of field blanks. Each site will receive one field blank. On arrival, there will need to be two people working with the samples. One is designated as the “clean hand” and the other as the “dirty hands.” The person labeled “clean hands” will be in charge of any contact that involves the sample bottle and the transfer of the sample from the sample collection device to the sample bottle. The person labeled “dirty hands” will be in charge of preparing the sampler and any other facets of the experiment. During the sampling it is important that the scientists wear clean, nontalk gloves when handling the sampling equipment and containers. To minimize contamination, samples will be collected facing upstream and upwind, whenever possible. In order to collect the sample, “clean hands” will wear shoulder-length polyethylene gloves. Since mercury is the analyte of choice, the sampling team must wear precleaned wind suits. Both the “clean hands” and “dirty hands” will put on PVC gloves. Once this is done, the water samples can be gathered.

“Dirty hands” will open the cooler and remove the double-bagged sample bottle from storage and unzip the outer bag. “Clean hands” will follow and open the inside bag and remove
the sample bottle. They will also close the inner bag. After, “dirty hands” will close the outer bag. Next, “clean hands” submerges the sample bottle, and partially fills it. “Clean hands” will then screw the cap on the bottle, shake the bottle several times, and finally empties the bottle away from the site. Two more rinsings are necessary. Once the three rinsings are completed, “clean hands” submerges the sample bottle in the water. Upon the bottle being filled, the bottle is inverted while submerged and “clean hands” caps it while inverted. After the bottle has been capped, “dirty hand” opens the outer plastic bag, and “clean hands” opens the inner bag and places the bottle inside. “Clean hands” then proceeds to close the inner bag, and after “dirty hands” closes the outer bag. The sample will be labeled appropriately. Then water samples will be filtered in situ through a 0.45 μm polyvinylidene fluoride filter (Millipore). In order to preserve the samples, we will add 0.4% (v/v) of ultra-pure hydrochloric acid (HCl) within 24 h.

The samples will then be sent to the laboratory where they will go through the Bubbler, Purge and Trap, Cold Vapor Atomic Spectrometer seen in Figure 4. This instrument has a method detection limit of 0.2 ng/L, which is perfect as data below this would be well below standards. In order to prepare the instrument for function it will be calibrated. To calibrate the Bubbler system there needs to be a minimum of five non-zero points and the results of analysis of three bubbler blanks. The lowest calibration point must be at the minimum level. There will be two mercury standards that are necessary for calibration, working standard A and working standard B. In order to create the standards, there will need to be a stock mercury standard, which is made by using National Institute of Standards and Technology (NIST) -certified 10,000-ppm aqueous mercury solution. Then a secondary mercury standard has to be created. For this, 0.5 L of reagent water and 5 mL of bromine monochloride (BrCl) are added to a 1.00-L Class A volumetric flask. Then 0.100mL of the stock mercury standard is added. Now to create
the working mercury standard A, 1.00mL of the secondary mercury standard is diluted in a 100 mL Class A volumetric flask with reagent water containing 0.5% by volume BrCl solution. To create the working standard B, 0.10 ML of the secondary standard is diluted in a 1000 mL Class A volumetric flask with reagent water containing 0.5% BrCl solution. Once the two standards are made, calibration can begin. 0.50 mL of the working standard B and 0.5 mL of stannous chloride (SnCl$_2$) are added to the bubbler. This is then swirled, and purged. After, 0.05, 0.25, 0.50, 1.0 mL of the working standard A will be added to produce standards. The standards will be analyzed starting with the lowest concentration and proceeding to the highest. The height or area for each peak will be tabulated. After, three blubber blanks need to be prepared and analyzed. The mean of the peak height or area of the bubble blanks will be calculated. Now, for each calibration point, subtract the mean peak height or area of the bubble blanks from the peak height or area of each standard. The calibration factor ($CF_x$) will be calculated using the following equation for each standard:

$$ CF_x = \frac{As - Abb}{Cx} $$

$$ As = \text{peak height or area for Hg in standard} $$
$$ Abb = \text{mean peak height or area for Hg blank} $$
$$ Cx = \text{mass in standard analyzed (ng)} $$

Once all the five $CF_x$ have been gathered, then the mean calibration factor ($CF_m$), standard deviation of the calibration factor, and the relative standard deviation (RSD) of the calibration factor will be calculated. If the RSD ≤ 15% then the recovery of the lowest standard using $CF_m$ must be calculated. If the RSD ≥ 15% and the recovery of the lowest standard is between 75%-125%, then the calibration is acceptable and the $CF_m$ can be used to calculate the concentration of mercury in samples. If the RSD ≥ 15% and the recovery of the lowest standard
is not between 75%-125%, the analytical system must be recalibrated and the test needs to be repeated. Once the system is calibrated, then the samples can begin to be added to the system.

Before analysis, 100 mL of all samples will be oxidized to Hg(II) with BrCl. After oxidation, the sample will be reduced with NH₂OH·HCl in order to destroy any free halogens. The sample should be allowed to react for 5 minutes in order to ensure that the halogens are destroyed. Now it is time to connect a fresh trap to the bubbler, and pour the reduced sample into the bubbler, add 0.5 mL SnCl₂ to convert Hg(II) into a volatile Hg(0). This will then be purged onto the gold trap with N₂ at 350 ± 50 mL/min for 20 minutes. During analysis of the Hg samples, the recovery is quantitative, and the organic interferences are destroyed.

After the sample has been reduced and purged, the Hg from the gold trap must be desorbed. In order to do this, the sample trap will be removed from the bubbler, and a Nichrome wire coil will be placed around the trap. This trap will then be connected to the analyzer train between the incoming Hg-free argon and the second trap (analytical) as seen in Figure 4. Now argon will pass through the sample and the analytical traps at a flow rate of about 30 mL/min for about 2 minutes. Then power will be applied to the coil around the sample trap for three minutes to thermally desorb the mercury from the sample trap onto the analytical trap. After three minutes, the power to the coil must be turned off, and the sample trap should be cooled using a cooling fan. Now it is time to turn on the chart recorder or the data acquisition device to start data collection. Now power will be applied to the Nichrome wire coil around the analytical trap. This will go on for three minutes. The mercury that is desorbed from the analytical trap is carried into the Cold Vapor Atomic Fluorescence Spectrometer (CVAFS) for detection. CVAFS is the method by which both the water and air samples will be analyzed. The way it works is that the sample is that a U-V light source, in this case a mercury-vapor lamp, is needed (Gasmet 2023).
The light is directed at the sample cell. Once the sample enters the sample cell, the mercury atoms are excited by the light. After, the excited atoms re-radiate the energy from the source, this is called fluorescence. The fluorescent light emitted is omnidirectional, and so a detector is placed at a 90° angle to the light source so that only the fluorescence light is detected. The detector will produce the data. Once this is done, data collection can stop, the power to the Nichrome coil can be turned off, and the analytical trap should be cooled to room temperature using a cooling fan. Then the next sample trap in line can be placed and analyzed.

**Figure 4.** Diagram of the Bubbler, Purge and Trap, Cold Vapor Atomic Spectrometer used for mercury measurements in water (US EPA 2002).
2.2 Mercury in Air

The location of the sample sites has not yet been determined. The best data would come if sampling points were chosen around emission sites, but due to safety and practical concerns it might not be possible to do it in these sites. For this reason, if the sample cannot be collected near and at emission sites, then the sampling will occur where the water sampling occurs. Then this experiment will serve as a survey for mercury pollution in the area. Finally, there will be a control location that is situated at a site where no amalgam evaporation is happening within the vicinity.

To measure the mercury in air, a Tekran Mercury Vapour Analyzer model 2537A will be used. The data is retrieved using Cold Vapour Atomic Fluorescence Spectrophotometry, which will give mercury concentrations in μg m⁻³. According to the general operational guidance from the EPA, the frequency of analysis can be varied from about every 4 minutes to every 15 minutes (Crowe 2017). The goal is to try and get a substantial amount of data to be able to determine trends. So, at each location the instrument will run for a month and will take data every 5 minutes. In areas where no power is available, a power generator will be necessary to connect the instrument. Sample flow can range between 0.7-1.5L/m and has sensitivity of <0.1 ng/m³ (Tekran 2023). A model of the mercury analysis instrument and how this system works is shown in Figure 5.

Before samples are collected there should be an internal calibration of the instruments. The calibration can happen in three ways. One way to calibrate the instrument is that the on-board computer can be programmed to calibrate at specific times.

Air samples are continuously pulled into the instrument through a sample inlet. The instruments’ on-board computer introduces the sample to one of two gold matrices at a time. While the sample goes through the cartridge, the mercury present will amalgamate on an encased
gold mesh screen. The second cartridge is analyzed by the on-board computer. To do this, argon gas sweeps the cartridge, and then it is heated up. In this way, the mercury that had been absorbed by the gold matrix will be released during the heating process. The mercury then flows into the detector with the help of argon gas. Once the mercury is in the detection site, Ultraviolet light at 253.7 nm excites the mercury atoms present. The fluorescence produced by the mercury is observed by the detector. Fortunately, the amount of mercury in a cell is proportional to the intensity of the fluorescence. Finally, once the computer calculates how much mercury is in the sample, it can proceed to calculate the concentration of mercury by dividing the mass of the mercury detected by the volume of air sampled.

**Figure 5.** Diagram of the analyzer Tekran 2537A used for mercury measurements in vapor (Pankratov 2015).
2.3 Data analysis

Water

In order to analyze the water data for mercury concentrations, the data from the CVAFS, which shows up as areas and peaks, will need to be converted into concentration of mercury in ng/L. The following equation must be used:

\[
[Hg](\text{ng/L}) = \frac{A_s - A}{C_{Fm} \times V}
\]

\(A_s = \text{peak height for Hg Sample}\)
\(A = \text{peak height for Hg blank}\)
\(C_{Fm} = \text{mean calibration factor}\)
\(V = \text{Volume of sample (L)}\)
3. Results and Discussions

3.1 Mercury in Water

The concentration of mercury in water will vary depending on location. The location of the evaporation of the amalgam is not known, but it is assumed that the closer the water source is to the points of emission the higher concentration of mercury, however this is complicated by the fact that the water is moving. Nevertheless, we expect to find concentrations of mercury in water that exceed any allowed standard for mercury as shown in Figure 6. These concentrations will decrease as distance increases from the emission points. The EPA has stated that there should not be more than 0.002 mg/L or 2 ppb of inorganic mercury in drinking water (US EPA 2023). Moreover, Canada’s standards for the amount of mercury permissible in water is 0.001 mg/L.

**Figure 6.** Bar chart showing mercury standards in water, as well as expected results (US EPA 2023) (British Columbia 2020).
These concentrations are the baselines, by which we will take into account the concentrations we find in our samples. Our expectation comes from the literature available on mercury in water at near emission sites. These values are mostly within the U.S. EPA standard, but half are above Health Canada’s standard. However, the goal is to have no mercury in the water, so any mercury found will be a sign that ASGM is creating mercury pollution.

### 3.2 Mercury in Air

![Bar Chart with mercury air standards along with expected results](image)

**Figure 7.** Bar Chart with mercury air standards along with expected results (US EPA 2021) (Ye et al. 2016).

Similar to the concentration levels of mercury in water, we expect that concentrations of mercury in air will exceed any standard, especially in zones where the amalgam is being evaporated as seen by Figure 7. Moreover, we expect the concentration of mercury in air to
decrease as the distance increases between the source and the point of sampling. The concentrations of mercury that a human can withstand depends on the duration of exposure time. Standard limits of mercury in air (Table 2) demonstrates the wide variety of concentrations that should not be exceeded. For example, both the labor administration in Korea and the United States state that the recommended amount of mercury concentration should not exceed 0.1 mg/m$^3$. The concentrations of mercury that are used within the amalgamation process is 1:1, and it is likely that the workers who evaporate the mercury exceed the limit that is placed. Our expectations are found in the literature that studies mercury air pollution. The range is very large, and we can expect to find mercury concentrations within the different standards. However, there are many concentrations that are above the standards shown in Figure 7 that we can expect to find as well, and this will probably occur the closer that the sampling site is to the emission site. The larger concentrations are significantly higher than the standard concentrations and could lead to serious health concerns.

3.3 Decreasing Mercury Emissions

Mercury air emissions are the primary source of pollutants in the mining process, so we expect these to be the largest source. For this reason, different methods that can be used to decrease the amount of mercury that is used in the mining process will be provided. If the amount of mercury can be decreased from the emission source, then we believe that the water will also benefit, therefore lowering the mercury concentrations in water.

Criminalizing and banning mercury use without a viable alternative is unfair and does not get at the root of the problem. Mercury can be smuggled to the gold miners, and it provides a way of living. Since mercury will continue to be used, there are certain suggestions and awareness that can be created for the safer handling of mercury. Studies have shown that
communities often use whole ore amalgamation rather than concentrating the ore before amalgamation (García et al. 2015). Therefore, it would be beneficial to teach communities safer means to concentrate their gold, which includes practices such as sluicing, which is a practice used to concentrate gold mentioned prior. By concentrating the ore, the amount of mercury used is reduced. Other methods of concentrating gold can be found in UNEP’s practical guide to *Reducing Mercury Use in Small-Scale Gold Mining*, and they include concentration methods that use magnets, centrifuges, and vortexes to name a few.

There are also several other methods that can be used. In Colombia specifically, the amalgamation usually takes place in large containers known as “cocos”. Usually, the miners and owners of these “cocos” do not use activated mercury (García et al. 2015). Mercury can become less effective in the amalgamation process when it has become contaminated through previous use or has been oxidized. Therefore, it is important to activate the mercury prior to using so that the oxidation layer of mercury is removed. This allows for mercury to coalesce and form fewer droplets during the amalgamation process, which results in less mercury lost to tailing and overall, less mercury use. The process by which mercury is activated is simple. Mercury is poured into a plastic, glass, or ceramic cup (UNEP 2012). In a separate cup mix table salad and water. When the salt is dissolved it can be partially poured over the mercury, however sodium hydroxide could also work and is safer. After the solutions are together, copper cables are connected. The negative pole of a 9V or 12V battery is connected to the mercury, while the positive side is connected to the solution. The surface of the mercury will become clean in five to ten minutes and is ready to be used for amalgamation. Another practice that can be implemented has to do with the speed at which the “coco” is spun. If “coco” is run at slower speeds, then there
are fewer droplets of mercury lost to tailing that can then turn into mercury vapor. These two methods can greatly reduce the amount of mercury that is used within the system.

As far as equipment is concerned, there are several items that could be useful for people who use mercury. To reduce the amount of mercury in the atmosphere it is crucial to use condensers, air filters, and retorts. A retort can be extremely effective to contain the evaporation of the mercury. A study found that by implementing a retort, there can be a recovery of mercury of around 90-95%. That was with an expensive retort however, and the same study found that a retort could be made with salad bowls from a local grocery shop. In this case, a salad bowl is placed over the evaporation of the amalgam, and the mercury will condense on the glass, as seen by Figure 8. This is coupled with wet sand around it. This method was not tested for effectiveness, but any measure that can capture mercury instead of releasing it into the air is useful for the reduction of mercury (García et al. 2015). However, there are methods that can completely eliminate the use of mercury.

![Figure 8. Glass bowl retort used in amalgamation process (García et al. 2015).](image)

Gemini Tables are an alternative method that has been used in French Guiana and a diagram is shown in Figure 9. They are constructed from fiberglass, have one-directional
movement, and variable speed. Gemini tables can produce clean gold concentrate, without the use of mercury at times or produce an effective concentrate. Moreover, the recovery efficiency is great if the pre-concentration methods, such as sluicing, are done effectively. This method is found to be effective with gold bearing black sand. The way that it works is that shaking tables are slightly inclined. There are small openings near the lower edge. The gold ore and water are added in their respective feeding mouths, and the motor begins to shake the table. The inclination, water flow, and shaking, results in particles moving towards the lower edge. Light particles are washed over the ridges, while the gold particles are caught. However, there are drawbacks to this method. For example, there needs to be a clean and constant water supply, which in some cases is not possible. Moreover, the Gemini tables are costly and are priced at around $8,000. This cost is not possible for small scale miners that rely on the profits to live off of (Davies 2014) (Vieira 2006). However, this does not mean that governments cannot look for ways to support their citizens and subsidize the cost.
Figure 9. Diagrams with labels of a Gemini Table (Metallurgist 2023).

Another method is the use of sodium tetraborate, ‘borax’, which can reduce the melting points of all minerals. The use of borax allows gold to be melted out of the concentrate. After the concentration of gold is made, three times as much borax is added by volume. Afterwards the mixture is heated. The result is the accumulation of gold at the bottom, which can be easily removed. Borax, unlike mercury, is environmentally benign. However, this method also has drawbacks, as this process is more technical, so it would require more training. Once trained, the process for borax extraction of gold is similar to the mercury method (Davies 2014). Moreover, a study has found the borax method to have greater gold extraction than mercury (Appel and Jønsson 2010). This method could be very useful, and provide a safer way to extract gold, it just requires more training. More methods exist than the three described in this paper for limiting
mercury exposure, but it is imperative to highlight that alternatives do exist and that there needs to be more work done to transfer to these alternatives.

3.4 Policy

Much of the policy around the world focuses on banning the use of mercury completely. A major push of this policy has been the Minamata Conference, where several regulations were put into place in order to eradicate mercury in the free system (Eriksen and Perrez 2014). The European Union has banned the export of mercury, most imports have also been banned, and there are numerous regulations on products that contain mercury (European Union 2017). Colombia has also put a ban on mercury, but regulation of this ban has been difficult to achieve. However, there is much to understand when it comes to the use of mercury. As mentioned above, mining provides a source of income, and sometimes it is the only way to live. Mercury has long been used by miners all over the world because the process is cheap and effective, at least in terms of being able to do the processing alone.

The socio-political context and history of Colombia creates a difficult situation for the ban on mercury. There is history of the effects of mercury caused by large corporations. A prime example is La Cianurada stream, where the Frontino Gold Mines Company and their heirs dumped mercury-polluted tailings in 1852 (Rubiano-Galvis n.d.). A ban on mercury does nothing for the effects from historic mining that are still being faced by the people and the environment. There was no attempt to recognize the past and destructiveness of mercury use.

Also, now gold mining and the armed conflict are directly intertwined. A report “Alluvial Gold Exploitation in Colombia” was written by the United Nations Office on Drugs and Crime. The reason for this is that where there is gold mining, there is usually drug trade as well. So, if they can deduce where the gold is being mined, they will be led to areas of drug cultivation. The
armed conflict is directly linked, and this creates issues in certain parts of Colombia, as armed actors control the mining industry. This makes it difficult for miners to join state programs that would allow for the transition from mercury.

Finally, by banning mercury, the state is criminalizing its use not only by large corporations and armed actors, but also by the small and medium scale mining operations. Smaller mining operations already struggle with attaining licenses to mine, which is why most of them operate informally, but by banning mercury the state is exacerbating the problem. The citizens who work the mines need the income that comes from mining, but at times there is not a way for them to do it without mercury because of the dangers of the armed conflict and the inability of the government to enact useful policy.

The development of effective policy is imperative. One policy should address the damage of past mercury. Colombia must deal with the legacy of mercury to move forward, as that legacy is still creating issues. Moreover, Colombia must remove its ban on mercury and move towards ways to work with its people. Miners in Colombia have previously expressed their frustrations of the armed groups and large companies, as well as the ineffective training and technology transition projects that have been conducted by numerous entities (Rubiano-Galvis n.d.). In order to be able to create long lasting policy, and policy that will be enacted, it is imperative to hear from the people of which the policy affects. Moreover, there needs to be more studies conducted in areas of mercury use. The ban of mercury does not mean that mercury is not being used, so data needs to be present to identify if the use of mercury is decreasing, or if it remains the same. Finally, the government must continue to provide alternative pathways for mining or create educational programs that teach about ways to use mercury more effectively and safely. The pathways can be created in different ways, but one example is that the government can subsidize...
the use of different methods. For example, the government can train their miners on the use of borax and supply their miners with borax, so that they might conduct the borax method. Many alternatives exist, and policy should include governmental programs that pay for technologies, so that miners can move away from mercury.
Conclusion

The use of mercury in mining is a grave issue that affects numerous parts of the world. Mercury has negative effects on the environment and on the people who are exposed to it. It is imperative to do more work around this issue as many of the populations that deal with mercury are vulnerable, and often this work is their only source of income. Many miners know the effects of mercury but continue to do this work because it is a necessity. The ban on mercury means nothing to people all over the world, who still need their basic necessities met. Years have passed since the ban of mercury, and it is ever-present. Banning mercury does not mean the reduction of mercury use, so it is imperative that Colombia and countries all over the world continue to conduct research on mercury emissions and impact. Little is known about the actual impact of mercury in certain parts of Colombia due to the armed conflict. Further studies should continue to investigate how deep the mercury pollution is, the lasting effects it can have on the human body, and the intergenerational effects. Several studies have begun to do work with biomarkers, and use blood, urine, and hair to investigate the amount of mercury concentration in the human body. Studies of this nature should be conducted in Colombia as well to gauge and correlate the health issues of the citizens to mercury concentrations. In all, there needs to be more research done on this topic, as there is not enough information on the environment or health impacts that are being faced by the people in Colombia. Besides additional research, the government must also enact policy that is useful to miners, such as creating policy that creates pathways for new technologies. Moreover, Colombia must deal with all past mercury pollution if it is to move forward. Policy should seek to remedy the mercury pollution in the environment and the mercury exposure that has been faced by people. If mercury emissions are to go down, then there needs to be more research and more government intervention.
Acknowledgments

This journey would not have been possible without all the people who have helped me out through my academic career. The teachers, professors, and staff in my life have been instrumental to my success. Special thanks goes out to Sami Atif, who encouraged me to pursue STEM, and has always had my back.

Also, I would like to thank Professor Purvis-Roberts for her support and wisdom throughout this process and through my academic journey at the 5Cs. Thank you professor for your countless edits and willingness to help. If I needed help at any point, I knew that I could reach out to you.

Thank you to Professor Fu, who, like Purvis-Roberts, provided me with many wonderful tips throughout my journey at the 5Cs. Thank you so much for helping me figure out what to do with my thesis, especially when it came down to my results and discussion section.

I appreciate Diego Lugo-Vivas who introduced me to this topic and several others during my time in Cali, Colombia and who introduced me to Christop Kaufmann, who played an instrumental role in providing me with sources for this topic.

Finally, thank you to my friends and my family. Shoutout to everyone in our research group- Claudia, Ellen, Daniel, Natalie, and Khylah - for being a part of this journey. A special shoutout goes to Claudia, who was my thesis-partner in crime. Our countless hours in Poppa have finally paid off. Also, I want to thank my friends Michelle, Sarahi, and Tandile, for your emotional support during this time. Last but not least, thank you to my brothers for supporting me my whole life and to my parents. Without you all, I wouldn’t be who I am or where I am. Muchas gracias mami, te quiero mucho.
Literature Cited


Successful Case of Mercury Reduction.” *Journal of Cleaner Production* 90 (March): 244–52. https://doi.org/10.1016/j.jclepro.2014.11.032.

14. “Gemeni Gold Table.” *911 Metallurgist*,


