Estimation of Mercury Losses and Gold Production by Artisanal and Small-Scale Gold Mining (ASGM)

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Abstract

Artisanal and small-scale gold mining (ASGM) utilizes mercury (Hg) for the extraction of gold (Au) and is responsible for the largest anthropogenic source of emissions and releases of Hg to the environment. Previous estimates of Hg use in ASGM have varied widely. In this effort, Hg losses in ASGM were derived from the difference between estimates of total Au production and the production reported by conventional gold mining. On the basis of this result, the average ratio of Hg lost to Au produced in ASGM was estimated to be 1.96 in Africa, 4.63 in Latin America, and 1.23 in Asia. The difference among regions can be attributed to the amalgamation procedure used by the miners, in which whole-ore amalgamation is predominant in Latin America and Asia. The obtained estimated ratio of $Hg_{\text{lost}}:Au_{\text{produced}}$ suggested the possibility to detect either Au or Hg smuggling from one country to another. On the other hand, the importance of considering cyanidation in ASGM was also suggested.

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Graphical Abstract

Keywords Artisanal and small-scale gold mining · Mercury · Minamata convention · Substance flow analysis · Ore concentration

Introduction

Mercury (Hg) released [1] to the environment, including air, water, and land, causes severe environmental and health impacts. Releases from artisanal small-scale gold mining (ASGM) operations are gaining global attention due to its high contribution to the overall pollution levels. Figure 1 shows the main method of gold (Au) extraction by ASGM [2, 3]. Gold is extracted by amalgamation of concentrates or the whole ore, and the amalgam, usually with 40–50% mercury, is heated. By heating, mercury is evaporated leaving behind the precious metals [4]. When miners amalgamate the whole ore in small ball mills, the mercury loss can be as high as 15 parts of mercury per part of gold produced [5]. It has been reported that the whole-ore amalgamation process requires 10–25 g of mercury for the production of 1 g of gold while the concentrate amalgamation process requires only 1–3 g of mercury [6].

Amalgamation of the concentrates can definitely reduce drastically the mercury losses since less mass of material is amalgamated, usually from 0.1 to 10% of the original ore mass [7, 8]. The selection of whole ore or amalgamation of concentrates depends on the type of ore. The whole-ore amalgamation is applied only for primary ores with relatively high grades of gold. On the other hand, as for secondary ores, which grades are usually low, miners must concentrate the gold before amalgamation [3, 4].

In addition, there are attempts to introduce and disseminate alternative technologies that can reduce or eliminate the use of mercury, for example, amalgamation of concentrates or cyanidation. However, most solutions are costly and complex for impoverished artisanal miners [6].

The mercury emissions, i.e., the part of the pollutant entering the atmosphere, by burning amalgams or melting gold *doré* at gold shops, represent the main health problem for miners and their communities as this process is usually

Fig. 1 ASGM processing for gold ores [2, 3]

conducted at the urban core of the artisanal mining towns [9]. The United Nations Environmental Programme [10] reported that in 2015, out of 2220 tons of mercury emitted to the atmosphere from all anthropogenic sources, ASGM represented 38%. Other reports pointed out that the total mercury released to the environment including atmosphere, water, and land by ASGM can reach 2,000 tons/a [11]. The number of artisanal miners has been increasing over the years, reaching approximately 45 million individuals directly involved [12] of which at least half of this contingent is involved in gold mining, extracting as much as 450 tons/a of gold in at least 70 countries [13]. The economic crisis in developing countries caused by the Covid19 outbreak together with the recent high price of gold, around US\$ 2000/oz [14], definitely will contribute to substantial increase in ASGM activities worldwide.

Inaccuracies on the estimates of the levels of mercury annually released by ASGM are also caused by the uncertainties on gold production in this highly unregulated sector. Gold is constantly smuggled from one country to another to evade taxes, and this does not appear in any official statistics [15, 16]. Even though after the UNEP *Minamata Convention on Mercury* that came into force in August 2017 and 128 countries signed until 2020 [17], the official imports and exports of mercury by countries also continue to be obscure. The Convention requires the country members to implement regulations to monitor the mercury trade from

one country to another and to limit the mercury use in end use. This monitoring can be effective for the identification of the stakeholders in the mercury supply chain mentioned by Fritz et al. [18], which can reduce the mercury trade and supply. However, some researches pointed out that the effect of the Convention on the illegal trade is limited [19, 20]. After implementing laws prohibiting the imports and use of mercury in ASGM operations, many countries have seen a large drop in reported mercury import and use. For example, Colombia that was importing 133 tons of mercury in 2015, has officially reported only 2 tons in 2018 [21]. This actually is symptomatic for all countries legally importing mercury for legitimate use, which is later diverted to ASGM. In addition, consulting the UN COMTRADE database [21], a UN database that reports imports and exports of goods from countries, the official metallic mercury quantity imported by Peru in 2015, coming from Mexico, was approximately 12 tons. In 2018, after the country ratified the *Minamata Convention* in January 2016, only 34 kg of mercury was officially imported. With numbers of Peruvian artisanal gold miners fluctuating between 100,000 and 500,000 [22, 23], it is obvious that a large part of the mercury they use is unofficially entering the country. These sudden changes in “official report” suggest the illegal and hidden flow of mercury. In addition, revealing the actual situation of the mercury and gold flow is important for achieving the purpose of the Convention.

The gold production from ASGM and conventional gold mining (CGM) companies is not usually reported separately making it difficult to estimate the gold production from ASGM alone.

Seccatore et al. [13] estimated gold production from ASGM based on the number of miners reported by different authors and using preliminary equations elaborated by Veiga [24] in Latin America. They used the price of gold, as an “adjustment factor” for each continent. As a result, the gold production from ASGM was estimated as 85 to 90 tons in Africa, 120 to 123 tons in Asia, 194 to 255 tons in Latin America, totaling 380 to 450 tons. In order to obtain accurate estimates, each region must be analyzed separately.

In the current study, the authors estimated the ratio of mercury releases to gold produced by ASGM using the statistical information on mercury losses from AMAP-UNEP [25] and gold production from ASGM and CGM from Wood Mackenzie (WM) [26], Gold Fields Mineral Services (GFMS) [27], and United States Geological Survey (USGS) [28]. The possibility of gold smuggling to and out of the selected countries was also considered.

Methods of Estimation

Gold Production

GFMS [27] has reported the total global gold production (P_{Total}) by countries in 2015 including ASGM and CGM companies. The data on gold production generated by WM [26] are only relative to the 2015 production of CGM companies. In the current study, the authors treated these data as gold production from CGM (P_{CGM}). Therefore, the ASGM gold production in 2015 (P_{ASGM}) was estimated by subtracting the two (Eq. 1).

$$P_{\text{ASGM}} = P_{\text{total}} - P_{\text{CGM}} \quad (1)$$

The current study selected countries in which ASGM is relevant, and data are supported by the authors' experience and literature. India, Nigeria, Sierra Leone, and Mozambique, where the only statistical data available for total gold production are from USGS [28], the gold production was estimated by the apportionment of “others” in the GFMS data, and applying the USGS data. The same methodology was applied to countries with both large amount of gold production and low accuracy of mercury information, such as China, Sudan, and Tanzania. In addition, the data from Ghana cited from USGS [28] have a significant difference from the gold production estimated by GFMS, but it was supported by other studies [29–31]. Another example of adaptation is the gold production from CGM companies in Zimbabwe, where the P_{CGM} was not recorded in the data

of WM [26]; however, Ndamba et al. [32] reported that approximately 42% of gold production was from ASGM. In Asia, Cambodia was excluded from our study because of the lack of gold production data and Laos because of its CGM production in 2015 exceeding the total production as reported by WM [26].

Mercury Losses

The UNEP Global Mercury Assessment estimated the amount of mercury released by artisanal miners to land and water [25] to be 59.3% of the total mercury lost, and the remaining 40.7% was emitted to the atmosphere. This organization estimated that ASGM in 81 countries lost to the environment in 2017 an average of 2058.9 tons/a of mercury with amounts ranging from 985.9 to 3131.9 tons/a. An error of the total mercury loss from ASGM was $\pm 74\%$. The AMAP-UNEP [25] estimates also considered the percentage of mercury that was used in the amalgamation of the whole ore in selected countries.

This work estimated the mercury lost per unit of gold produced as U_{Hg} calculated by Eq. (2). In this formula, Hg_{lost} is the quantity cited by AMAP-UNEP [25] and Au_{produced} is the estimated gold production from ASGM (P_{ASGM}).

$$U_{\text{Hg}} = \frac{Hg_{\text{lost}}}{Au_{\text{produced}}} \quad (2)$$

This ratio was then compared with the proportion of whole-ore amalgamation in the selected countries suggested by AMAP-UNEP [25]. As mentioned above, the whole-ore amalgamation would cause larger U_{Hg} than the amalgamation of concentrates. If there are inconsistencies between the U_{Hg} and the proportion of whole-ore amalgamation, the discrepancy can be attributed to mercury or gold smuggled from one country to another, for example.

Table 1 shows the targeted countries, mercury loss in ASGM, and total gold production with their sources [25, 27, 28]. In the current study, the authors focused on the countries with a high reliability of the information on mercury loss to calculate the U_{Hg} .

Results and Discussion

Global Trend

Table 1 shows the total gold production and the proportion coming from ASGM in the selected countries. Figure 2 shows U_{Hg} in ASGM and the percentage of mercury being used in whole-ore amalgamation, according to assessment from AMAP-UNEP [25].

Table 1 Target countries, their Au production data, and estimated results in the current study

Country	Hg loss in ASGM process, L_{Hg} / tons year ⁻¹ [25]	Total Au production, P_{total} / tons year ⁻¹	ASGM proportion (%) [26–28]	Hg loss unit, U_{Hg} (t/t)
<i>Africa</i>				
Burkina Faso	35.1	38.0 [27]	Less than 10	10–20*
Ghana	70	125.3 [28]	25–50	1–3
Guinea	19.1	20.0 [27]	10–25	3–5*
Mali	12.5	49.0 [27]	10–25	1–3
Mozambique	4	1.52×10^{-1} [27, 28]	100	20–30*
Nigeria	20	3.15×10^{-3} [27, 28]	100	Over 1000*
Senegal	3	5.8 [27]	Less than 10	20–30*
Sierra Leone	11	6.75×10^{-2} [27, 28]	100	100–200*
Sudan	83	82.4 [28]	90–100	1–3
Tanzania	35	46.8 [27]	10–25	3–5*
Zimbabwe	25	22.0 [27]	042	1–3
<i>Latin America</i>				
Bolivia	120	12.2 [27]	90–100	20–30*
Brazil	105	84.8 [27]	10–25	5–10*
Colombia	175	53.2 [27]	90–100	3–5
Ecuador	85	17.6 [27]	100	3–5
French Guiana	7.5	3.0 [27]	100	1–3
Guyana	15	15.7 [27]	90–100	1–3
Honduras	5	2.6 [27]	Less than 10	Over 1000*
Nicaragua	3.5	8.0 [27]	25–50	1–3
Peru	327	177.9 [27]	25–50	3–5
Suriname	63	23.9 [27]	50–75	3–5*
Venezuela	102	24.2 [27]	100	3–5
<i>Asia</i>				
China	100	454.1 [27]	50–75	Less than 1
India	6	1.8 [27, 28]	100	3–5
Indonesia	420	176.3 [27]	25–50	3–5
Mongolia	11.5	31.3 [27]	25–50	1–3
Philippines	70	46.7 [27]	50–75	1–3

The calculated ratio with * indicates possible exaggeration on Hg loss or underestimation of gold production

Causes can be gold smuggling, gold production from artisanal by cyanidation, or even errors on the original estimates of Hg and Au

In most African countries, the proportion of gold production by ASGM represents 10 to 20% of the total gold production of the countries, as CGM companies have a larger importance. The exception is those countries with exclusive (100%) gold production from artisanal gold operations but with small amount, like Mozambique, Nigeria, and Sierra Leone. In contrast, except for Brazil and Peru, the participation of ASGM in gold production in Latin America is high in most countries. In Asia, this proportion ranged from 25 to 75%, except in India as its reported gold production is 2 tons/a from a CGM company and no significant ASGM is reported.

The $Hg_{\text{lost}}/Au_{\text{produced}}$ ratio, U_{Hg} was estimated lying between 1 and 5 in most countries, with a global average of 2.6. However, this ratio was above 10 in some countries,

where whole-ore amalgamation in ball mills is predominant [5].

Africa

As well observed by AMAP-UNEP [25], there is no evidence that African countries are extensively using whole-ore amalgamation in ball mills. Some countries, like Zimbabwe, use whole-ore amalgamation on copper-amalgamating plates but the mercury losses are at least 5 times less than when the ore is ground with mercury [33]. In the cases of Nigeria and Sierra Leone, the high U_{Hg} ratios were caused by the discrepancy between the reported gold production and the large mercury use and lost in these countries. The total gold productions in 2015 in these countries were estimated

Fig. 2 Percentage of mercury used in whole-ore amalgamation and the estimation of ratio $Hg_{lost}/Au_{produced}$

as 0.0675 tons/a and 3 kg/a for Sierra Leone and Nigeria, respectively [27, 28], while the use of mercury was reported as 5.5 tons/a and 10 tons/a, respectively [25]. However, the gold production in Nigeria was reported as 4 to 8 tons in the other publications [34, 35] and even 13.7 tons/a (97 tons between 2012 and 2018) in a press article [36]. The U_{Hg} ratios of both countries would be approximately 1 considering that these reports and results match the ratio typically related to amalgamation of concentrates [3, 4]. In general, these high ratios were likely caused by either the underestimation of gold production in these countries or overestimates of mercury losses. In most cases, the underestimation of gold production is the main reason of the high U_{Hg} .

In 2006 and 2008, it was observed in the field in Manica, Mozambique that artisanal miners were using manual-driven ball mills made of gas tanks, which was followed by gold concentration by panning [37, 38]. At that time, miners were amalgamating only the concentrates, but, despite the low loss of mercury, of on average 4 tons/a, our data suggest that whole-ore amalgamation is currently occurring in the country. The calculated U_{Hg} ratio for Mozambique is high if we consider the total production of 0.242 tons/a of gold in 2015 exclusively from ASGM. However, the USGS [28] indicated that Mozambique produced exclusively by ASGM approximately 2.6 tons/a and 2.4 tons/a of gold in 2016 and 2017, respectively. It is assumed that the gold production information of this country is uncertain, and more gold than officially reported was actually produced in 2015.

All artisanal miners in Africa, except the Zimbabwean miners produce their gold exclusively from amalgamation of gravity concentrates. One reason for this less polluting

method is the fact that each individual miner uses very primitive manual method and mercury is an expensive item in the process. The whole-ore amalgamation proportion indicated by AMAP-UNEP [25] in Zimbabwe was 80%, which seems correct as most processing centers use copper-amalgamating plates after the grinding process [7, 39]. However, Zimbabwean miners extract gold using a combined amalgamation and cyanidation process [7]. This means that the portion of the produced gold from ASGM (using mercury) will be overestimated, and U_{Hg} will be underestimated in our methodology.

The lack of accountability together with gold smuggling makes it hard to obtain reliable figures about gold production by ASGM in some countries. This is supported by a previous study by UNEP [10]. This causes a systematic increase in the U_{Hg} ratio. For example, the mercury losses in Sierra Leone are on average 11 tons Hg/a [25], whereas the gold production reported by USGS [28] was 0.107 tons in 2016. As the gold in the country comes entirely from ASGM, this generates a very high U_{Hg} ratio. One of the important factors for this is that likely gold has been smuggled from Sierra Leone to neighboring countries as observed by other studies [35, 40]. Assuming that gold has been smuggled, the mercury loss is accounted for Sierra Leone without producing gold, while the gold produced is accounted for the neighboring countries without mercury lost. This inconsistency causes a very high U_{Hg} .

Gold smuggling from Zimbabwe [41] also makes it difficult to quantify the actual production levels in this country. It is interesting to notice that the estimates of U_{Hg} suggest the possibility of detecting smuggling operations.

The U_{Hg} of Burkina Faso was between 10 and 20, and that of Guinea was between 3 and 5. These seem high values, considering that, as observed in the field, most gold has been produced from gravity concentration processes. This might be caused by the wrong estimates of mercury lost or gold produced caused by smuggling. For example, the gold smuggled from Burkina Faso to Togo was estimated in 2017 as over 7 tons/a [42] while P_{ASGM} was reported as less than 3 in 2015. This means that the undetected P_{ASGM} may be larger than the official reported gold production. In addition, Burkina Faso is reported to be responsible for much of the illegal mercury trade in the region [35]. This uncertainty causes the exaggerated U_{Hg} of Burkina Faso.

In the current study, the production of gold from ASGM in Mali was considered as less than 3 tons/a. The obtained U_{Hg} for Mali was between 1 and 3 which is similar to previous studies [3, 43] despite the lack of reliable data [42]. This estimate reflects the results of government enforcement against informal mining operations [44].

Moreover, gold smuggling in the West Africa region including Burkina Faso, Cote d'Ivoire, Guinea, and Mali is highlighted [42]. The governments of these countries charge a 3% export tax. However, in Mali, this applies only to the first 50 kg while other governments apply this to all exported gold. This tax difference suggests that Mali is the “loophole” or the “biggest conduit” of the gold smuggling in this region [42]. This also suggests the requirement of more reliable investigation of the smuggling activities in this region for the accurate quantification of gold production from ASGM and U_{Hg} . Ghana's U_{Hg} was calculated to be between 1 and 3. Several scholars reported that most gold has been produced

from amalgamation of concentrates in this country [25, 45]. For example, 210 g of mercury was added to a concentrate (and not all was lost) and around 200 g of gold was obtained [46]. ASGM in Ghana is often operated by informal miners called as “galamsey” [47]; however, both legal and informal operators use similar methods [46]. Our calculation results matched previous studies [3, 43]. The authors had information from Ghanaian experts about the operation of hundreds of small processing centers in Ghana using amalgamation and cyanidation that, as a result, reduces the estimated U_{Hg} . This was also mentioned by Armah et al. [48]. Therefore, the U_{Hg} of 1–3 seems appropriate for this country with more than 1 million artisanal miners [47, 49].

The U_{Hg} of Senegal was estimated between 20 and 30 which is extremely high, as this ratio was estimated as 1.37 in 2018 by the Artisanal Gold Council (AGC) [50]. This difference is caused by the underestimation of gold production by Senegalese ASGM. Most gold produced in the country is from CGM and a good part of gold produced by ASGM might be smuggled to Mali as pointed out by Alvarez et al. [51].

Tanzania's U_{Hg} of 5, where miners amalgamate only the concentrates, seems to be relatively high considering that the amalgamation of concentrates generates a U_{Hg} around 1–3 as described above [3, 4]. This can be caused by the large-scale gold smuggling as mentioned by Blore [52]; for example, in 2010, the gold export from Tanzania to Kenya was only 1.3 tons while smuggling to Dubai was 13.5 tons.

Figure 3 shows U_{Hg} in ASGM and the % of the mercury being used in whole-ore amalgamation of Africa, extracted from Fig. 2. The average percentage of the mercury used in

Fig. 3 Percentage of mercury used in whole-ore amalgamation and the estimation of ratio $\text{Hg}_{\text{lost}}/\text{Au}_{\text{produced}}$ of Africa

whole-ore amalgamation and U_{Hg} for the targeted countries in Africa was 6.3% and 1.96, respectively. These results are similar to the ones from previous studies [3, 43].

Latin America

According to AMAP-UNEP [25], the percentage of the mercury that is used for whole-ore amalgamation in Latin American countries is over 50%, and in some cases, like in Nicaragua, 100%. However, the average U_{Hg} was estimated between 1 and 3, and this seems to be underestimated considering the high predominance of whole-ore amalgamation. In fact in Nicaragua, like in other Central American countries, the use of the whole-ore amalgamation in the rudimentary grinding “rastras” is the predominant method and main cause for mercury losses to the tailings [7, 53]. Mercury is added to the “rastras” which are blocks of stones rotating over a cement floor, and copper plates capture part of the mercury that comes out in the overflow of the pulp. In this process, the U_{Hg} usually becomes higher than 6 [54]. Nevertheless, a large number of miners also extracts gold from alluvial ores with dredges where they use no or very little mercury to amalgamate the concentrates [56]. Therefore, the average U_{Hg} between 1 and 3 seems adequate to reflect the country’s average.

On the other hand, U_{Hg} of Honduras was estimated as over 1,000, and, even with the intense use of “rastras” for whole-ore amalgamation, this huge ratio was caused by the underestimation of gold production from ASGM or smuggling. In Honduras, the number of workers in ASGM has increased rapidly since the early 2000s [57], whereas the reported total gold production has been decreasing [27] in particular due to the closure of the Vueltas del Rio Mine operation from the CGM company Rio Narcea in 2004 [58]. This contradiction suggests the unreported production of gold.

In South America, U_{Hg} was extremely large in Bolivia and relatively large in Brazil and Suriname while much lower in Guyana. The U_{Hg} in Bolivia was between 20 and 30, and this was caused by three factors: (1) the tendency of adding mercury in small ball mills, (2) the underestimation of the gold production due to the inaccurate information or smuggling [59, 60], and (3) Bolivia has been exporting the imported mercury to neighboring countries [61]. The calculated U_{Hg} in Brazil was between 5 and 10 which seems exaggerated as, despite the evidence of the use of copper-amalgamating plates, most artisanal miners, in particular in the Amazon region, work with low-grade alluvial or colluvial ores, where only concentrates are amalgamated [62]. It was observed in the field that many miners do not sell gold through official channels and transform it into jewels. This can be a reason for this high U_{Hg} . Another reason is that, since 1989, mercury cannot be used in ASGM without a government

certificate [63]; therefore, most mercury enters Brazil clandestinely, likely from Guyana [64]. The only official data of metallic mercury imports to Brazil revealed 20.1 tons in 2019 coming from Japan, whereas nothing was imported in 2015 [21]. On the other hand, gold productions from ASGM in 2015 and 2019 in Brazil were very similar [27].

The amalgamation of the whole ore in ball mills by artisanal miners is the dominant process in Bolivia, Colombia, Ecuador, and Peru, in which the U_{Hg} can be as high as 15 [5]. Except in Bolivia, where miners have their own processing plants, gold ores are extracted in processing centers that provide, for a nominal fee, the amalgamation of the whole-ore extracting, on average, less than 30% of the gold. Then the centers use cyanidation to extract the residual 70–80% gold from tailings [7]. The gold produced by cyanidation in these rudimentary processing centers contributes to reducing the U_{Hg} resulting in a ratio between 3 and 5. On the other hand, the reported U_{Hg} in previous studies was 2.10 in 2013 in Ecuador [65] and 2.8 in 2007 in Peru [66], respectively. These results were relatively lower than our estimation. However, these studies targeted specific gold production sites where a large number of miners amalgamate only concentrates and also cyanidation is a common practice to extract gold from tailings [7].

The illegal flow of mercury in the Guianas, consisting of Guyana, Suriname, and French Guiana, is well known and it has been a long-term problem. Only Guyana can import mercury legally while Suriname has established more restrictive rules, and French Guiana has prohibited mercury imports [67]. In addition, the imported amount of mercury into Guyana was larger than the amount used by ASGM. At last, there is no official export of mercury from Guyana after 2003 [67]. According to UN COMTRADE [21], Suriname and French Guiana did not report any import or re-export of mercury in the last 5 years. Meanwhile, Guyana has imported, 29 tons of metallic mercury in 2015, 35 tons in 2016, 10.5 tons in 2017, and approximately 22 tons in 2018. However, the AMAP-UNEP [25] reported the average use of 63 and 7.5 tons of mercury in Suriname and Guyana, respectively. It is very possible that some of the mercury imported by Guyana has been sold in the neighboring countries, but other sources of mercury would be needed to match the Surinamese data from AMAP-UNEP [25]. Veiga and Marshall [68] indicated that Cuba has been importing high amounts of mercury from Canada since 2011; for example, according to UN COMTRADE [21], in 2016, 2017, and 2018, Canada exported or re-exported 76, 125, and 91 tons of mercury to Cuba, respectively. It is not clear what the use of mercury is in Cuba as there is no information about exports of mercury from this country. Also in the case of Suriname, 63 tons of mercury use and lost [25] seems to be inaccurate, as most Surinamese miners extract gold from wet and dry alluvial deposits as well as from colluvial deposits. The gold grades

in these ores are very low, and therefore, miners need to concentrate the gold before amalgamation [69–71]. Our calculated U_{Hg} of 3 and 5 for Suriname seems too high for the types of ores mined and processed in the country.

In Venezuela, in spite of the gold production by cyanidation from a state-owned company [72], the proportion of gold produced by ASGM was considered herein as 100% as a result of our calculation. The reported production of this company, CVG Minerven, has decreased from 4.2 tons/a in 2009 to 0.43 tons/a in 2015 according to Siverio [72] or, according to Wagner [73], from 2.0 tons/a in 2012 to 0.87 tons/a in 2014. In addition, CGM gold production by Venezuela was recorded until 2013 by WM [26] and declined to zero after 2014. This drastic decrease of gold production from the official sector seems to be the cause of the lack of information by WM [26].

Figure 4 shows U_{Hg} in ASGM and the percentage of the mercury being used in whole-ore amalgamation in Latin America, extracted from Fig. 2. The average percentage of the mercury used in whole-ore amalgamation ratio and U_{Hg} for the targeted countries in Latin America was 73.8% and 4.63 t/t, respectively. These results are similar to those from previous studies [3, 43].

Asia

Indonesia is one of the most active countries in terms of ASGM operation. It has been estimated that 1 million artisanal gold miners are active in 27 provinces out of the 34 provinces in the country [74, 75]. A report has indicated that 380 tons of mercury are released and emitted annually to the

environment [76]. From the production of artisanal mercury mines [77], the country changed from importing 10 tons of mercury in 2009 to exporting nearly 700 tons in 2016 [21]. Indonesian artisanal miners are losing 213.5 tons/a of mercury to the environment as 83.3% of the mercury is used in the whole-ore amalgamation process [25], usually in small ball mills (“tromols”) [78]. Veiga et al. [7] mentioned that the gold production in Indonesia is not clearly publicized but the government believes that it must be between 60 and 80 tons/a. We have estimated that the Indonesian gold production by ASGM was approximately 80 tons in 2015. The average calculated U_{Hg} was between 3 and 5 which reflects a mix of whole-ore amalgamation, amalgamation of concentrates in alluvial deposits in Kalimantan and cyanidation [7, 77].

The AMAP-UNEP [25] estimates for the Philippines were that ASGM loses in average 35 tons/a of mercury of which 75% in whole-ore amalgamation. Using our methodology, the calculated gold production from ASGM was approximately 25 tons in 2015, and the calculated U_{Hg} was near to 3. This result may be underestimated considering that the whole-ore amalgamation was the predominant procedure in Philippines [7, 79]. The extraction of gold by cyanidation from tailing in Philippines is also reported [6]. This means that part of gold from ASGM was produced without mercury, and the U_{Hg} would be underestimated in our methodology. In addition, with as many as 500,000 artisanal gold miners, and producing approximately 37 tons of gold in 2018 [80], the actual production may be higher, due to gold smuggling that can affect up to 90% of the ASGM production [81]. In fact, the government of Philippines recognizes the smuggling problem as the purchasing of gold

Fig. 4 Percentage of mercury used in whole-ore amalgamation and the estimation of ratio $\text{Hg}_{\text{lost}}/\text{Au}_{\text{produced}}$ of Latin America

by the Central Bank, the only official gold buyer, in 2010, was approximately 28 tons and declined to 0.31 tons in 2019 [82]. These factors caused the underestimation of Philippines's U_{Hg} .

In Mongolia, the AMAP-UNEP [25] estimated 11.5 tons of mercury on average lost by ASGM in the country, of which 50% is due to the whole-ore amalgamation. According to Singo and Seguin [83], the ASGM sector contributed in 2017 with more than 50% of the country's gold production, involving over 60,000 miners. In our calculation, U_{Hg} might be approximately or even lower than 2. This result suggests the prevailing amalgamation of concentrates at the end stage of the gravity concentration.

The AMAP-UNEP [25] report considered that 3 tons/a of mercury was lost to the environment by ASGM in India. Deb et al. [84] described a number of sites where artisanal miners extract gold from placer and primary rocks in India. Deb [85] estimated that 60–80 kg of gold is produced annually by this sector releasing 6 to 8 tons of mercury. This seems exaggerated but, in fact, despite the detailed description of the sites mined by artisanal gold miners [86], very little information is available in the literature about how these miners use mercury in India. The predominant idea is that mercury is used to amalgamate concentrates; however, our calculation derived a U_{Hg} of 3 and 5 indicating that mercury is also used to amalgamate the whole ore, disagreeing with the AMAP-UNEP [25] estimate that mercury is exclusively used in gravity concentrates. This estimate must be carefully used due to the lack of information about ASGM activities in the country.

The main gold mine in Laos, Sepon Mine owned by China's Chifeng Jilong Gold Mining, intends to produce from 1 to 1.6 tons of gold in 2020 and 7 tons in 2021 [87]. The USGS [28] reports approximately 6 tons of gold produced in the country in 2017. Laos is a promising country for CGM companies, with 35 known primary gold deposits and 115 placer gold sites, which is translated into a total of 100 gold mining permits granted in 2017 [88]. These authors mentioned that, despite the presence of 1000 artisanal miners extracting placer gold, these informal activities were considered illegal in 2006 and little information is available. However, Moretti and Garrett [89] estimated between 15,000 and 50,000 full-time artisanal miners in the country. The main gold placer operations occur in the Mekong River and the Nam Ou River in Luang Prabang Province. Baker et al. [90] reported that 8,000 miners are active in the Bokeo and Luang Prabang provinces but with possibility of reaching 15,000 miners. These authors reported that the U_{Hg} ratio in alluvial operations was approximately 1 to 2 as only gravity concentrates, obtained by panning or sluicing, were amalgamated. However, when primary ores were processed in hammer mills and copper-amalgamating plates, this ratio was approximately 3. Most information about gold production

in Laos is 15–20 years old and reports a gold production of much less than 10 kg gold per year. In spite of the estimates of AMAP-UNEP [25] of an average of 1.5 tons of mercury being lost annually in the Laotian ASGM operations, we adopted the U_{Hg} ratio of 2.

China is another country with little information about the gold production by ASGM. Gunson and Veiga [91] estimated that approximately 6.5 million artisanal miners extract many different minerals of which coal, iron ore, and gold are the main ones. These authors cited that the U_{Hg} ratio in ASGM operations is very variable from 1, for alluvial operations, to 14 for grinding ore with mercury but very likely averages approximately 3, as most observed operations were using whole-ore amalgamation in Chilean mills followed by copper-amalgamating plates. However, China's U_{Hg} , estimated by our procedure, was less than 1. The AMAP-UNEP [25] estimated that ASGM loses in average 100 tons of Hg of which 25% of the operations are whole-ore amalgamation. China officially banned ASGM in 1990s; however, ASGM has been continued because of its large economic profits. The lack of official numbers and documents about artisanal gold mining in China makes it difficult to obtain reliable estimates about the gold production and mercury losses.

Figure 5 shows U_{Hg} in the Asian ASGM sector and the percentage of the mercury lost when the whole-ore amalgamation is used. The average percentage of the mercury used in whole-ore amalgamation and U_{Hg} for the targeted countries in Asia were approximately 79% and 1.23, respectively. These results do not fit the tendency of previous researches [3, 43]. These inconsistencies were caused by the uncertainty in the data from China gold production and the mercury losses.

Conclusion

In the current study, the authors estimated a ratio $\text{Hg}_{\text{lost}}/\text{Au}_{\text{produced}}$ (U_{Hg}) in the ASGM operations of selected countries. As a result, the U_{Hg} for the African countries, where most artisanal gold is produced from amalgamation of gravity concentrates was approximately 1 to 2, whereas in Latin America and Asia, where whole-ore amalgamation combined with cyanidation of the tailings is the predominant process, the U_{Hg} was between 4 and 5. The whole-ore amalgamation, in particular in small ball mills, loses larger proportions of the mercury initially introduced in the process than amalgamation of gravity concentrates. Whole ore amalgamation, in particular in ball mills, derives a U_{Hg} usually above 10, but with adjustments of the process, for example reducing the mill speed, this can be reduced to 6, which is still high [54]. This high ratio occurs due to the pulverization and oxidation of the mercury drops in the grinding process.

Fig. 5 Percentage of mercury used in whole-ore amalgamation and the estimation of ratio $Hg_{lost}/Au_{produced}$ of Asia

Mercury loses coalescence and does not amalgamate the gold. This study confirms this trend.

The very high estimated U_{Hg} for some countries was caused by the underestimation of gold production or the overestimation of mercury loss. In the countries with high estimated U_{Hg} , the smuggling of mercury or gold has been highlighted in various studies which justifies our results. This suggests that this methodology has a possibility to detect unregulated flows of mercury and gold.

As described in the Introduction, the *Minamata Convention on Mercury* often caused the unregulated flow of mercury, although it targets the mercury trade monitoring and the use limitation in end use. This flow was caused by the illegality of mercury supply and use in ASGM activities, e.g., the management by illegal groups in Burkina Faso [35]. Moreover, not only criminal organizers but also corrupt governments are involved in the illicit ASGM activities [92]. Such situation can create a regional network of mercury trade, sometimes mentioned as a “pipeline” as observed in the Amazon region [93]. It has been very difficult to obtain accurate information about mercury sales, as most developing countries have adhered to the *Minamata Convention* and they prefer to officially report to UN COMTRADE that no more mercury is officially entering the countries. From now on, most data on mercury losses and gold production must rely on field research projects, local informers, and investigating reporters, since official numbers from governments are not reflecting the reality [94, 95].

Our procedure which evaluated individual results with regional averages from previous studies, enabled us to

detect unregulated flows of mercury and gold, although the assessment of U_{Hg} was limited to the countries with consistent information in the current study. This enables the Minamata Convention signatory countries to prioritize actions to curb mercury smuggling as well as illicit gold trades.

The increasing production of gold by artisanal cyanidation of amalgamation tailings, as observed in Bolivia, Colombia, Ecuador, Ghana, Indonesia, Peru, Philippines, Zimbabwe, and other countries, decreases the U_{Hg} giving the impression that mercury losses are being reduced. This is nowadays a major pollution concern as Hg-cyanide complexes are toxic to aquatic life [96]. The current study calls attention that future studies of mercury and gold production by ASGM should consider the cyanidation of Hg-contaminated tailings.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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