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Mercury Challenges in Mexico: Regulatory, Trade and Environmental Impacts

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Abstract: Primary artisanal mercury (Hg) mining in Mexico continues to proliferate unabated, while official Hg exports have declined in recent years amid speculation of a rising black market trade. In this paper, an assessment of primary Hg mining in Mexico was conducted, with a focus on four sites in Querétaro State. Atmospheric Hg concentrations were measured at two of those sites. In addition, trade data was examined, including Hg exports from Mexico and imports by countries that have a large artisanal gold mining (AGM) sector. Results showed that while annual Hg production in Mexico has ramped up in recent years, official Hg exports reduced from 307 tonnes in 2015 to 63 tonnes in 2019. Since 2010, mercury exports to Colombia, Peru and Bolivia have represented 77% of Mexico's total Hg trade. As the large majority of Hg trade with these countries is apparently destined for the AGM sector, which is contrary to Article 3 of the Minamata Convention, there is evidence that increased international scrutiny has led to an increase in unregulated international transfers. Atmospheric Hg concentrations at the mines show dangerously high levels, raising concern over the risk of significant health impacts to miners and other community members.

Keywords: primary artisanal mercury mining; Mexico; Hg trade data; atmospheric mercury concentrations; Minamata Convention

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1. Introduction

On 16 August 2017, the Minamata Convention of Mercury entered into force for the first block of countries (Parties) that had both signed and ratified the international accord. Out of a total of 128 States (Signatories) that have signed the Convention, to date 124 countries have ratified the accord, with Pakistan being the last on 16 December 2020. This agreement, under the umbrella of the United Nations Environment Program (UNEP), provides a regulatory framework with the aim to "protect human health and environment from anthropogenic emissions and releases of mercury (Hg) and mercury compounds." Specifically, there are imperatives to establish strict controls on mercury trade, gradually stop primary mercury mining and limit the use of mercury or mercury compounds in manufacturing processes, including chlor-alkali production and vinyl chloride monomer used to make polyvinyl chloride-PVC [1]. However, it is important to point out that the Minamata Convention only provides guidelines for the parties to follow, with the implementation of regulatory solutions solely on the responsibility of member countries.

One of the first objectives of the Minamata Convention of Mercury was to push for the phase-out the supply of mercury-added products by 2020, a directive that was officially ratified in September 2019 [2]. This includes the manufacture, import and export of batteries, switches, fluorescent lamps, cosmetics, pesticides, barometers, and thermometers, as well as discouraging the use of mercury in dental amalgams. Another important target is limiting the use of mercury by artisanal gold miners (AGM), who number between 16–20 million and operate in more than 70 countries worldwide [3].

Artisanal gold miners are the world's largest users of mercury, who apply rudimentary amalgamation techniques to recover gold, causing severe impacts to human health and the environment [4–6]. In developing countries, artisanal mining activity plays a crucial role in rural or remote areas, where diversification of the local economy is limited or irregular [4,7]. Poverty and a lack of opportunities leads low-income or unemployed rural inhabitants to pursue AGM, where a gram of gold is currently worth approximately US $61. In addition, the implementation of lockdown measures forced by measures to contain the COVID-19 pandemic have left hundreds of thousands of people unemployed, which only exacerbates the situation.

Worldwide, AGM annually produces approximately 400 tonnes of gold or 12% of total global production, generating US $24 billion in revenue [3]. Concomitantly, AGM is the largest source of anthropogenic mercury emissions, with an estimated average loss of 2058 tonnes of mercury being used and annually released into the environment [8], both from fluvial and atmospheric emissions, which accounts for 37% of total Hg emissions worldwide [9]. However, AGM miners continue to use mercury to produce gold despite well-known environmental and health impacts, as it is accessible, relatively cheap and easy to use [10].

For the implementation of the Minamata Convention directives in each country, the importance of reducing and eliminating the supply and trade of mercury is paramount to being able to regulate its use. As of August 2017, the development of new primary mercury mines has been banned and existing mines have 15 years to complete a total phase-out [9]. In addition, there are restrictions for the use of mercury in product manufacturing and disposal, as well as new regulations to control the import and export of mercury between Parties and Non-Parties [9]. According to the U.S. Geological Survey (USGS), in 2019, approximately 4000 metric tonnes of mercury were produced worldwide, with China (3500 tonnes) and Mexico (240 tonnes) being the top countries, while smaller amounts were produced by Tajikistan (100 tonnes), Peru (40 tonnes), Argentina (30 tonnes), Kyrgyzstan (20 tonnes) and Norway (20 tonnes) [11]. While Indonesia is also considered to be one of the world's largest mercury producers and exporters, there is little information on Hg production. However, UN COMTRADE data showed that Hg exports from Indonesia ramped up to 680 tonnes in 2016 from 284 tonnes in 2015 and 0.81 tonnes in 2014, before dropping down to 152 tonnes in 2017, then only 29 tonnes in 2018 and 13 tonnes in 2019. With an estimated 1 million artisanal gold miners working in 27 provinces in Indonesia [12,13], it appears that Indonesian mercury production is principally used for domestic consumption.

Although it is widely known that Mexico is a significant primary mercury producer, the USGS categorizes it as an export country that "reclaims mercury from Spanish colonial silver-mining waste" [11]. Article 3 of the Minamata Convention states that any mercury produced must only be used in the manufacturing of mercury-added products in accordance with Article 4 (e.g., batteries, fluorescent lamps, cosmetics, pesticides, etc., which are to be phased out in 2020, apart from the continuing use of dental amalgams), in manufacturing processes in accordance with Article 5 (e.g., chlor-alkali production, which is to be phased out in 2025) or be disposed of in accordance with Article 11 [1].

While the Minamata Convention is explicit that mercury is not to be exported for its use in artisanal gold mining, an INECC (Mexican Institute of Ecology and Climate Change) report in 2017 examining the challenges, needs and opportunities to apply the Minamata Convention in Mexico, stated that the main destination of mercury produced in Mexico was for exports principally to Latin-American countries that use it in artisanal gold mining [14]. It is apparent that the increase in Mexican mercury production has occurred as a result of export bans imposed by the United States and the European Union since 2011. In 2010, UN COMTRADE data showed that global mercury imports and exports had been 2600 tonnes and 3200 tonnes, respectively. However, by 2015, global Hg imports and exports had decreased to 1200 tonnes and 1300 tonnes, respectively, while mercury production kept on increasing. Since then, in order to avoid scrutiny due to Minamata Convention compliance, there has been increased evidence of informal or illicit transfers, especially involving Indonesia, Colombia and Mexico [15].

Primary mercury mining typically uses artisanal methods, including the roasting of cinnabar (HgS) ores in rudimentary wood-fired ovens, which heats and condenses the released mercury in the form of metallic mercury. Cinnabar is a mercury sulfide mineral composed of 85% mercury and 15% sulfur, which upon calcination releases mercury vapors. Due to the rudimentary method used by artisanal mercury miners, the mercury vapor contaminates the surrounding local environment and also the lungs of workers operating the ovens, who generally do not use any personal protective equipment [16]. It is well known that exposure to mercury vapor enters into the lungs and circulatory system, causing accumulation in the kidneys and brain, leading to serious neuro-cardiovascular problems [4,17–19].

In this paper, we conducted an assessment of primary mercury mining in Mexico, with a focus on four sites in Querétaro State, including Camargo, Bucareli, San Gaspar and Plazuela. This included a brief history of mercury mining in Mexico and a description of the key stages of the mercury mining process, as well as an analysis of the Hg supply and trade situation with several countries in South America that have a large AGM sector, leading to examination of the regulatory control suggested by Minamata Convention directives. In addition, the environmental impacts of primary mercury mining in Mexico are highlighted by atmospheric Hg concentrations measured at mine sites in two different municipalities in Querétaro. There is also a discussion of the economic alternatives that could be promoted in the region to substitute the destructive practices associated with primary mercury mining.

2. Material and Methods

2.1. Field Study and Data Research

Field observations were conducted in the Sierra Gorda region of Querétaro, Mexico, between July 2015 and February 2017 to complement preliminary information obtained in 2014. The first findings indicated that there were four main areas of influence at Sierra Gorda where artisanal mercury miners (AMMs) obtained cinnabar from underground mines and then used rudimentary technologies to produce metallic mercury at primitive processing centers. This information was corroborated by the Secretariat of Sustainable Development (SEDESU) in Querétaro, which confirmed that irregular activities from local miners had been taking place at Sierra Gorda. They indicated that the main activity of these miners was the informal production of primary metallic mercury. Furthermore, SEDESU provided the contact information for some community leaders in order to obtain access and observe its mining and community activities.

In August 2015, a mercury assessment was conducted in the areas of Camargo and Plazuela in Peñamiller Municipality, as well as Bucareli and San Gaspar in the municipality of Pinal de Amoles (Figure 1). This assessment was designed to gather basic information on extraction processes in the underground mines and what techniques were being used at the processing centers. In order to accomplish those objectives, interviews were conducted with owners of mine concessions, AMM leaders and technicians in the processing centers. These interviews were qualitative in nature, which used informal discussions with the participants to better understand the mining and processing methods employed, safety precautions or lack thereof, inherent risks involved, production rates, number of workers involved, legalities and typical salaries for workers.

In March 2016 and February 2017, site investigations were conducted at an artisanal mercury mine located close to Camargo (Figure 2). The site investigations included atmospheric mercury sampling of the area using a Jerome J405 atomic absorption spectrometer (AAS) in 2016 and 2017, as well as a Lumex RA-915M AAS in 2017. While the mercury sampling in 2016 focused on measuring Hg concentrations in and around the cinnabar distillation ovens in the processing area, the 2017 sampling began first in the center of

Camargo village at the police station and then continued on to the mine and mercury processing area (Figure 3). These atmospheric Hg concentrations were then compared to other measurements made in June 2016 at La Soledad mercury mine in Pinal de Amoles Municipality, Querétaro.

Figure 1. Map of study area showing the location of active primary mercury mines in the State of Querétaro, including Camargo and Plazuela in Peñamiller Municipality and Bucareli and San Gaspar in Pinal de Amoles Municipality. The map has been modified using an image sourced from Via Michelin.

Figure 2. Artisanal primary mercury mine in Camargo, Peñamiller Municipality, State of Querétaro Arteaga, Mexico. Photo taken in February 2017 by Bruce Marshall.

Figure 3. Wood-fired ovens at an artisanal primary mercury mine in Camargo, Peñamiller Municipality, State of Querétaro Arteaga, Mexico. Photo taken in February 2017 by Bruce Marshall.

Data research was also conducted looking at mercury exports from Mexico, as well as mercury imports by countries in South America that have a large artisanal gold mining sector.

2.2. Study Area

The town of Camargo is located in Peñamiller Municipality at an elevation of 1755 m and only 8.6 km by road from Peñamiller, which is the capital of the municipality. Approximately 80% of the territory of Peñamiller Municipality lies within the Sierra Gorda Biosphere of Querétaro.

Camargo has a population of 852 inhabitants, whose overall literacy rate is very low (8.1%). As there are few economic activities in the region, unemployment is generally high, with only 44% of the men and 15% of the women employed [20]. INEGI data has shown that both Peñamiller and Pinal de Amoles municipalities have a high poverty index, with approximately 35% of the populations in extreme poverty [20]. The main economic drivers of both municipalities include small shops and businesses, tourism and mining, as well as a small portion of agriculture and livestock (most of it is used for domestic consumption) [20]. The area is very arid and the terrain is desertic with thin layers of soil, which makes extensive agricultural production a significant challenge. Due to the lack of opportunities and low-income jobs, a high percentage of young people has been migrating to the U.S. in search of a better life.

Although the municipalities of Peñamiller and Pinal de Amoles have some rich deposits of various minerals, including hydrothermal veins of gold, silver, lead, zinc, copper and antimony [21], mercury has always been the most exploited. In 2017, the Instituto Nacional de Ecología y Cambio Climático reported that the State of Querétaro had a total of 19 working mercury mines, producing approximately 102 tonnes/a. The mine in Camargo in Peñamiller Municipality produced one-fifth of that or ~20 tonnes/a, while San Gaspar in Pinal de Amoles Municipality produced approximately 16 tonnes/a [22]. However, in 2019, a new report stated that Querétaro State had 189 mines registered with the Secretariat of Economy, which apparently produced a total of 804.6 tonnes of mercury in 2017 [23]. Furthermore, only four of those mines corresponding to two mining concessions had valid permits with SEMARNAT (Secretariat of the Environment and Natural Resources), which is the authority in charge of carrying out the environmental impact assessment and authorizing the mining activities for the exploitation, exploration and benefit of mercury. Although these permits were set to expire in November and December of 2020, they had been issued prior to the Minamata Convention coming into force [23]. It is important to remember that the development of new mercury mines have been banned for all countries that ratified the Convention and that existing mines have 15 years to close their operations [9].

There is concern that on-going production of mercury in the region will compromise nature conservation areas, especially mines in close proximity to the Sierra Gorda Ecological Reserve, which was declared a Biosphere Reserve by UNESCO in 2001. Sierra Gorda is centered in the northern third of the Mexican state of Querétaro and extends into the neighboring states of Guanajuato, Hidalgo and San Luis Potosí. Within Querétaro, the Sierra Gorda ecosystem extends from the center of the state starting in parts of San Joaquín and Cadereyta de Montes municipalities and covers all of the municipalities of Peñamiller, Pinal de Amoles, Jalpan de Serra, Landa de Matamoros and Arroyo Seco, for a total of 250 km^2 of territory [24]. The reserve constitutes one of the most diverse natural areas in Mexico and is home to a number of threatened wildlife species and 15 types of vegetation. In addition, it has been estimated that the Sierra Gorda region has among the largest cinnabar reserves in the world, even considering other old and active mercury mines such as Almadén (Spain), Nuevo Almadén (California, EU), Hidrija (Slovenia), Huancavelica Register (Peru), Virginia Quindien (Colombia) and the Province of Kweichow (China).

2.3. The Mercury Mining Process

Informal mercury mining in Mexico consists of excavating underground shafts in mountainous areas that have rich volcanic deposits in search for cinnabar (mercury sulfide) ores. Crews of artisanal mercury miners (AMM) work hundreds of meters inside the mountains following cinnabar deposits in tunnels 0.5 to 2 m wide. The miners typically use explosives purchased on the black market to blast mineralized quartz veins, which they then extract using pneumatic hammers or, in some cases, simple picks and shovels. The work is extremely physically demanding and often the youngest men are the ones who work inside the mines. After blasting and extraction, the material is then put into sacks and brought to the surface, while the waste rock is used to fill old tunnels.

Once outside of the mine, the cinnabar ore is transported to the processing center, where a crew of AMMs manually break up the rock with hammers to reduce the pieces to 1.5 to 4 cm in diameter. The visual selection process separates the rocks with some red (cinnabar) stains from the waste material (an experienced mine supervisor further screens the waste pile to recover valuable material). All of the waste rock is then piled into heaps in open areas nearby. The selected material is then crushed manually or in a jaw crusher and the classification process is done using a 3–5 mm steel screen.

The next step involves roasting the cinnabar ore in old-fashioned retort furnaces, which are composed of bricks, cement and steel cylinders to receive the condensed mercury. In the roasting process, heat is applied to the cinnabar sulfide ore, raising the temperature above its mercury boiling point (356.7 °C), which creates an oxidized reaction (O_2) to form sulfur dioxide (SO_2):

$$HgS + O_2 \rightarrow Hg + SO_2 \quad (1)$$

Artisanal miners also mix quicklime (CaO) with the cinnabar ore to improve the mercury vapor formation according to the equation:

$$4HgS + 4CaO \rightarrow 4\ Hg + 3CaS + CaSO_4 \quad (2)$$

This allows the mercury to be liberated in vapor form together with water and other substances of the process. Then, all the vapors pass to a cooling system, where mercury is the first element to be condensed into liquid and the other vapors are either captured or vented into the surrounding air. The mercury is then collected and filtered to remove impurities (dark film and scum), leaving 99% pure mercury ready to be packaged. This mercury has adequate enough quality to be directly used in the artisanal gold-silver mining sector; however, for its application in many products such as thermometers, electric switches, barometers, etc., it needs to be further re-distilled.

2.4. History of Mercury Mining in Mexico

For centuries, Mexico has mined cinnabar ores, culminating in the production, trade and use of mercury, beginning in 1555 [25]. In 1557, the Spanish merchant Bartolome de Medina introduced the Patio Process of Mercury Amalgamation in Mexico, which solved the problem of recovering low-grade silver ores. Silver mines quickly adopted this process and silver production boomed in Mexico [25,26].

In 1821, when Mexico declared its independence from the Spanish monarchy, the silver industry became one of the key economic drivers of the new government, which required a steady supply of mercury. In order to meet these requirements, the government eliminated old, established mercury supply restrictions that had been implemented by Spain and promoted the domestic mining of cinnabar [25]. Authorities offered benefits such as tax elimination and rewards when mines annually produced more than 90 tonnes of mercury. As a result of these incentives, old mines re-initiated operations and new mercury mines were gradually opened in the Mexican territory [25].

During the Post-Colonial period (1821–1920), domestic mercury production and mercury imports were used to meet the supply demands for amalgamating silver [25]. However, at the beginning of the twentieth century, cyanide processes for leaching gold and silver were introduced in Mexico [25]. This new technology increased the recovery of both gold and silver, maximized production, eliminated the use of mercury and decreased the environmental impacts caused by mercury use and release [27].

By 1921, Mexican silver mines gradually adopted cyanidation and substituted the Patio Process. Nevertheless, local and international markets required mercury for other applications. According to Castro-Diaz [25], primary mercury production between 1922 and 1967 totaled 18,000 tonnes, with an annual average of 400 tonnes. In 1968, the Mexican Commission of Mining Development (Comision de Fomento Minero) reported a total of 1119 mercury mines operating throughout the country. The Mexican States that had the highest concentration of mines were: Querétaro: 322 mines; Durango: 214 mines; Zacatecas: 212; and San Luis Potosí with 100 mines [25].

From 1968 to 1994, primary mercury production decreased to an average of less than 300 tonnes/a, totaling 7700 tonnes for the 26-year period, with Querétaro being the largest producer [25]. Between 1990 and 1992, the Mineral Resources Council of Mexico (CRM) reported 83 mines operating in the country, including in Querétaro [28], Durango, EdoMex, Guanajuato [27], Guerrero, San Luis Potosí and Zacatecas [29]. Then, in 1994, as large-scale or medium-scale mining companies started exploring more lucrative gold, silver or copper deposits, primary mercury mines did not report any production for that year. Between 1994 and 2013, the mining authorities did not report any primary mercury production whatsoever, with no official registration of any informal or small-scale activity [25].

In 2010, the Mexican Secretariat of Economy reported the existence of 314 metallic mercury mines in the country, although most of them were either inactive or abandoned [25]. The states with the most mercury mines were Querétaro with 75 sites and San Luis Potosí with 56 sites [25]. However, in recent years there have been reports about the potential reactivation of the primary mercury industry in Mexico [22,23,30].

Since 2010, Mexico has been increasing its role as one of the largest suppliers of mercury in the world, together with China and Indonesia. Prior to this, the USA and Spain were the largest mercury exporters over a span of decades, until the European Union banned exports in 2010 and the United States quickly followed suit. However, up until recently, official communication by the Mexican government has contradicted this information. The Secretariat of Economy and the mining government office have repeatedly stated that Mexico has not produced metallic mercury from primary mines since 1995, only formally recognizing production obtained through secondary processes, which has been occurring in Mexico for more than a hundred years [25]. Tailings accumulated from the Patio Process during the Colonial and Post-Colonial eras have presented profitable opportunities for those companies capable of reprocessing waste materials for mercury production, mainly in the State of Zacatecas. However, the estimated annual production of mercury generated from the reprocessing of waste materials (20–24 tonnes) does not match Mexico's total annual production of 240 tonnes [11], which in itself could be vastly underestimated [23], and also does not align with recent annual exports of 230–300 tonnes/a (UN Comtrade). It appears that a significant portion of Mexico's mercury exports come from primary mercury mining; the vast majority of which is unreported and unregulated [15,23].

3. Results

3.1. Assessment of the Primary Mercury Mining Process in Mexico

The results from our assessment showed that the mining and mineral processing methods used in the underground mines at Camargo, San Gaspar, Bucareli and Plazuela were very rudimentary. It was apparent that all of these mines have planning and mine design issues, due to a lack of health and safety standards applicable to the mining metallurgical industry. Typical problems faced by AMMs include mine access, roof control, poor ventilation and illumination, rock slides or cave-ins, rudimentary material transportation, lack of personal protective equipment, as well as general health and safety issues.

For example, it was found that miners at Camargo and San Gaspar used simple winches and railway wagons to transport the cinnabar ore out of the shafts, while Bucareli miners transported the ore material in wheelbarrows, which was then loaded onto their backs.

In terms of processing, the centers at Camargo, San Gaspar, Bucareli and Plazuela all use rudimentary old-fashioned ceramic retort furnaces to roast the cinnabar ore and extract metallic mercury. The AMMs prefer this kind of furnace, due to its simple method of extraction and low capital cost. According to the miners, this type of furnace should address specific heavy-duty requirements in order to be efficient. It must be simple to construct, relatively unaffected by thermal extremes during the roasting process and strong enough to withstand the mechanical stresses of loading and unloading of the ore material.

There is also evidence that some miners process the cinnabar ore with small retort furnaces in the backyards of their homes. All mercury obtained during the week by each informal miner is packaged in empty 600 mL plastic soda bottle containers, which weigh 8 kg each. These soda bottle containers are the vessels in which metallic mercury has been traded for years.

In regards to legalities of the mercury concession holders in Peñamiller and Pinal de Amoles municipalities, it was verified that they are all national Mexicans, possess mining titles that were granted before the Sierra Gorda was declared a Biosphere Reserve, and have their mining taxes paid up to date. In other words, they are all meeting the requirements imposed by the mining regulations in Mexico. However, the concessions also have further obligations required by Mexican mining law which include exploration, mine safety and environmental protection mitigation conducted in accordance with mining metallurgical industry standards, as well as allowing for periodic inspections of their operations by the Secretariat of Energy and Mines and the Secretariat of the Environment and Natural Resources. The concession holders who were interviewed stated that "they didn't have the resources and the technical knowledge to follow all of the legal requirements" and that "the rules should not be the same for small operations as for medium and large-scale mining companies".

Interviews with the AMM leaders revealed that there are more than 1000 miners directly involved in this activity in Camargo, San Gaspar, Bucareli and Plazuela, with more than 40,000 people involved indirectly. In addition, the leaders explained that concession holders have been sub-leasing the mines to local organized artisanal miner groups, albeit with varying agreements in each area. For example, in exchange for full control of the mining operation, concession holders have negotiated a royalty of between 15% and 20% of the final weekly or monthly mercury production. In other cases, groups of miners agreed to pay a percentage of the final production, as well as allowing preference for the concession holder to buy a part or all of the final product. In other cases, the concession holder becomes one of the members of the group of miners and the production is divided equally among the members. However, it is important to note that these organized groups of miners do not constitute any type of legal entity, mining company or mining association. In other words, this informal economy is not recognized, regulated or protected by the State. The structure of these organized groups of miners can range from a simple and functional small mine to a larger and more sophisticated operation.

As stated by the artisanal mercury miner leaders, product value has a strong correlation not only with demand, but also with the market price in Mexico as established by the middlemen (this price is not the same as the international mercury price) and the production rate per week. Overall, the average income for AMMs has fluctuated between $2000 and $3000 Mexican pesos (US $105 to US $158) per week before expenses.

3.2. Mexican Hg Supply and Trade

In 2013, it was estimated that Mexico had reserves of approximately 56 thousand tonnes of mercury primarily in the form of probable Hg ore reserves, secondary mercury from mining wastes, and in the chlor-alkali industry, with lesser amounts as by-product mercury from the base metals production sector and secondary production from recycling [25].

Primary mercury mines contribute nearly 75% of these total reserves or 42,000 tonnes, while secondary mercury from mining wastes contributes approximately 25% or 14,000 tonnes [25]. A 2017 report by the government National Institute of Ecology and Climate Change (INECC) indicated that eight of the 31 Mexican states have mercury mines that feed the national trade in dental amalgams, lamps and raw materials for artisanal gold mining, as well as the growing export [14].

UN COMTRADE (United Nations International Trade Statistics Database) data show that Mexico exported a record of approximately 1994 tonnes of metallic mercury from 2010–2018, while also importing 64 tonnes from a variety of sources [31]. The reported exports rose sharply from approximately 26 tonnes/a in 2010 to a peak of 307 tonnes/a in 2015, before declining to 267 tonnes/a in 2016, 200 tonnes/a in 2017 and 230 tonnes/a in 2018 (Figure 4). Although UN COMTRADE data does not show any figures for Mexican Hg exports in 2019, SIAVI (Tariff Information System via Internet) data from Mexico showed an export total of approximately 63 tonnes/a in 2019 [32] (Figure 4). However, it is likely that the vast majority of the estimated production total of 240 tonnes reported by the United States Geological Survey [11] was destined for export, underlying a critical discrepancy with the trade flow data.

The large majority of the mercury exported between 2010 and 2018 (1668 tonnes or 83% of the total) was sent to countries in South America, while the rest was divided between Central America and the Caribbean (6%), Asia (5%), Africa (3%) and North America and Europe with less than 1% each [31].

In an interview with a Mexican mercury exporter in 2017, he declared that there were only a few exporters in the whole country at the time and he was earning US $32,000/month with his business, exporting mercury principally to Colombia and some other Latin American countries.

Since 2010, 42 countries have bought mercury from Mexico. However, mercury exports to Colombia, Peru and Bolivia have represented 77% of the total trade (1545 tonnes of metallic mercury) (Figure 4). During the period 2010–2018, Colombia bought a total of 456 tonnes of mercury from Mexico (22% of the total), with the highest totals being in 2014 (116 tonnes out of a total of 127 tonnes that Colombia imported from all countries) and 2015 (115 tonnes out of a total of 133 tonnes). In that 9-year period, 58% of Colombia's total mercury imports came from Mexico. However, there is no data regarding imports of mercury by Colombia for 2019 [31].

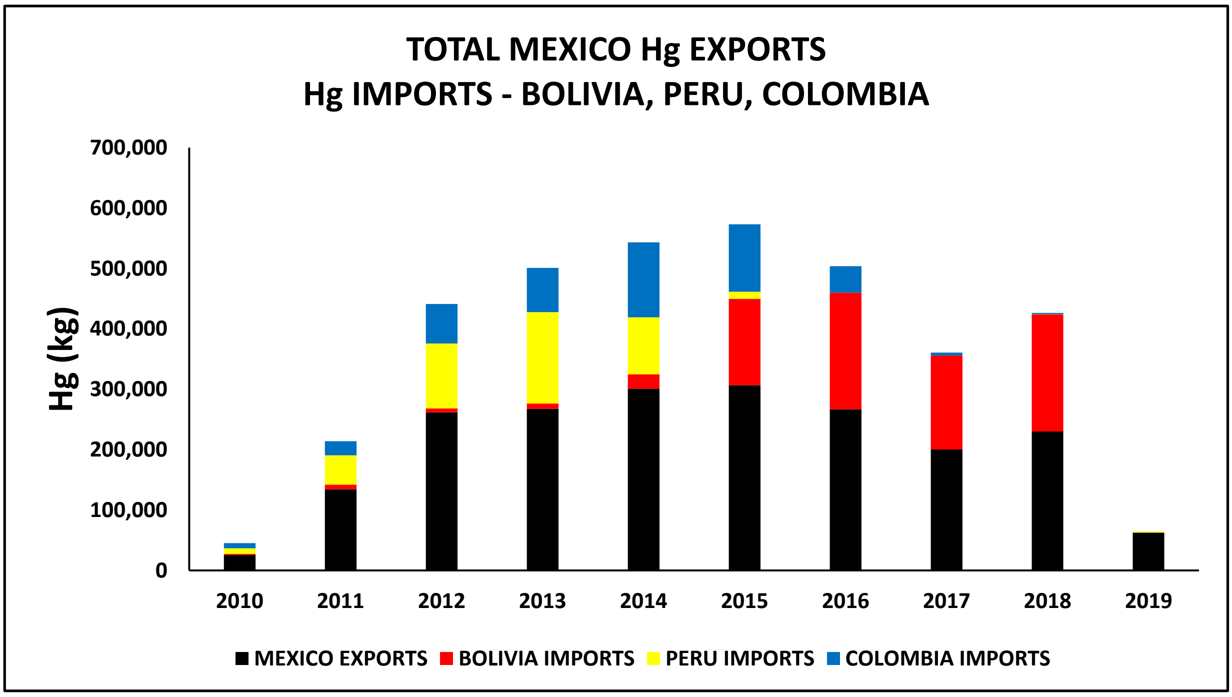

Figure 4. UN COMTRADE data showing the total amounts of mercury exported by Mexico globally for the years 2010–2019 and the import totals of Mexican mercury by Bolivia, Peru and Colombia during the same time period.

From 2010–2014, the second largest receiver of Mexico's mercury exports was Peru with 415 tonnes (27% of total Mexican Hg exports and nearly 60% of all Peruvian Hg imports), whereby 107 tonnes were imported in 2012 (out of a total of 111 tonnes from all countries), 147 tonnes in 2013 (out of a total of 169 tonnes) and 94 tonnes in 2014 (out of a total of 102 tonnes). Subsequently, Peru's total mercury imports drastically declined to 11 tonnes in 2015, with all of it coming from Mexico, while Peru at the same time exported 2.4 tonnes of mercury to Bolivia. Then, in 2016, due to agreements associated with the Minamata Convention, Peru proudly declared that it had stopped all Hg imports (and exports). However, by 2017 Peru began importing mercury once again, totaling 5.2 tonnes for the year, with 0.2 tonnes coming from Bolivia and 5 tonnes from Japan. Then, in 2018, Peruvian Hg imports only reached a total of 0.034 tonnes, with all of it coming from Mexico. However, in 2019 Peruvian imports showed a total of 7.9 tonnes, the highest since 2015, with 1.9 reported tonnes coming from Mexico and the rest from Japan. In total, 59% of Peru's total Hg imports in the period 2010 to 2019 came from Mexico. It is also important to point out that while Peru imported 7.9 tonnes of mercury in 2019, it also exported 91.5 tonnes, with most of it (approximately 88 tonnes) going to the Netherlands [31].

At the same time that Peru's Hg imports declined significantly in the last few years in comparison to the highs reached from 2010 to 2014, Bolivia dramatically increased its official imports from Mexico over a three-year period, from 12 tonnes in 2014 to 139 tonnes in 2015 (out of a total of 143 tonnes imported from all countries), and then 193 tonnes in 2016 (out of a total of 224 tonnes). In 2017, the import total reduced slightly to 180 tonnes, with most of this coming from Mexico (155 tonnes), while smaller amounts came from Spain (10.9 tonnes), Japan (6.9 tonnes) and India (6.7 tonnes). Then, in 2018, Bolivia imported a total of 196 tonnes, with the majority (194 tonnes) coming from Mexico, although a very small amount was also imported from Peru (0.003 tonnes). Other Hg imports in 2018 came from Turkey (2.6 tonnes), USA (0.005 tonnes) and Spain (0.001 tonnes). In total, over the period 2010 to 2018, 91% of Bolivia's Hg imports came from Mexico. However, there is no data regarding imports of mercury by Bolivia for 2019 [31].

This data shows that while Peru decreased its mercury imports from Mexico from over 150 tonnes/a to zero over a three-year period, Bolivia increased its imports approximately

23 times during the same period. In addition, other Latin-American countries such as Panama, Argentina and Paraguay have also been increasing their Mexican imports since 2015, with Argentina importing 12 tonnes in 2019, its highest total since it imported 15 tonnes in 2015. For the 128 countries that signed the Minamata Convention, 31 have traded metallic mercury with Mexico in the last 7 years (this includes 16 parties and 15 signatories). However, since 2018, it has become increasingly difficult to find accurate import/export data, as a large part of the mercury trade has clearly gone underground to avoid scrutiny.

In addition to a lack of current trade data, it has also been noticed that UN COMTRADE data [31] shows discrepancies between the amount of mercury exported by a country and the amount that was imported. For example, an analysis of the Mexican Hg imports by Bolivia, Peru and Colombia highlighted some interesting results. For Peru, the difference between the amounts that Mexico exported and what was imported by Peru ranged from 0% to 24% for the years 2014 to 2015, while both countries reported 0 exports for 2016 and 2017. However, in 2018, Mexico reported exporting 207 kg to Peru, while Peru reported importing only 34 kg. Then, in 2019, while Peru reported an import total of 1.9 tonnes of mercury from Mexico, Mexico did not report any mercury exports (or imports).

For Colombia, the discrepancies between the imported amounts from Mexico and the export totals reported by Mexico were only 3% to 6% for the period from 2014 to 2016, but then in 2017, 2.5 tonnes was the reported export amount from Mexico, while the imported amount by Colombia was 4.6 tonnes (a difference of 45%). Then, in 2018, both countries reported the exact same amount that was exported by Mexico and imported by Colombia: 2.0 tonnes. However, in 2019, neither country declared any mercury trade whatsoever [31].

Finally, for Bolivia there was a large difference in the reported amounts through UN COMTRADE data in 2014, when Mexico reported a total of approximately 24 tonnes exported to Bolivia, while Bolivia reported a total of approximately 12.1 tonnes imported from Mexico, which is a difference of nearly 50%. During the years 2015 to 2018, when Bolivia imported on average 171 tonnes per year from Mexico, the export/import variances ranged from 3% to 16%, with the latter high occurring in 2018 when Mexico reported an export total of 163.3 tonnes to Bolivia, while Bolivia reported a total of approximately 194 tonnes from Mexico. Then, in 2019, there has been no information whatsoever whether Bolivia imported any of the reported 62.6 tonnes of mercury that Mexico officially exported to the world [32].

3.3. Atmospheric Hg Concentrations at Primary Mercury Mines in Mexico

Atmospheric mercury concentrations measured at primary mercury mines in Camargo in Peñamiller Municipality and La Soledad in Pinal de Amoles Municipality showed extremely high levels that workers are exposed to over long periods (Table 1). At the Camargo Mine, in close proximity (0.5–6 m) to the retort furnaces, measurements taken in March 2016 using a Jerome J405 showed atmospheric mercury concentrations that ranged from a low of 9360 ng/m^3 to a high of 62,940 ng/m^3, the latter measured next to the mercury condenser while the furnace (oven) was in operation. It is important to point out that the ovens at the Camargo mine are located outside in a well-ventilated area, which may reduce the Hg concentration levels measured by the spectrometer.

Table 1. Mercury atmospheric concentrations (ng/m^3) in the proximity of two primary mercury mines in Querétaro State, Mexico.

Mercury Mine	Date	Mercury Analyzer	Site Location	Measurements (n)	Min-Max Atm. Hg (ng/m^3)	Avg. Atm. Hg (ng/m^3)
Camargo, Peñamiller Municipality	March 2016	JEROME J405	Workers' changeroom	1	3360	-
			Inside ovens 2 days after processing	2	13,650–14,830	14,240
			3–6 m from ovens operating	6	9380–22,190	18,738
			Next to mercury condenser while oven in operation	2	55,110–62,940	59,025
	February 2017	LUMEX RA 915M	At the Camargo police station	1	29	-
			En route to the mine	4	132–200	168
			1 km from the mine	1	307	-
			10 m from the processing area	6	1800–8000	5050
			Entrance to the mine where the cinnabar is extracted	1	6000	-
		JEROME J405	20 m from the mine	1	2290	
			10 m from the mine	1	2780	
			At the entrance to the mine	1	2850	
			3–10 m from the ovens	8	1800–15,000	7037
			1 m from the retort furnace, where cinnabar ore had been roasted 24–36 h before	2	37,460–50,000	43,730
			Ore feeding door	1	22,020	
			Next to mercury condenser	2	45,821–51,760	48,790
La Soledad, Pinal de Amoles Municipality	June 2016	JEROME J405	5–10 m away from mercury ovens in operation	4	3600–47,100	18,475
			1–4 m away from ovens in operation	8	131,900–438,700	237,412

In comparison, measurements taken within 1–10 m of the retort furnaces at the same Camargo mine in February 2017 using a Jerome J405 showed a low of 1800 ng/m^3 and a high of 51,760 ng/m^3, the latter taken right next to the condensation pipes in front of the ovens where the cinnabar ore had been roasted 24–36 h before and where fresh cinnabar was waiting to be processed (Table 1). It was surprising how similar the Hg concentrations were between the two visits in March 2016 and February 2017, especially considering the latter measurements were taken more than 1 day after roasting a batch of cinnabar ore.

The study in February 2017 also measured atmospheric mercury concentrations using a Lumex 915M beginning at the police station in Camargo, which showed a level of 29 ng/m^3 (Table 1). It is important to note that prior to arriving in Camargo we stopped on the highway from Extoraz, Peñamiller, to get a background Hg concentration, which showed a measurement of 2–5 ng/m^3. Normally, current levels of mercury in outdoor air, except for regional “hot spots,” are generally in the order of 2–10 ng/m^3 [33].

From the police station in Camargo, atmospheric Hg concentrations were then monitored using the Lumex while driving the short distance to the mercury mine (approximately 3-4 km), which showed concentrations between 132–300 ng/m^3. At the entrance to the mine tunnel where the cinnabar is extracted, concentrations using the Lumex that averaged 6000 ng/m^3, while the Jerome showed concentrations averaged 2850 ng/m^3 (Table 1).

When approaching the area of the ovens where the cinnabar ore is roasted to produce liquid mercury, only the Jerome was used, as there was concern that the Lumex could become contaminated. At a distance between 3 and 10 m from the ovens, the Hg concentrations using the Jerome were in the range of 1800 to 15,000 ng/m^3. At a distance of approximately 1 m from the ovens, where mercury had been processed 24–36 h prior and fresh cinnabar was waiting to be inserted into the kilns, atmospheric mercury levels spiked to 37,460–50,000 ng/m^3, which is 19 to 25 times above the tolerable concentration of 2000 ng/m^3 for long-term inhalation exposure to elemental mercury vapor [34].

At La Soledad mercury mine in Pinal de Amoles Municipality, where atmospheric mercury concentrations were measured in March 2016 using a Jerome J405 (Table 1), at a distance of 5 to 10 m from ovens in the midst of roasting a batch of cinnabar ore, Hg levels ranged from 3600 to 47,100 ng/m^3, which are comparable to the concentrations measured at the Camargo mine. However, when reaching 1–4 m from the operating ovens, Hg concentrations ranged from a low of 131,900 ng/m^3 to a high of 438,800 ng/m^3, which is 66 to 219 times higher than the long-term inhalation exposure limit.

Figure 5 shows Hg atmospheric concentrations at both Camargo and La Soledad mines in relation to distance from ovens in operation, as well as ovens at Camargo 24–36 h after processing. As the mercury processing area at La Soledad mine is in a closed area with poor ventilation, the Hg concentrations are much higher than at Camargo Mine, which is located in an open area with good air flow. However, at both mines Hg concentrations decrease in relation to increased distance away from the ovens, with similar concentrations being measured at 8–10 m.

At Camargo Mine, it was surprising to see how high the mercury concentrations were 24–36 h after processing, especially within 0.5 m of the ovens. Right next to the mercury condenser, Hg concentrations were 45,821–51,760 ng/m^3, which were very similar to levels measured when the ovens were operating, varying from 55,110 to 62,940 ng/m^3 (Table 1, Figure 5). As many workers are present to collect the mercury from the ovens the day after processing, including cleaning out the old residues and preparing the kilns for further roasting of cinnabar ore, this data shows that the risk of exposure does not dissipate particularly quickly over time, especially in close proximity to the ovens.

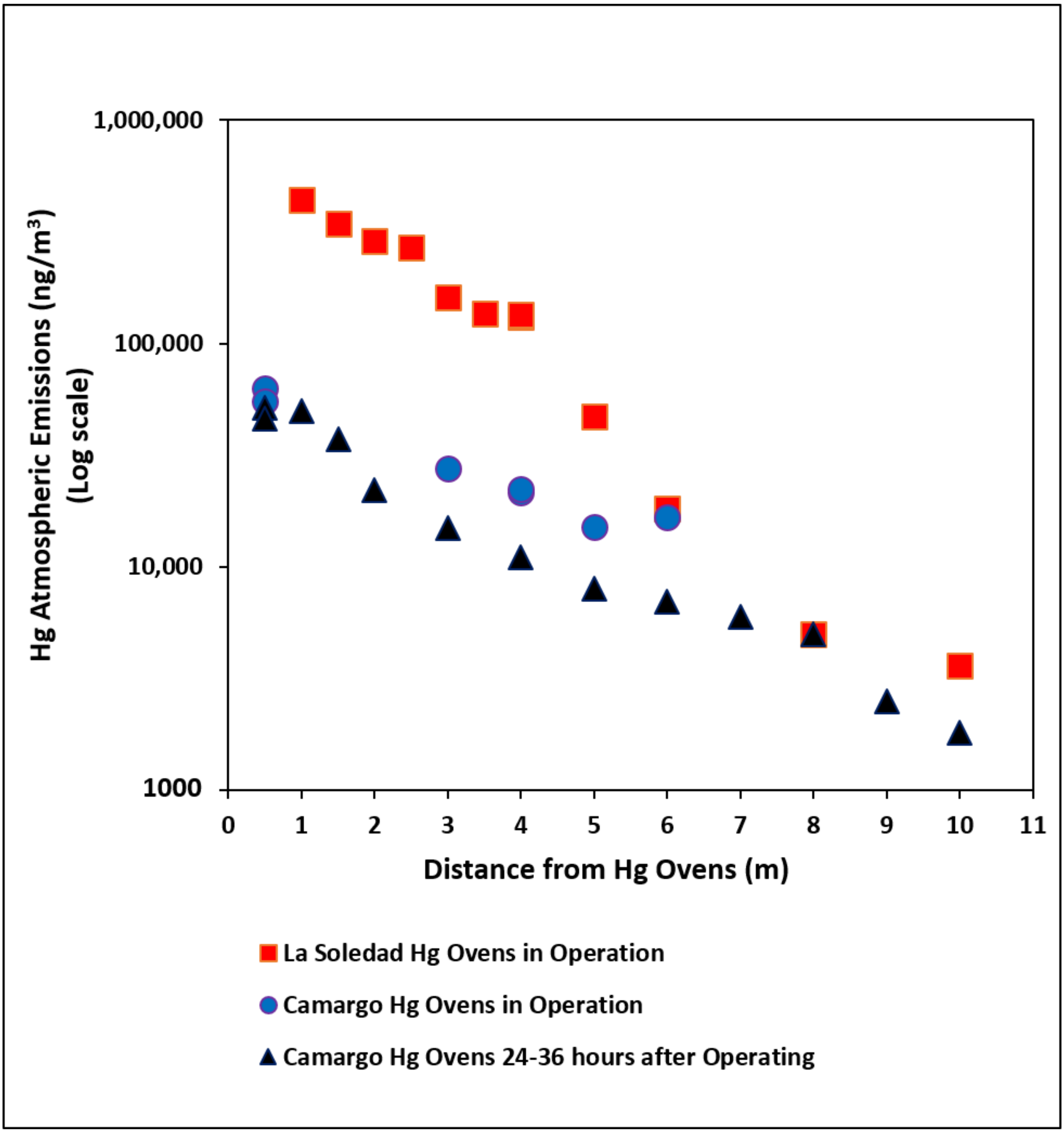

Figure 5. Mercury atmospheric emissions (ng/m^3) at Camargo and La Soledad mines in relation to distance from ovens in operation, as well as ovens at Camargo 24–36 h after processing.

4. Discussion

4.1. Mexican Mercury Supply Chain and International Markets

In 2017, after the Minamata Convention entered into force for signatory parties that signed the agreement four years prior, the global trade in mercury had shifted significantly, due to export bans put in place by the United States and the European Union (EU). Not only had the center of the mercury trade shifted from the Northern Hemisphere to Asia and South America, but the main sources of mercury for the trade had moved from chlor-alkali industries to production stemming from artisanal mercury mines.

UNEP's 2017 report on the supply, trade and demand of global mercury revealed that the amount of available chlor-alkali residual mercury on the market, which is used in various industrial processes, had reduced significantly since 2011, largely due to the export bans. In the EU alone, those prohibitions removed an estimated 650 tonnes of mercury off the market [15].

In order to make up for the demand, artisanal mercury mines in Mexico and Indonesia, two of the world's largest producers, began ramping up production starting in 2011. In Mexico, although official primary mercury mining ceased in 1994 due to low global mercury demand and prices, the Mexican Geological Service in 2011 reported that three mercury mines appeared to have reopened and were working intermittently [25]. By 2015, it was estimated that annual mercury production had reached 400–600 tonnes, which would require significant production provided by several hundred artisanal mines [15]. In 2015, 306 tonnes were exported internationally through legal channels, with suspected additional exports made illegally as well.

Studies from the University of Querétaro and the University of San Luis Potosí, a neighboring state, have estimated that 300–400 tonnes of mercury are extracted in Querétaro each year [30]. One visiting group of researchers in 2017 corroborated this estimate, stating that approximately 1000 miners were producing nearly 300 tonnes of mercury per year in Querétaro [35], with a large majority of that production earmarked for export. However, according to the latest report by the Instituto Nacional de Ecología y Cambio Climático [23], it appears that Hg production in Querétaro could be more than 800 tonnes per year, with the vast majority of that production coming from unregulated mines. For Minamata Convention parties like Mexico, which ratified the commitment with the Convention on 29 September 2015, new primary mercury mines were prohibited after the Convention came into force in August 2017, with all existing mines mandated to be phased out within 15 years of that date [9].

As the trade data in this study showed, 83% of the Mexican Hg exports between 2010 and 2018 were destined for countries in South America, with Bolivia, Colombia and Peru comprising 77% of that total. It is also clear that the majority of the imported mercury by these countries ends up in the AGM sector, where it is used to amalgamate gold, generating the world's largest source of mercury pollution. The UNEP report in 2017 estimated that artisanal gold miners globally use the highest amount of mercury (37%), while the second highest use is for the production of vinyl chloride monomer (26%), occurring mainly in China and likely using mercury produced within their own borders [15]. As Mexico, Bolivia, Peru and Colombia have all signed and ratified the Minamata Convention, the trade of mercury for gold amalgamation contravenes Article 3 of the Convention, which states that mercury cannot be used for this purpose [1].

The drastic reduction in Mexican Hg exports in 2019 and the reduced total imports of mercury by countries like Bolivia, Peru and Colombia signal that increased scrutiny regarding the official transfers and illegal use of mercury have obfuscated the transparency of international transactions, thereby driving suspicion of a thriving black-market trade. However, in terms of official databases like UN COMTRADE and SIAVI from Mexico, it is also possible that there are discrepancies with the data due to the following reasons: (a) the statistical manner in which re-exports and transshipments or transiting goods have been treated; (b) errors in transferring information from manual documents to digital; (c) lack of clarity with regard to the actual origin and destination of goods; (d) inaccurate coding of commodities (i.e., mercury compounds instead of listing as mercury); and (e) the occurrence of undocumented shipments, especially goods passing through bonded warehouses or Foreign Trade Zones [15].

It is the occurrence of undocumented shipments that is the most concerning, given that the official global mercury trade has reduced significantly over the past 15 years, while the demand continues to remain strong. For example, in 2005, 3400 tonnes of mercury were traded worldwide, while in 2017 only 984 tonnes were traded globally, while demand was estimated to be between 4500 and 5000 tonnes [36]. In addition to the reasons for data discrepancies mentioned above, including the uncertain quality of data reported to the UN COMTRADE and data transparency issues, there is also evidence of a 2-tier mercury price caused by the export bans, which encourages illegal transfers. This includes corruption schemes involving the re-selling of waste mercury from chlor-alkali plants as pure mercury destined for AGM operations around the world (i.e., the DELA affair in Germany) to circumventions around the export ban in China [15,36].

The major shift in international mercury trading hubs over the past 9–10 years, combined with increased scrutiny over the source and destination of mercury shipments, has fueled a significant increase in informal and illicit transfers among countries, including Indonesia, many African nations, Mexico, Colombia and Bolivia, among many others. In a country like Mexico, these illicit transfers from the producer (AMM) to the consumer (e.g., AGM in Bolivia, Peru or Colombia) require the facilitation of middlemen, who are able to somehow circumnavigate regulatory controls to expedite export shipments. However, a consequence of all of this is an increase in mercury price, which has risen nearly 9-fold in the last 10 years. In 2010, the price in Mexico was US $17/kg, while in 2020 it has skyrocketed to more than US $186/kg [37]. In countries such as Colombia, Peru, Ecuador and Brazil, the price in AGM areas can reach US $350/kg [10].

4.2. Mexican Artisanal Mercury Miners and Their Future

A combination of high unemployment and a lack of economic opportunities in Querétaro municipalities, such as Peñamiller and Pinal de Amoles, have led to the proliferation of poorly regulated and illicit primary mercury mine operations in the Sierra Gorda region that pump out hundreds of tonnes of mercury annually. Although there are 189 concessions in Querétaro registered with the Secretariat of Economy [23], the actual number of mines could be much higher. Information culled from our interviews with AMMs in Camargo, Plazuela, Bucareli and San Gaspar from 2014–2017 showed that during that period it was estimated that there were more than 100 retort furnaces in the region, which was likely an underestimate.

For the artisanal mercury miners, working either in the mines extracting cinnabar ore or manning the ovens to produce metallic mercury offers a better standard of living than other menial labor, as AMMs earn 2 to 5 times more than the standard minimum wage in Mexico. However, as international pressure mounts from the United Nations Environment Programme and Mexican government authorities to clamp down on "new" illicit operations that were not already legal and in existence prior to ratification of the Accord, the livelihood of AMMs becomes increasingly uncertain.

Apart from the miners themselves, it also remains unclear how apparently "legalized" concessions have been extracting cinnabar for the purposes of producing primary mercury without adequate oversight administered by the Mexican mining and environmental authorities. Considering that the vast majority of mercury mines occur in two of the poorest municipalities in the State of Querétaro, with high rates of unemployment, low salaries and few economic opportunities, the lack of supervision and enforcement may have a political basis. Given the economic reality of the region, it is without question that Hg mines and the mercury they produce provide an important source of livelihood for these communities.

According to SEDESU in Querétaro, the increase in mercury price, as well as the increase in gold price for the AGM sector, has caused the surge in reactivation of old mines to extract cinnabar and produce liquid mercury. Although the concessions have been granted to people or groups of people who know the traditional and rudimentary methods, they do not have the financial capacity to improve their practices or provide the necessary mining infrastructure. Nonetheless, many of these sites do not meet the minimum requirements established by the mining authorities. Furthermore, as mercury is a heavy metal and a pollutant, its exploitation must be conducted with security measures, as well as with strict environmental stewardship. As with the AGM sector, mining and environmental authorities seem reluctant to get involved, due to a lack of resources, politics, public protest and an understanding that informal employment is such a strong driving factor in economic sustenance for a vast majority of the population.

Similar to other developing countries, informal employment has been and continues to be a significant part of the Mexican economy. According to the International Labour Organization (ILO) and the National Institute of Statistics and Geography (INEGI), it was estimated that informal employment in Mexico increased to 59% of the total workforce in 2013 [38]. The study found that approximately 30 million people had informal employment in Mexico. The Mexican mining industry is not exempt from this phenomenon, as the ILO report indicated that the rate of informal employment in the mining and quarries industries was approximately 15% in 2013. Considering the economic fallout caused by the coronavirus, where 12 million Mexican workers have lost their jobs in 2020 over the past 9 months, it is clear that informal employment has likely risen sharply, as families struggle to make ends meet [39].

4.3. Health Impacts and Community Issues of Primary Mercury Mining

The extremely high atmospheric mercury concentrations measured at two different mine sites in Querétaro highlight the dangers that artisanal primary mercury miners working either in the mines or in the processing areas producing metallic mercury are exposed to over long periods of time. The health impacts caused by chronic exposure even to moderate atmospheric Hg concentrations can be very serious, leading to damage to the kidneys and brain, resulting in lasting neurological effects. Although the LOAEL (Lowest Observed Adverse Effect Level) for mercury vapor is between 15,000 and 30,000 ng/m^3, with an 8-h time weighted average (TWA) for occupational exposure set at 25,000 ng/m^3, the NOAEL (No Observed Adverse Effect Level), which is a guideline for public exposure of inorganic mercury vapor, has been established at 1000 ng/m^3 as an annual average [33].

In order to determine the health quality index or hazard quotient (HQ) for workers exposed to mercury vapor, the following equation for chronic exposure could be used: HQ = EC/Toxicity Value or Reference Dose (RfD), where EC (exposure concentration) (ng/m^3) = (CA $\times$ ET $\times$ EF $\times$ ED)/AT. Specifically, CA (ng/m^3) = contaminant concentration in air, ET (hours/day) = exposure time, EF (days/year) = exposure frequency, ED (years) = exposure duration, and AT (ED in years $\times$ 365 days/year $\times$ 24 h/day) = averaging time [40]. For occupational exposure, the RfD could be set at 25,000 ng/m^3.

In this study, exposure to atmospheric Hg concentrations at the Camargo and La Soledad mines increased significantly in relation to closer proximity of the ovens. At 10 m from the ovens, concentrations averaged approximately 2700 ng/m^3, while at 5 m concentrations averaged 23,000 ng/m^3, at 3 m 67,680 ng/m^3, and at 1 m 244,350 ng/m^3. In this example: the ET might be 8 h a day; the EF is calculated as 240 days/year (at 5 days a week); a typical ED might be 30 years; and the AT is therefore equal to 262,800 (30 years $\times$ 365 days/year $\times$ 24 h/day).

For calculation of the HQs for chronic exposures at 10 m, 5 m, 3 m and 1 m, the results would be: 10 m = 0.02; 5 m = 0.2; 3 m = 0.6; and 1 m = 2.1. When the Hazard Quotient is >1, then the Toxicity Value has been surpassed and the exposed populations could be at risk. In this case, although it may appear that the workers are only at potential risk when exposed to extremely high Hg concentrations (~244,000 ng/m^3 measured at 1 m from the ovens), the calculation of HQs done in this way could be underestimating the risk, as Hg production typically involves batches of ore to be processed, followed by days without high exposure. Therefore, it could be more appropriate to consider the exposures as acute in nature, which would be calculated using EC = CA, then EC/RfD. In this way, the results would be: 10 m = 0.1; 5 m = 0.9; 3 m = 2.7; and 1 m = 9.8, which are significantly higher and likely better denote the actual risk unprotected workers face when exposed to atmospheric mercury concentrations.

In 2016, field investigations by a team of researchers from the University of San Luis Potosí (UASLP), examining the health and environmental impacts of primary mercury mining at different mine sites, found highly elevated urinary mercury concentrations in miners at Camargo [41]. Urine samples from a total of 103 miners working at the site showed that 99% had Hg urine concentrations above 35 µg/g creatinine, which is the risk threshold for men, although the LOAEL for renal toxicity has been established at 4 μg/g creatinine [42]. While the minimum concentration found was 31 μg/g creatinine, the median was 275 μg/g creatinine, while the maximum concentration was 2599 μg/g creatinine, which is 74 times above the risk threshold. When the urine mercury concentration exceeds 100 μg/L, neurological symptoms can develop, and above 800 μg/L can be fatal [43].

Considering that quite often women and young children can also be involved in the mercury mining operations, often helping with menial tasks or breaking the cinnabar ore into smaller pieces, chronic exposure to elevated atmospheric mercury concentrations for these populations can be especially detrimental. A study investigating mercury levels in the urine of artisanal primary mercury miners, women and children living in Plazuela in Peñamiller Municipality, where there are three mercury mines, found that average concentrations were 53, 35 and 22 μg/g creatinine, respectively, with maximum concentrations of 144, 63 and 37 μg/g creatinine, respectively [16]. As the risk threshold for women and children has been established at 20 μg/g creatinine, these numbers are very concerning, especially when you consider that renal toxicity can occur at concentrations above 4 μg/g creatinine [42].

For these vulnerable populations chronically exposed to dangerous levels of atmospheric mercury concentrations, further health assessments should be conducted to investigate clinical damage to the kidneys or central nervous system. In addition, verification of a health issue for both miners and community members require implementation of personal protective equipment protocols to safeguard against on-going occupational risk.

5. Conclusions

As the gold price remains high and artisanal gold mining using mercury amalgamation proliferates around the world, demand for mercury from countries like Mexico and Indonesia will continue unabated, even with implementation of international agreements like the Minamata Convention. While countries that have signed and ratified the Convention press on with the implementation of National Action Plans to reduce Hg use in products and manufacturing processes, while also finding ways to mitigate against legacy sites of mercury-contaminated wastes, the demand for mercury used to produce vinyl chloride monomer (mainly in China) and in the AGM sector (in more than 70 countries around the world) continues to be an on-going problem with no end in sight. As the United Nations Environment Programme (UNEP) stated in their report: “it is evident that global mercury demand will have to be reduced in parallel with supply, or else supplies–formal or informal–will continue to be generated in one manner or another to meet demand” [15].

As official mercury trade through imports and exports have reduced from historic highs in 2015 to negligible levels in 2019, there is strong evidence of increasing volume in illicit and informal transfers, which is attracting more international attention. The heightened scrutiny of Mexico and Indonesia legal exports since the Minamata Convention came into force in 2017 appears to have been the causal factor in the dramatic reduction of official exports and the vast majority of the mercury trade being pushed underground. As Peter Maxson reported in 2020, it has become clear that the mercury trade is increasingly following the gold trade, which is centered in areas like India, the United Arab Emirates and their intermediaries, and the drug trade, in places like Colombia [36].

Due to the close linkages between the mercury trade and the AGM sector, finding a solution to reduce Hg use is difficult, although the alternatives certainly exist. Through education, capital investment and training, it is feasible to introduce mercury-free, clean and efficient gold extraction methods to AGM communities, as well as taking steps to shorten the gold value chain. What this requires though, is a concerted effort by funding agencies, international partners and national government ministries to curb illegal mercury production, illicit trade and Hg demand through the implementation of better economic and technological alternatives, as well as vigilant enforcement of criminal activities by racketeers.

6. Recommendations and Future Steps

For the artisanal mercury miners in Querétaro, Mexico, a number of incentives are desperately needed to tackle the problems associated with informal and unregulated Hg production using rudimentary methods, as well as the rampant unreported trading of primary mercury. It is clear that task forces need to be set up to ensure that clandestine mines are closed, as well as providing crucial oversight of mercury mines that were operating legally prior to Mexico ratifying the Convention, which also requires enforcement of legislation regarding proper mercury waste management practices.

This includes the implementation of programs to ensure that workers exposed to dangerous levels of atmospheric mercury have access to personal protective equipment, as well as sufficient training and education to learn about new mining and processing technologies. In addition, more health monitoring of both miners and community members exposed to atmospheric Hg concentrations needs to be conducted, including investigation into potential medical issues suffered by newborn children.

On an economic front, before shutting down any mercury mines and putting vulnerable populations out of work, other alternatives need to be introduced, including new industries that create jobs in the region. As Rodríguez-Galeotti argued [44], conventional small or medium-scale mining of available minerals such as gold, silver, lead, antimony and zinc could be viably exploited, although it would still require adequate oversight and regulatory controls to avoid any negative environmental impacts to the Sierra Gorda Biosphere.

Another economic possibility is the idea of developing eco-tourism in the Biosphere, which constitutes the greatest ecosystem diversity found in Mexico. There are 1700 plant species, 30% of all of the butterfly species in the country and 600 vertebrate species, including black bears, macaws, spider monkeys, jaguars, mountain lion, bobcat, margay, ocelot and jaguarundi. However, in order to satisfy the demands and comfort level of tourists, the local infrastructure would have to improved, which would require significant investment by the State.

Although agriculture is currently practiced in the region, mainly for local consumption, selective crops with high export value like oregano and alfalfa could be exploited in a selective way, as well as expanding grape production for an incipient wine industry in Querétaro. However, as Hg concentrations in residential soils close to primary mercury mines have been found to be up to 150 times above the Mexican guideline [16], care would have to be taken to develop commercial agriculture in areas free from contamination, including verification of heavy metal concentrations in the soils and sediments. Tree-farming has also been raised as another possibility, but the poor soils of the desertic region pose a limiting factor for wide-spread success.

Since primary mercury mining has been practiced in the region for hundreds of years, there is also the challenge of social acceptance by locals to move away from this activity, to modify the current rudimentary practices, or to mine another kind of min-eral from known deposits in the region. In addition, as mercury miners can make up to 5 times the minimum wage, other economic activities need to be equally as lucrative to entice community endorsement. Shutting down the mercury trade not only affects the miners and their communities, but also the regional economic spin-offs that middlemen and the export supply chain support indirectly.

In order to curb unreported and illegal transfers of Mexican mercury to fuel its use in the AGM sector in countries like Bolivia, Peru and Colombia, it is necessary to understand the dynamics of the illicit trade, assemble inter-agency working groups, develop public-private partnerships, enhance the scale-up of anticorruption task forces, establish better cooperation with law enforcement and support non-governmental organizations on the ground.

In October 2018, the INECC in Mexico submitted a proposal for GEF funding titled "Reducing global environmental risks through the monitoring and development of alternative livelihood for the primary mercury mining sector in Mexico." The concept was approved in December 2018 for GEF funding totaling US $7,035,000 and co-funding of an additional US $51,068,844, although the project is still currently waiting to be implemented. However, once it finally gets underway, this kind of initiative shows excellent promise in being able to provide better oversight of the primary artisanal Hg sector in Mexico, as well as develop other economic alternatives for vulnerable populations.

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References

1. UNEP—United Nations Environment Programme. *Minamata Convention on Mercury: Text and Annexes*; UNEP: Nairobi, Kenya, 2013.
2. UNEP—United Nations Environment Programme. Reducing Mercury in Artisanal and Small-Scale Gold Mining (ASGM). 2019. Available online: https://web.unep.org/globalmercurypartnership/our-work/reducing-mercury-artisanal-and-small-scale-gold-mining-asgm (accessed on 25 September 2019).
3. Seccatore, J.; Veiga, M.M.; Origliasso, C.; Marin, T.; Tomi, G.D. An estimation of the artisanal small-scale production of gold in the world. *Sci. Total Environ.* **2014**, *496*, 662–667. [CrossRef] [PubMed]
4. Veiga, M.M.; Baker, R. *Protocols for Environmental and Health Assessment of Mercury Released by Artisanal and Small-Scale Gold Miners*; GEF/UNDP/UNIDO Global Mercury Project: Vienna, Austria, 2004; p. 289.
5. Betancourt, O.; Narváez, A.; Roulet, M. Small-scale gold mining in the Puyango River basin, southern Ecuador: A study of environmental impacts and human exposures. *EcoHealth* **2005**, *2*, 323–332. [CrossRef]
6. Marshall, B.G.; Veiga, M.M.; Kaplan, R.J.; Adler Miserendino, R.; Schudel, G.; Bergquist, B.A.; Guimarães, J.R.D.; Gonzalez-Mueller, C. Evidence of transboundary mercury and other pollutants in the Puyango-Tumbes River basin, Ecuador-Peru. *Environ. Sci. Proc. Impacts* **2018**, *20*, 632–641. [CrossRef] [PubMed]
7. Verbrugge, B. The economic logic of persistent informality: Artisanal and small-scale mining in the Southern Philippines. *Dev. Chang.* **2015**, *46*, 1023–1046. [CrossRef]
8. AMAP/UN Environment. Chapter 3: Methodology for Estimating Mercury Emissions. In *Technical Background Report for the Global Mercury Assessment 2018*; Arctic Monitoring and Assessment Programme: Oslo, Norway; UN Environment Programme, Chemicals and Health Branch: Geneva, Switzerland, 2019.
9. UN Environment. *Global Mercury Assessment 2018*; UN Environment Programme, Chemicals and Health Branch: Geneva, Switzerland, 2019.
10. Veiga, M.M.; Marshall, B.G. Teaching artisanal miners about mercury pollution using songs. *Extr. Ind. Soc.* **2017**, *4*, 842–845. [CrossRef]
11. U.S. Geological Survey—USGS. *Mineral Commodity Summaries 2020*; U.S. Geological Survey: Reston, VA, USA, 2020; p. 200.
12. Balifokus. IPEN Mercury Treaty Enabling Project, Indonesia. 2015. Available online: https://16edd8c0-c66a-4b78-9ac3-e25b63f72d0f.filesusr.com/ugd/13eb5b_e95e7961efb04b6e9248f446629036f2.pdf (accessed on 20 November 2020).
13. Balifokus. Mercury Trade and Supply in Indonesia. 2017. Available online: https://16edd8c0-c66a-4b78-9ac3-e25b63f72d0f.filesusr.com/ugd/13eb5b_bf0b2658eccf40cc9dbbb3a6514e9d64.pdf (accessed on 20 November 2020).

14. Martínez Arroyo, A.; Páramo Figueroa, V.H.; Gavilán García, A.; Martínez Cordero, M.A.; Ramirez Muñoz, T. *Asesoría para la Identificación de Desafíos, Necesidades y Oportunidades para Aplicar el Convenio de Minamata en México*; Instituto Nacional de Ecología y Cambio Climático: Mexico City, Mexico, 2017; p. 114.
15. UN Environment. *Global Mercury Supply, Trade and Demand*; United Nations Environment Programme, Chemicals and Health Branch: Geneva, Switzerland, 2017.
16. Camacho, A.; Van Brussel, E.; Carrizales, L.; Flores-Ramírez, R.; Verduzco, B.; Ruvalcaba-Aranda Huerta, S.; Leon, M.; Díaz-Barriga, F. Mercury mining in Mexico: I. community engagement to improve health outcomes from artisanal mining. *Ann. Glob. Health* **2016**, *82*, 149–155. [CrossRef] [PubMed]
17. Lim, H.E.; Shim, J.J.; Lee, S.Y.; Lee, S.H.; Kang, S.X.; Jo, J.Y.; In, K.H.; Kim, H.G.; Yoo, S.H.; Kang, K.H. Mercury inhalation poisoning and acute lung injury. *Korean J. Intern. Med.* **1998**, *13*, 127–130. [CrossRef] [PubMed]
18. World Health Organization. Exposure to mercury. In *Public Health and Environment*; World Health Organization: Geneva, Switzerland, 2007.
19. Park, J.-D.; Zheng, W. Human exposure and health effects of inorganic and elemental mercury. *J. Prev. Med. Health* **2012**, *45*, 344–352. [CrossRef] [PubMed]
20. National Institute of Statistics and Geography. *Economic Census Data, Mexico in Figures*; National Institute of Statistics and Geography: Mexico City, Mexico, 2019.
21. Servicio Geológico Mexicano. *Anuario Estadístico de la Minería Mexicana*; Servicio Geológico Mexicano: Mexico City, Mexico, 2018.
22. Martínez Arroyo, A.; Páramo Figueroa, V.H.; Gavilán García, A.; Martínez Cordero, M.A.; Ramirez Muñoz, T. *Generar Información Cualitativa y Cuantitativa de las Fuentes Minero-Metalúrgicas en México*; Instituto Nacional de Ecología y Cambio Climático (INECC): Mexico City, Mexico, 2017; p. 217.
23. Instituto Nacional de Ecologia y Cambio Climático (INECC). Anexo de la decisión MC-1/8. Formato de presentación de informes del Convenio de Minamata sobre el Mercurio. In *Información Sobre las Medidas que se han de Adoptar para Aplicar las Disposiciones del Convenio, la Eficacia de Esas Medidas y las Dificultades con que se ha Tropezado*; Instituto Nacional de Ecología y Cambio Climático (INECC): Mexico City, Mexico, 2019. [CrossRef]
24. Velasco Mireles, M. El mundo de la Sierra Gorda. *Arqueol. Mex.* **2006**, *13*, 28–37.
25. Castro Díaz, J. *An Assessment of Primary and Secondary Mercury Supplies in Mexico*; Commission for Environmental Cooperation: Montreal, QC, Canada, 2013.
26. González-Reyna, G. *Riqueza Minería y Yacimientos Minerales de México*; Monografias Industriales del Banco de México, S.A.: Ciudad de México, Mexico, 1947.
27. Camargo, J.A. Contribution of Spanish–American silver mines (1570–1820) to the present high mercury concentrations in the global environment: A review. *Chemosphere* **2002**, *48*, 51–57. [CrossRef]
28. Consejo de Recursos Minerales. Monografía geológico-minera del estado de querétaro. In *Serie Monografías Geológico Mineras (in Spanish)*; Secretaría de Energía, Minas e Industria Paraestatal: Ciudad de Mexico, Mexico, 1992.
29. Consejo de Recursos Minerales. Monografía geológico-minera del estado de zacatecas. In *Serie Monografías Geológico Mineras*; Secretaría de Energía, Minas e Industria Paraestatal, Consejo de Recursos Minerales: Ciudad de México, Mexico, 1991. (In Spanish)
30. UAQ-UASLP. *Plan de Desarrollo Humano y Tecnológico, Sostenible, Para la Zona Produtora de Mercurio del Estado de Querétaro*; Universidad Autónoma de Querétaro, Universidad Autónoma de San Luis Potosí: Queretaro Santiago, Mexico, 2016.
31. UN Comtrade. United Nations Statistical Division. 2020. Available online: http://comtrade.un.org/ (accessed on 15 August 2020).
32. Sistema de Información Arancelaria Via Internet. Available online: http://www.economia-snci.gob.mx/ (accessed on 28 August 2020).
33. World Health Organization. *Chapter 6.9 Mercury, Air Quality Guidelines*; WHO Regional Office for Europe: Copenhagen, Denmark, 2000.
34. International Programme on Chemical Safety. *Concise International Chemical Assessment Document 50: Elemental Mercury and Inorganic Mercury Compounds: Human Health Aspects*; World Health Organization: Geneva, Switzerland, 2003.
35. Spiegel, S.J.; Agrawal, S.; Mikha, D.; Vitamerry, K.; Le Billon, P.; Veiga, M.; Konolius, K.; Paul, B. Phasing out mercury? Ecological economics and indonesia's small-scale gold mining sector. *Ecol. Econ.* **2018**, *144*, 1–11. [CrossRef]
36. Maxson, P. Mercury Material Flow: Supply, Demand and Trade. Available online: http://www.mercuryconvention.org/News/fromtheConvention/MOFlowTrade/tabid/8570/language/en-US/Default.aspx (accessed on 29 September 2020).
37. Mercado Libre Mexico. Available online: https://www.mercadolibre.com.mx/ (accessed on 10 November 2020).
38. International Labour Organization. Informal employment in Mexico: Current situation, policies and challenges. Notes on formalization. In *Programme for the Promotion of Formalization in Latin America and the Caribbean (FORLAC)*; International Labour Organization: Geneva, Switzerland, 2014.
39. Reuters. *Mexico Loses 12 Million Jobs, Workers in Informal Sector Grow*. Available online: https://nationalpost.com/pmn/health-pmn/mexico-loses-12-million-jobs-workers-in-informal-sector-grow (accessed on 10 November 2020).
40. Environmental Protection Agency. *Risk Assessment Guidance for Superfund Volume I: Human Health Evaluation Manual (Part F, Supplemental Guidance for Inhalation Risk Assessment)*; Office of Superfund Remediation and Technology Innovation, EPA: Washington, DC, USA, 2009.

41. Camacho, A.; Rebolloso, C.; Carrizales, L.; Van Brussel, E.; Flores, R.; Díaz-Barriga, F. *Minería Artesanal de Mercúrio—Riesgos en Salud*; University of San Luis Potosí (UASLP): San Luis Potosi, Mexico, 2016.
42. US Centers for Disease Control and Prevention (CDC). *Third National Report on Human Exposure to Environmental Chemicals*; CDC: Atlanta, GA, USA, 2005.
43. Goldman, L.R.; Shannon, M.W. Technical report: Mercury in the environment: Implications for pediatricians. *Pediatrics* **2001**, *108*, 197–205. [CrossRef] [PubMed]
44. Rodríguez-Galeotti, E. La minería de mercurio en México. Boletín de Mineralogía. In *Quadrum Metals & Minerals*; Universidad Autónoma del Estado de Hidalgo, Academia de Ciencias de la Tierra: Pachuca, Mexico, 2006; Volume 17, pp. 29–36.