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Review

A systematic review on the management and treatment of mercury in artisanal gold mining

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HIGHLIGHTS

- Many interventions try to remove mercury in artisanal gold mining.
- This review found social, technical, environmental aspects must be considered.
- A systematic review determined barriers involved with current solutions.
- Removing mercury in AGM requires a comprehensive approach.
- Technology, education, mineralogy, and government support are needed.

GRAPHICAL ABSTRACT

Solutions addressing mercury in artisanal gold mining must be comprehensive.

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ABSTRACT

Artisanal gold mining (AGM) continues to be a pervasive global health issue. While there are various problems associated with AGM, mercury exposure is the primary hazard contributing to adverse health effects in exposed human populations. Over the last several decades, many interventions have been developed and implemented to curb mercury emissions and releases, notwithstanding a comprehensive review of context specific effectiveness. A systematic review was conducted in order to specifically assess the impact of current mercury interventions within the AGM sector worldwide. To aid in this review, a resource pool of information on AGM and mercury, treatment and management of emissions and releases, and interventions was assembled through a search conducted via multiple search engines. This search determined that there have been many strategies used to reduce or eliminate mercury, through interventions or programs focusing on education, processing centers, or mercury alternative techniques. Education has focused on environment or health awareness or more specifically on cleaner or alternative techniques. Processing centers offered artisanal miners rudimentary equipment for grinding and amalgamation that extract less than 30% of the gold as an exchange for their tailings. Some techniques reduced mercury releases including retorts, mill leaching, vat-leaching, and others replaced mercury from the process such as magnets, direct smelting, sluices, and borax. There are both positive and negative outcomes associated with every intervention. Novel and comprehensive strategies—including mercury removal technology, miner education on mercury hazards, economic gains, and policy—are needed to address mercury public health issues associated with AGM.

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Contents

1. Introduction

Artisanal gold mining (AGM) is an extractive sector that has managed to not only maintain its presence across decades but has also grown. This situation has occurred for a variety of reasons: 1. mining can occur independently; 2. the unfaltering market value of gold; and 3. ease and accessibility of technology applied. AGM has evaded cultural differences and is a viable resource worldwide. In fact, the combination of these factors has contributed to the widespread adoption and use of AGM. There are approximately 50 million people involved in the sector in approximately 70 different countries (Telmer and Veiga, 2009; Veiga and Baker, 2004).

The main problem with this type of mining is that miners use mercury to extract gold from ore. Amalgamation by mercury is an inexpensive, easily accessible, and uncomplicated procedure that extracts an adequate amount of gold from ore, thereby economically sustaining the lives of participants (Spiegel et al., 2006). Unfortunately, AGM has numerous problems associated with it that directly stem from mercury use through emissions and exposures. Both human health and environmental ramifications exist from mercury use. The environment is affected through high levels of river siltation and mercury pollution in sediment and soil (Lebel et al., 1995, 1998; Taylor et al., 2005; Babut et al., 2003). On the other hand, exposed human populations can suffer from chronic or acute exposure to mercury, which may result in dose-dependent adverse health effects. Acute, low-dose exposure to mercury can lead to respiratory symptoms such as chest pains, dyspnea, cough, hemoptysis, impairment of pulmonary function, and interstitial pneumonitis; while acute, high-dose exposure can be fatal or lead to permanent damage within the central nervous system (EPA, 2011; Poulin et al., 2008). Perhaps more common in AGM are chronic, low to moderate-dose exposure levels, which are characterized by less pronounced symptoms such as fatigue, irritability, loss of memory, vivid dreams, and depression (EPA, 2011). These varying degrees of adverse health effects provide evidence to the toxic nature of mercury exposure, in general, and specifically in the field of AGM.

Millions of dollars have been spent on sector-specific policies and regulations for decreasing mercury emissions (Hilson, 2008). In 2007, most of this funding (e.g. from United Nations, The World Bank, Global Environmental Facility, German Technical Cooperation Agency, and GiZ) had failed to facilitate marked improvements regulating mercury and miners continue to be exposed to potentially hazardous levels of mercury (Hilson, 2008). Since then, it is likely that additional interventions have attempted to decrease and eliminate mercury emissions; however, information on the effectiveness of recent efforts have not been reviewed in its entirety and disseminated. One study (see Davies, 2014) reviewed alternative solutions to mercury removal in AGM, although this review did not follow a rigorous search of the literature (e.g. only included a few studies, information was dated beyond the current scope of knowledge, etc.). Therefore, the state of research regarding attempted or potential solutions addressing mercury in AGM continues to be ill-defined (Hilson, 2009). Thus, the goal of this review was to comprehensively evaluate current efforts aimed at managing and treating mercury emissions or releases in AGM. These interventions were then analyzed in order to understand economic and context-specific dimensions pertaining to each effort, and to understand the sustainability and transferability of each intervention from a worldwide perspective.

2. Methods

A search was conducted and included relevant published scientific literature using ProQuest, JSTOR, Springer Link, ScienceDirect, and Sage Journals website. The search was designed to identify any studies on the management or interventions developed to address mercury emissions within the AGM sector. Search terms included: “small mining” or “small scale mining” or “small artisanal gold mining” or “artisanal mining” or “artisanal gold mining” or “mercury” or “alternative” or “alternatives” or “solution” or “solutions”. The search was date restricted to gather articles from January 2007 to December 2017, in order to retain current data—or within the last ten years. The search was not restricted by language. References cited in identified articles were also reviewed. Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines were used for reporting the search and selection of results. All references were imported into an EndNote Library and duplicates were removed manually within EndNote leaving a total of 5492 results (5482 from electronic databases and 10 from hand-searching). A two-stage screening method was conducted, where titles alone were screened first, followed by screening of titles and abstracts of those not rejected in the first stage (Mateen et al., 2013). The researchers then reviewed the full-text of articles uncovered by the search. Any discrepancies were resolved through discussion until consensus was reached. The criteria for studies included any intervention or program that ultimately sought to curb mercury emissions and releases. Some studies were theoretical or lab-based, but those were included as well, as long as they were specific to AGM. Gathered information for each study included the reference and year of publication, location of the intervention, type of intervention, purpose of the study and brief description on the results. The brief description was used to describe how the intervention worked, the benefits of it, and the negative aspects. Gold extraction gains and emissions reduction were also included to enhance the cost-benefit associated with the intervention. The expectation was that the culmination of these factors would highlight interventions and context-specific traits that could contribute to future effective implementation and change.

Our literature search identified 28 applicable studies, which focused on varying methods of addressing mercury exposure by managing, educating, or providing alternative methods to mercury usage (Fig. 1). Six articles were excluded from inclusion in the review (Jonsson et al., 2013; Nyanza et al., 2017; Balzino et al., 2015; Davies, 2014; Teschner et al., 2017; Hylander et al., 2007). The first article was a discussion on some mercury-free alternatives, but while this article was not included, it was hand-searched for potential articles that met the criteria in the present review. The second eliminated article discussed the appropriateness of retorts, but did not evaluate the success of any particular retort project. The third eliminated article focused on describing the gold recovery process using mercury amalgamation and did not include an intervention. The fourth eliminated article focused on knowledge and adherence to the cyanide code among small-scale gold miners. The fifth and sixth articles that were excluded from this review discussed the effectiveness of two sluicing methods. The total final review included 22 studies (Table 1).

2.1. Limitations

This review focused solely on interventions or programs addressing mercury emissions or exposures from AGM; moreover, additional exposures (e.g. cyanide), health outcomes, or other environmental contamination issues were not specifically addressed. Information was assessed based on the overall success of the project in the study along with negative or challenging factors associated with it. While the location of the study was gathered, it should be noted that public health infrastructure, as well as the economic and political state of affairs within each country are difficult to categorize and assess and were removed from consideration in this review; it should be noted that these aspects could be considered primary contributors in the success or failure of projects. Lastly, the burden of AGM at a population level remains limited to the scope of interventions evaluated and may not fully determine the comprehensive nature of this issue.

3. Results

The reviewed studies (n = 22) occurred in various locations, including Brazil, Lao PDR, Sudan, Mozambique, Zimbabwe, Tanzania, Ecuador, Bolivia, Nicaragua, Peru, Colombia, Indonesia, Philippines, and Ghana. All of the studies took place between 2007 and 2017. Each study focused on a specific type of intervention or program controlling or decreasing mercury emissions or releases. Interestingly and perhaps some knowledge on the depth of the AGM situation, there were different viewpoints on how best to address mercury exposure. Some of these interventions focused solely on the education regarding adverse health and environmental effects, while others focused on the removal of mercury from the process completely. Most of these interventions had both positive and negative aspects associated with them. Financial outcomes (e.g. gold extracted) were also evaluated and confirmed that these also were associated with some level of variation, depending on the intervention.

3.1. Educational interventions

Educational interventions were proposed and implemented in study sites located in Mozambique, Indonesia, Lao PDR, Sudan, Tanzania, Brazil, Zimbabwe, Ecuador, Peru, and Colombia. These educational interventions focused on providing awareness on AGM and mercury exposure and demonstration of cleaner technologies; however, the

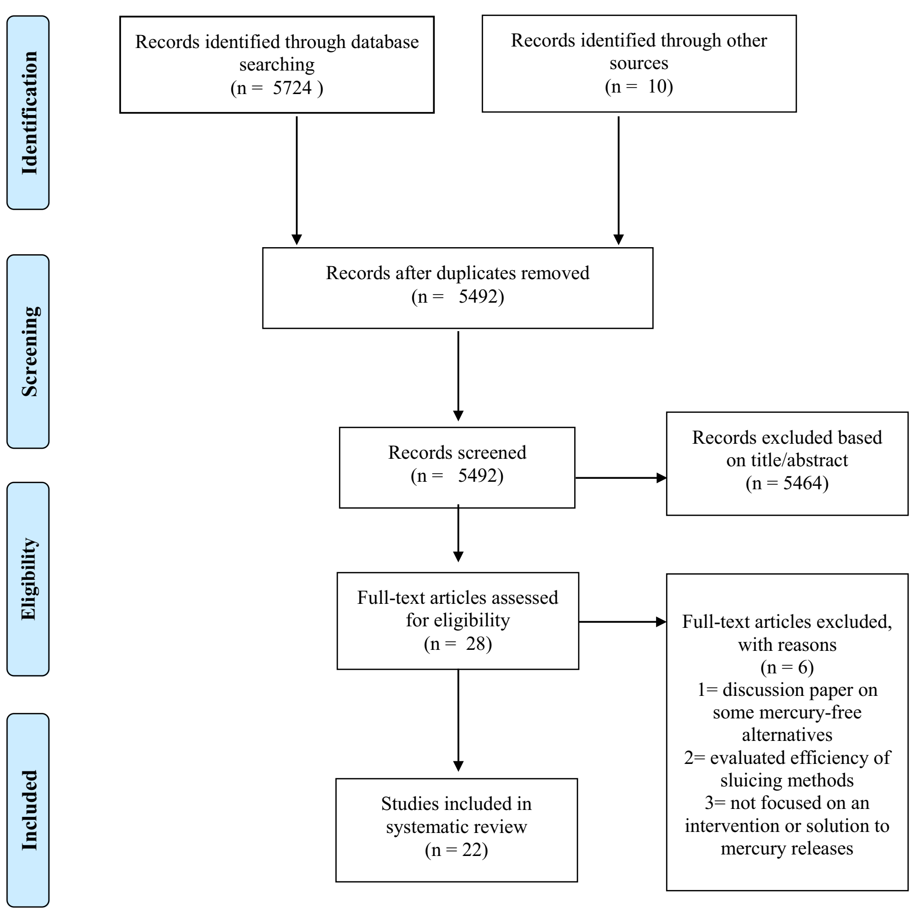

Fig. 1. PRISMA flow chart: study selection for systematic review of interventions or program to control or reduce mercury emissions.

Table 1
Solutions targeting mercury in AGM.

Education			
Intervention	Source(s)	Location(s)	Level of success (successful, fairly successful, fairly unsuccessful, unsuccessful)
Awareness/demonstration	Sousa and Veiga, 2009 Shandro et al., 2009 Veiga et al., 2015 Garcia et al., 2015 McDaniels et al., 2010	Brazil, Mozambique, Peru, Colombia, Indonesia, Lao PDR Sudan, Tanzania, Zimbabwe, Ecuador	Fairly successful
Didactic theatre	Metcalf and Veiga, 2012	Zimbabwe	Fairly unsuccessful
Parody songs	Veiga and Marshall, 2017	Colombia, Peru, Ecuador	Fairly successful
Processing centers	Veiga et al., 2014a Velasquez-López et al., 2010 Goncalves et al., 2017	Nicaragua, Peru, Colombia, Indonesia, Ecuador	Fairly unsuccessful
Techniques to reduce mercury releases			
Intervention	Source(s)	Location(s)	Emissions reduction
Retorts	Jonsson et al., 2009	Tanzania	80%
Vat leaching using gravity concentration prior to cyanidation	Sousa et al., 2010	Brazil	100%
Mill leaching	Veiga et al., 2009	Ecuador	100%
Alternative techniques to mercury amalgamation			
Intervention	Source(s)	Location(s)	Extraction efficiency
Magnets	Drace et al., 2012	Mozambique	89–93%
Borax	Appel and Jønsson, 2010 Appel and Na-Oy, 2014 Appel and Na-Oy, 2013 Appel and Na-Oy, 2012 Steckling et al., 2014	Philippines, Indonesia, Tanzania, Bolivia and Zimbabwe	Two to three times more than mercury in 30% less time
Direct smelting of gold concentrates	Amankwah et al., 2010 Styles et al., 2010	Ghana	98.3% in 45 min
Cyanidation	Velasquez-López et al., 2011 Veiga et al., 2009	Ecuador	93% in 6 h 95% in 8 h

knowledge presented varied in each study. Shandro et al. (2009) focused primarily on technique demonstrations in gold recovery and production alongside information focusing on mercury as a hazard and adverse health effects. Sousa and Veiga (2009) presented a more comprehensive program with cleaner techniques available and offered varying tools (e.g. retorts, hammer mill, ball mill, etc.) with a focus more so on mercury reduction indicators, relying less on environment, health, sanitation, and gold recovery outcomes. Veiga et al. (2015) took a different approach and delivered theoretical classes on topics such as cleaner technologies, mineralogy, health and safety in mines, policy and regulations, and training on more efficient techniques (e.g. gravity concentration, flotation and cyanidation) in a demonstration plant to train Peruvian miners. A similar approach was used by Garcia et al. (2015) in the Colombia Mercury Project to educate and train Colombian miners in a demonstration plant, along with enforcement from local authorities. Another project was the Global Mercury Project (GMP) that was implemented in six pilot sites in countries such as Brazil, Indonesia, Lao PDR, Sudan, Tanzania, and Zimbabwe (McDaniels et al., 2010). This project consisted on health awareness and technology demonstration campaigns delivered to miners and community members to reduce mercury exposure and releases (McDaniels et al., 2010). For example, some strategies used were transportable demonstration units (TDUs) to deliver trainings, field demonstration of technologies, and promotional programs discussing the health and environmental consequences of mercury (e.g. booklets, brochures, advertisement and radio programs) (McDaniels et al., 2010).

Two other studies used unconventional methods to educate miners on mercury use. Metcalf and Veiga (2012) used a street theatre program to raise awareness on mercury hazards. This didactic program consisted of street performances focused on the hazards of mercury use followed by discussions, trainings, and demonstrations with the local miners on safe mercury use and more efficient gold recovery methods (e.g. retorts) (Metcalf and Veiga, 2012). In the same vein, Veiga and Marshall (2017) used parody songs as a simple way to educate miners about the environmental and health impacts of mercury use in hopes to promote positive changes in gold recovery practices.

Because of the incomparable nature of the results, it was difficult to determine which program achieved more success, though Veiga et al. (2015) and Garcia et al. (2015) used a similar approach and reported significant reductions in mercury levels. Veiga et al. (2015) reported that three years after the project began mercury concentrations the region were reduced by approximately 50%. Garcia et al. (2015) reported that the project reduced 43% of mercury entering the whole ore amalgamation in the gold processing centers and 63% of mercury losses in the amalgamation process from 2010 to 2013. This resulted in 46 to 70 t/a less mercury lost to the environment. Sousa and Veiga (2009) reported that annual mercury emissions had been reduced by 10% because of the 120-day training. Shandro et al. (2009) reported several changes necessary to garner lasting changes in miners including more decision power, accessible equipment, and increased gold recovery, thus suggesting less applicability and less program success. Metcalf and Veiga (2012) reported limited success due to the unstable economic and political environment in Zimbabwe; however, the program brought awareness on safer mercury use to nearly 9000 people and 700 miners were trained on safer gold recovery methods. McDaniels et al. (2010) reported that the GMP was successful in training 300 trainers who educated over 30,000 miners and community members in six countries on cleaner mining technologies (e.g. retorts and fume hoods), and the environmental and health impacts of mercury. The use of transportable demonstration units increased the transferability and sustainability of this project, by enabling access to more miners, and easier implementation (McDaniels et al., 2010). Moreover, in some pilot sites such as Tapajos basin in the Amazon of Brazil, survey data showed that 90 days after implementing training, 90–100% of miners were still following the program guidelines for cleaner and sustainable mining practices (McDaniels et al., 2010). Lastly, Veiga and Marshall (2017) reported successfully using parody songs to teach artisanal miners about the impacts of mercury pollution in Ecuador, Peru, and Colombia, though this level of success was not quantified in any manner.

3.2. Processing centers

Processing centers offer rudimentary crushing, grinding, and amalgamation equipment to artisanal miners to process their ore, reaching a gold recovery of less than 30% (Veiga, 2011). In order to offer payment in exchange for services rendered, miners leave their tailings in the centers to be further processed by cyanidation to extract residual gold (Veiga, 2011). Historically, processing centers have been effective in reducing mercury discharges into the environment by discouraging miners from using mercury in their operations and moving tailings disposal to a centralized center (Veiga et al., 2014a). That said, the newer adaptation of processing centers more frequently provides inefficient processing techniques to miners, though output does depend on implemented techniques and technology (Veiga et al., 2014a; Veiga, 2011). In this review, the studies focused on processing centers with varying ore to amalgam techniques. The Chilean-mill—where ore is ground, concentrated, and amalgamated—and a Chancha center—where whole ore is amalgamated—were implemented in several countries (Velasquez-López et al., 2010).

Veiga et al. (2014a) conducted a general review of processing centers in Nicaragua, Peru, Colombia, Indonesia, and Ecuador, while Velasquez-López et al. (2010) and Goncalves et al. (2017) focused specifically on processing centers in Ecuador. It was determined that processing centers were not only inefficient in amalgamating gold, but also resulted in additive environmental waste exposure due to the combination of mercury and cyanide (Velasquez-López et al., 2010; Veiga et al., 2014a). Velasquez-López et al. (2010) reported that 22.9% of mercury is lost in processing centers when whole ore is amalgamated, while only 1.4% of mercury is lost in tailings when miners amalgamate only gravity concentrates—or concentrated gold product after using the difference between gold gravity and gangue minerals (Veiga et al., 2006).

When comparing the two studies conducted in Ecuador in 2008 and 2013 in terms of mercury losses from the amalgamation of the whole ore and leftovers, a 28.4% reduction of initial mercury use was observed, which resulted in approximately 16% less total mercury being lost (Goncalves et al., 2017; Velasquez-López et al., 2010). Velasquez-López et al. (2010) reported an average of 48.3% total mercury lost from an average of 356.3 g or mercury entering the Chanchas, whereas Goncalves et al. (2017) reported an average of 32.2% total mercury lost from an average of 255.3 g of mercury. Goncalves et al. (2017) reported that the reduction in mercury loss was likely due to improved knowledge in the processing of ore and better understanding that excessive use of mercury is unnecessary and inefficient. Moreover, Velasquez-López et al. (2011) reviewed how the Merrill-Crowe—the process using filters and vacuums that separates gold from solution through cyanide leaching—and Carbon-in-pulp (CIP)—gold extraction process using cyanide in tanks where leaching is followed by adsorption—could modify mercury discharge during cyanidation of mercury-rich tailings in processing centers through trapping and dissolution techniques. CIP process increased the percentage of dissolved mercury by 31% and Merrill-Crowe by 15% (Velasquez-López et al., 2011).

Mercury amalgamation is the most common process used in AGM. This technique uses mercury combined with gold-containing ore, which forms an amalgam that dissolves and extracts the gold from the silt. Mercury exposure is associated with this processing technique, hence the reason many alternatives exist in AGM. Solutions suggested and implemented by the reviewed studies included techniques to reduce mercury releases (i.e. retorts, mill leaching, vat-leaching), and alternative techniques that replace mercury (i.e. cyanidation and borax). All of these interventions were implemented in various countries, but the success of some of these projects relied specifically on the environment (e.g. composition of ore).

3.3. Techniques to reduce mercury releases

Some methods were created to reduce occupational exposure to mercury. Retorts are an example, wherein amalgam is placed at the end of a plug and the mercury in the amalgam vaporizes and condenses in the tube during the heating process (Jonsson et al., 2009). Jonsson et al. (2009) employed the use of retorts in Tanzania, where five months after project initiation, 18 of 20 miners had removed all suspicions regarding gold loss and continued using their retorts, recycling 10 k of mercury.

Mill and vat leaching are used to leach gravity or flotation concentrates in small ball mills. Vat leaching seeks to replace mercury by applying a lixiviant (e.g. cyanide, thiourea, bromine, iodine, etc.) to percolate a static bed or ore. This is typically an inexpensive method used by processing centers to extract gold from mercury contaminated tailings. This process is better than many other classical cyanidation techniques and it is faster because of the grinding process used in gold dissolution as well as using hydrogen peroxide that decreases time for gold leaching; however, this process requires knowledge on chemistry, an investment in equipment and reagents, and the education of miners on the risks of cyanide (Veiga et al., 2009). Sousa et al. (2010) proposed gravity concentration prior to cyanidation in the ball mill to replace amalgamation in the process. An advantage of this process was the reduction in operating costs and time, as traditional vat leaching can last over 20 days to finalize the extraction process recovering 50% of gold, while gravity concentration can finish in approximately 24 h and can recover up to 98% of the gold in the concentrate (Sousa et al., 2010). Gravity concentration reduced the mass of material that needed to be amalgamated by mercury or leached with cyanide. However, this process was more relevant to mine owners and associations, as it required an investment in equipment that many artisanal miners could not afford (Sousa et al., 2010).

3.4. Alternative techniques to mercury amalgamation

Another solution replaced mercury by cyanidation in the ball mill, which causes gold to react with the cyanide and dissolve into the solution. This technique reported achieving gold extraction up to 93% in 6 h of leaching and 95% in 8 h of leaching compared to approximately 30% using mercury (Veiga et al., 2009). This was a simple and inexpensive process which drastically increased gold recovery without the investment of new equipment (Veiga et al., 2009). The amount of gold extracted through these processes was an economic benefit to miners; however, a challenge with this technique revolved around the organization of miners and division of work in mining sites, as many artisanal miners were not actually conducting the cyanidation process (Veiga et al., 2009).

Finally, interesting novel techniques were proposed to eliminate mercury entirely from AGM. The methods included using magnets, the direct smelting of gold concentrates, and borax as mercury alternatives. These studies were primarily conducted as pilot or field trials. Drace et al. (2012) employed magnets to remove gangue materials in Mozambique, resulting in 89–93% pure gold, mostly due to the mineralogy of the ore in the area. This study was conducted in a privately-owned mine where workers received salaries not commensurate upon gold recovery, suggesting low practicability and replicability of this method to other mining sites (Drace et al., 2012). That said, the project was quite successful, which was attributed to the organization of the privately owned mine alongside having access to specific resources (e.g. stable working conditions, consistent income, safety equipment, etc.) as well as the mineralogic conditions of the area, and the mine owner's awareness about the impact of gold mining on the health of employees, the environment, and the local community (Drace et al., 2012). Appel and Jønsson (2010) used another novel technique in Tanzania, replacing mercury with borax to purify gold concentrates. They reported that borax could recover up to twice as much gold as when used in the amalgamation process, without any additional knowledge or equipment used (Appel and Na-Oy, 2014; Appel and Jønsson, 2010). Appel and Na-Oy (2012) also implemented the borax method in the northern Philippines and reported that the borax method was almost three times more efficient in recovering gold compared to mercury amalgamation. While borax appeared to be a viable solution, it can only be used on ore deposits with visible gold, thus confirming poor transferability of the method (Appel and Na-Oy, 2014; Appel and Na-Oy, 2013). More than that, artisanal miners remained unconvinced the borax method had higher gold recovery rates than mercury amalgamation (Appel and Na-Oy, 2014; Appel and Jønsson, 2010; Steckling et al., 2014). Appel and Jønsson (2010) reported that materials used in the process were expensive (acetylene gas) and were not readily available in the region (borax); consequently, lack of resources affect the adoption and success of this technique. Moreover, the process would also only be useful in areas with specific ores, such as those without sulfides, and for miners who were only producing small amounts of gold per day (Veiga et al., 2014b). That said, this mercury-free method did successfully extract up to twice as much gold in the same amount of time as amalgamation in small-scale sites located in the Philippines, Indonesia, Tanzania, Bolivia, and Zimbabwe (Appel and Na-Oy, 2014; Appel and Jønsson, 2010). Demonstration projects and training programs are needed to provide evidence of technique effectiveness in gold recovery, to increase environmental awareness, and to maintain technical support from government authorities to guide miners in adoption of the borax method (Appel and Na-Oy, 2014; Appel and Jønsson, 2010). Lastly, Amankwah et al. (2010) used direct smelting, which replaces the need for amalgamation and retorts, in Ghana as an alternative to mercury amalgamation. In laboratory tests, direct smelting yielded 99.8% gold recovery compared to 97% for mercury amalgamation (Amankwah et al., 2010; Styles et al., 2010). A locally-fabricated furnace averaged 98.3% gold recovery in a shorter time compared to 88% for amalgamation, being more cost-effective (Amankwah et al., 2010; Styles et al., 2010). Though, this technique was not efficient for samples with low gold content (Amankwah et al., 2010). This field trial had many problems associated with it, including the interference of free metallic compounds in scavenged material, grinding surfaces mixed in the concentrate, the chamber needed improved ventilation, waste acid must be neutralized, and crucibles cracked during smelting (Amankwah et al., 2010). Another limitation of direct smelting was that the fuel used—charcoal—was not environmentally friendly, but was cheap, easily accessible, and of high calorific value (Amankwah et al., 2010). Thus, an alternative fuel should be identified to replace charcoal in this process.

4. Discussion

The present review found a total of 22 articles about interventions or solutions used to manage and treat mercury emissions or releases in AGM, confirming the limited scientifically-conducted research on this topic in the last decade. This outcome may be a result of: 1) the primary focus on research assessing the harmful effects of mercury exposure on AGM-miners, —communities and –environment (water, air, soil), and 2) the oversight of the AGM sector in policy, economic development, and project/program implementation efforts in many countries (Hilson and McQuilken, 2014; McDaniels et al., 2010). Nevertheless, the studies included in this systematic review provide important information to understand the sustainability and transferability of interventions to manage and treat mercury in AGM worldwide.

Mercury is used to extract gold from ore; thus, mercury exposure occurs in AGM. Because mercury affects population health, many interventions have been implemented to curb the rates of exposure. Results determined positive and negative outcomes associated with every intervention, thereby confirming the fact that a single solution managing and treating mercury currently does not exist. Techniques for alternative method practices should be designed with a myriad of factors in mind (e.g. populations at risk, availability and accessibility of materials (e.g. cyanide), amount of government support for regulations and policy, etc.). That said, after a review of the literature, there were four main barriers that arose with these interventions: 1. complexity of intervention, 2. mineralogy, 3. economic gains, and 4. social aspects. Ultimately, these core barriers need to be considered before successful implementation of interventions can take place and mercury exposure is addressed. Moreover, these aspects are merely those experienced on the ground and ultimately, change in AGM needs to occur on a multitude of levels and include policies, strategies, and "adopted standards" worldwide to decrease mercury exposure from AGM.

4.1. Complexity of interventions

While created with good intentions, there were several interventions that were too difficult to implement. The intervention either needed to be supplemented with additional education or used processes that required many steps that were difficult to follow. Some of these included nearly every intervention with cyanide as well as vat leaching. In addition, miner education also needed to highlight how much gold was actually recovered during the processes, as this appeared to be a common theme with miners who used retorts or the borax replacement alternative technique.

In many mercury reduction techniques, miners needed to retain necessary knowledge and exposure awareness before appropriately implementing the proposed techniques (Jonsson et al., 2009; Sousa et al., 2010; Velasquez-López et al., 2011). For example, the cyanidation process is typically conducted by operators in the processing centers, while artisanal miners are offered less efficient techniques (e.g. amalgamation) in exchange for their mercury contaminated tailings (Veiga et al., 2009). This leads to the use of cyanide and mercury in the same process, which commonly results in the pairing of mercury with cyanide contributing to twice the amount of hazardous exposures (Veiga et al., 2009). Lack of awareness, knowledge, and understanding for the gold recovery process contribute to the mixing of mercury and cyanide (Velasquez-López et al., 2011). Velasquez-López et al. (2011) reviewed how the Merrill-Crowe and Carbon-in-pulp (CIP) methods could modify mercury discharge during cyanidation of mercury-rich tailings through trapping and dissolution techniques, but the additional solutions used to minimize mixing also likely required sufficient education to complete them.

Besides cyanide, other alternative replacements for mercury were proposed, used, and tested. These types of alternatives included vat-leaching, magnets, direct smelting of gold, and borax amalgamation. These techniques focused on removing or reducing mercury from AGM. One primary proposed solution was leaching. Leaching appeared to be a useable process, though each study suggested that miners must have proper education on the system before implementing these techniques, such as knowledge on chemistry, an investment in equipment and reagents, and the education of miners on the risks of cyanide (Veiga et al., 2009; Sousa et al., 2010). Amankwah et al. (2010) suggested that direct smelting could replace mercury and retorts because of its ease of use and transparency; unfortunately, many problems arose primarily because of the free metallic components that interfered with the smelting process (Amankwah et al., 2010; Styles et al., 2010). Thus, this process again became too complex and needed to be fine-tuned and re-examined before being implemented on a larger, more realistic scale.

4.2. Economic gains

Some interventions were not widely accepted because the miners did not believe that the process removed as much gold as possible. For example, retorts have been commonly used as interventions in AGM, though retorts do not remove mercury, but rather provides a method that seeks to control mercury emissions. This system has been widely implemented, as it is simple, inexpensive, and recovers about 95% of mercury emissions (Babut et al., 2003; Hinton et al., 2003). However, miners have yet to adopt this technique because of the efficiency for gold recovery from mercury (Hilson, 2006). Miners remain unconvinced that the same amount of gold is recovered from this process, which in turn results in less money.

Large-scale processing centers offer simple techniques (e.g. amalgamation) at no cost or a low fee in exchange for mercury contaminated tailings, which are later processed using better techniques (e.g. cyanidation) to recover additional gold from the ore (Velasquez-López et al., 2010; Veiga et al., 2014a). This discrepancy—in terms of technology and mining methods—affects the introduction of cleaner technologies, as miners are limited to basic methods and simple technologies (Veiga et al., 2014a). In addition, immediate payment for gold recovered through amalgamation as well as time spent during processing were factors creating resistance in the adoption of cleaner techniques (Veiga et al., 2014a). The lack of knowledge about mineralogical characteristics of the ore and the simple technologies offered to miners in processing centers affect gold recovery and also increase the use of mercury during amalgamation (Velasquez-López et al., 2010). Miners extracted less than 30% of gold using amalgamation in the processing centers (Velasquez-López et al., 2010; Veiga et al., 2014a). This was a serious loss of financial revenue for miners using these centers. Despite these losses, miners continued to sell ore to processing centers because of lack of capital to obtain equipment and lack of water and electricity services (Veiga et al., 2014a). However, cleaner technologies used in processing centers could be brought to the attention of miners; unfortunately, lack of knowledge, technical skills, and low capital hinder the adoption of these technologies (Velasquez-López et al., 2010; Veiga et al., 2014a; Veiga, 2011). Also, hidden interests of local processing centers may be limiting the spread of information on more efficient techniques and the formalization and growth of AGM miners (Veiga, 2011).

4.3. Mineralogy

Some interventions have used completely different materials to replace mercury in the gold extraction process. Magnets and borax were proposed and employed as mercury replacement alternatives. These both appeared to be efficient in eliminating mercury and recovering gold, although a specific type of ore was needed, thereby restricting these types of interventions (Appel and Na-Oy, 2014). Due to the heterogeneity in the geology of mining sites, a geologic sampling and metallurgical analysis must be conducted to improve these methods accuracies and to avoid introducing alternative technologies that reduce gold recovery rates compared to those currently used (Teschner et al., 2017).

4.4. Social aspects

Culture is a large part of change in intervention success, in general. Therefore, it was not unexpected that challenges regarding social aspects and change were experienced in intervention development. Before intervention acceptance can happen, cultural beliefs and traditions, socioeconomic conditions, community stability, disease patterns, and health services needed to be considered in developing and implementing interventions—especially educational or knowledge-based programs—in mining sites. This is because gold mining is generally viewed as a positive social contribution through gainful economic means and income-generating activities (Shandro et al., 2009). These factors influence miner's attitudes and behaviors with respect to adapting to new methods that may affect financially gain (Sousa and Veiga, 2009; Shandro et al., 2009). In addition to the challenges of providing education, diseases (e.g. tuberculosis, malaria, sexually transmitted diseases, human immunodeficiency virus/acquired immune deficiency syndrome), safety problems (e.g. injuries from extraction and transport processes, such as broken legs, arms and ankles), lack of basic life requirements (e.g. potable water and sanitation), and mercury pollution exposure are rarely identified by miners as factors against gold mining and reasons for leaving the sector (Shandro et al., 2009; Sousa and Veiga, 2009). Therefore, interventions must include an assessment of the mining community context alongside miner's needs to develop site specific interventions (Sousa and Veiga, 2009; Shandro et al., 2009; Zolnikov, 2012, 2017). In addition, illiteracy in these communities should also be considered when developing educational interventions to maximize the understanding for health and environmental consequences of mercury (Shandro et al., 2009; Sousa and Veiga, 2009). Alongside these community-specific program changes, long-term support from the government could also facilitate the sustainability of educational and technological initiatives, which could fully address issues associated with AGM. This could also be enhanced through local ownership of introduced initiatives, legalization of mines, control of mercury use, and training of miners on legal procedures, mercury-associated-risks, and mercury-free technologies (Sousa and Veiga, 2009; Shandro et al., 2009).

As mentioned, retorts are often used in interventions, but social aspects that contributed to success of retorts were largely attributed to detailed preparation, participatory planning, reciprocity of trust, and training and monitoring (Jonsson et al., 2009). Jonsson et al. (2009) reported that the technology needed the support of local entrepreneurs to ensure the production and availability of retorts; moreover, to increase applicability of the retorts, miners needed to modify them to accommodate their own specific requirements (Jonsson et al., 2009). Unfortunately, these ideas may not be viable solutions because gold mining sectors are typically associated with low education, limited geological and technical knowledge, and low investment rates. Before promoting the use of retorts—or any intervention, in general—an evaluation of the socioeconomic context should be conducted to assess affordability and availability of retorts in the region. For example, the use of retorts in Tanzania is mandatory, except that they are not commonly used by miners due to inadequacy in the introduction of this technology, limited technical support and monitoring, lack of involvement of miners and neglect of the social context of mining sites (Jonsson et al., 2009). Proper introduction and monitoring could increase the use of retorts (Jonsson et al., 2009; Jonsson et al., 2013). Ultimately, considering the dynamics of mining and miners needs and wants could also help introduce more well-received and context-specific technologies (Jonsson et al., 2009).

4.5. Improvements

The reviewed literature reported many barriers regarding the successful implementation and change of techniques in AGM, such as complexity of interventions, specific ore needed, perceived or real decreased gold processing output, and social factors hindering acceptance. These challenges need to be addressed, but that said, novel ideas to promote change also need to include other various aspects. One idea could focus on encouraging collaborations to guide project success; local authorities and government could organize and support the implementation of alternative techniques, while promoting education on environmental and health risks (Veiga et al., 2009; Sousa et al., 2010; Velasquez-López et al., 2011). In the same vein, miners could also be provided with information and knowledge on the benefits of adopting new technologies on improved personal health hazards and decreased environmental consequences of using mercury (Sousa et al., 2010; Velasquez-López et al., 2011). An appropriate introduction of these technologies to miners is imperative, as many mining communities have high levels of illiteracy, operate informally, and are skeptical towards outside interventions (Jonsson et al., 2013). The political environment can also often be overlooked in many of these intervention settings, but it is also important to note that change must occur on these levels as well. Governmental investment and support are important to provide control in policy, regulations, enforcement, and formalization of the AGM sector (Velasquez-López et al., 2010; Veiga et al., 2014a). Formalization of miners has not been successful due to the bureaucratic laxity and the inconvenient process for obtaining mining rights. Alongside this type of governmental guidance, strategies could ultimately promote the use of alternative or cleaner techniques (e.g. retorts, cyanide in mill-leaching, etc.) in addition to providing more training alongside the active participation of miners in the decision-making process and formalization of the AGM sector (Velasquez-López et al., 2010; Veiga et al., 2014a; Davies, 2014; p, 2017). In summary, several aspects need to be taken into consideration for a successful introduction of alternative or cleaner methods in AGM, including appropriate technical communication, socio-cultural context, local conditions, affiliation with local authorities and miners, involvement of miners in the planning and implementation stages, formalization of miners, and proper monitoring and evaluation.

5. Conclusion

This review provided evidence of the challenges faced in reducing or eliminating mercury use within the AGM sector. This dilemma, at its most basic roots, can be reduced to a single ancient Chinese proverb, 'Father's debt, son to give back.' It is widely known that AGM is a difficult issue without a single solution, but that to create change for the future, new generations must be entrusted to understand and correct the mistakes of the past. This paper reviewed current existing barriers on implemented alternative techniques or solutions to AGM, thereby confirming the need for a more comprehensive approach to be developed. This approach needs to include a full understanding of mercury removal technologies as well as miner education on the hazards of mercury to health and environment, economic gains from various techniques and technology, and support from government through policy inclusion. It is also important to consider low stability and sustainability of the interventions; for example, completed research projects in AGM often dovetail with loss of locally available technical support which causes miners to fall back into original mining methods using mercury. Projects ultimately need to be supported by governments to uphold training process implemented by advanced research solutions (Hilson et al., 2007). In fact, all of this information could be further developed into a model that could be applied to each setting of AGM to determine specific intervention needs alongside metalogic conditions, cultural needs, and education, which could then be used fine-tune current policy measures in country. Solutions that are focused specifically on community dynamics (e.g. resources available, operator's needs, etc.) along with governmental support are likely to prove more sustainable and appropriate interventions.

Future research could focus on including education and an economically feasible, high gold-recovery alternative method to eliminate mercury within AGM. This strategy should be paired alongside collaborations between governmental, non-governmental, and academic organizations to create long-term sustainable solutions to AGM and mercury exposures worldwide.

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