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Review

Aquatic Mercury Pollution from Artisanal and Small-Scale Gold Mining in Sub-Saharan Africa: Status, Impacts, and Interventions

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Abstract: Mercury (Hg) pollution remains an environmental global concern due to its non-degradable and toxic nature. Natural and anthropogenic sources of Hg adversely affect the functioning of aquatic ecosystems and biological processes. In sub-Saharan Africa (SSA), unregulated artisanal and small-scale gold mining (ASGM) contributes up to 20% of global gold production and uses 205–496 tonnes/yr of Hg. Despite being a vital economic driver for 20–30 million people, ASGM threatens the health of aquatic systems from Hg pollution, presenting a complex challenge that demands urgent interventions. This review seeks to (1) establish the current status of aquatic Hg pollution, (2) explore the environmental impacts of aquatic Hg, and (3) highlight the proposed interventions for aquatic Hg pollution in SSA. We examined publications and institutional reports between 2000 and 2023 addressing aquatic Hg pollution, impacts, and interventions in the ASGM of SSA. Results indicate a rise in aquatic Hg pollution due to the expansion and intensification of ASGM. West Africa remained the highest contributor (50.2%), followed by Central Africa (39.6%), Southern Africa (9.6%), and Eastern Africa (<1%). Contamination of freshwater ecosystems, toxicity to aquatic biota, and environmental health risks to humans were evident. Alternative Hg-free ASGM technologies, including physical, metallurgical, and pyrometallurgical, were investigated from case studies and recommended for adoption.

Keywords: aquatic mercury pollution; Minamata Convention; mercury-free technologies; artisanal and small-scale mining (ASGM); sub-Saharan Africa; Global Mercury Assessment (GMA); Minamata Initial Assessment (MIA)

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1. Introduction

Mercury (Hg) pollution and toxicity remain an environmentally relevant global concern across the different biospheric matrices due to its ubiquitous and non-degradable nature [1]. Studies have identified the impact of natural and anthropogenic sources of Hg on the functioning of ecosystems and biological processes [2]. Chemically, Hg occurs in three major forms: elemental or metallic (Hg0), organic (OrgHg), predominantly methyl mercury (MeHg), and inorganic (IHg), mainly as mercuric chloride ($HgCl_2$) [3,4]. These different forms are cumulatively called total mercury (THg) [5,6]. Hg, a non-essential

element, is liquid at ambient temperature and highly volatilises into the atmosphere. Atmospheric Hg can be transported and deposited in terrestrial and aquatic environments [1,7,8]. MeHg is among the top 10 highly toxic contaminants that negatively impact aquatic biota, accounting for up to 50% of THg pollution [9,10].

In the aquatic ecosystem, under favourable environmental conditions, microbially-mediated biogeochemical (e.g., sulphate-reducing bacteria) and abiotic processes (e.g., transmethylation) transform the IHg into the most bioavailable and toxic MeHg [11–13]. Mercury methylation in aquatic environments results in the bioaccumulation and biomagnification of MeHg, which increases the toxicity risk to higher trophic-level biota [14,15] and humans [4].

The fourth Global Mercury Assessment report [16] catalogued the trends of Hg emissions from key sectors in 2015 (Figure 1). The contribution of atmospheric THg increased by 450% to 4400 tonnes/yr, and almost half of this (2500 tonnes/yr) came mainly from anthropogenic emissions from industrial and artisanal mining and mineral processing, energy production, and losses from Hg-based products and processes. Approximately 600 tonnes entered the freshwater ecosystems, at least 30% of which were conveyed to the marine environment. Natural Hg, releases from volcanic processes, soils, and vegetation burning, accounted for 2100 tonnes of Hg in the atmosphere, while the oceans contributed 250% of Hg (3400 tonnes) in emissions. In the terrestrial environment, natural sources, including organic and mineral soils, retained 750,000 tonnes/yr. The oceanic Hg cycle retained about 2600 tonnes/yr in surface waters, 310,000 tonnes/yr (37%) of the land, and atmospheric THg deposits in the intermediate and deep waters. Net losses of THg from the marine environment contributed about 45–55% of THg to the atmosphere, both transported to land and freshwater or redeposited in the oceans.

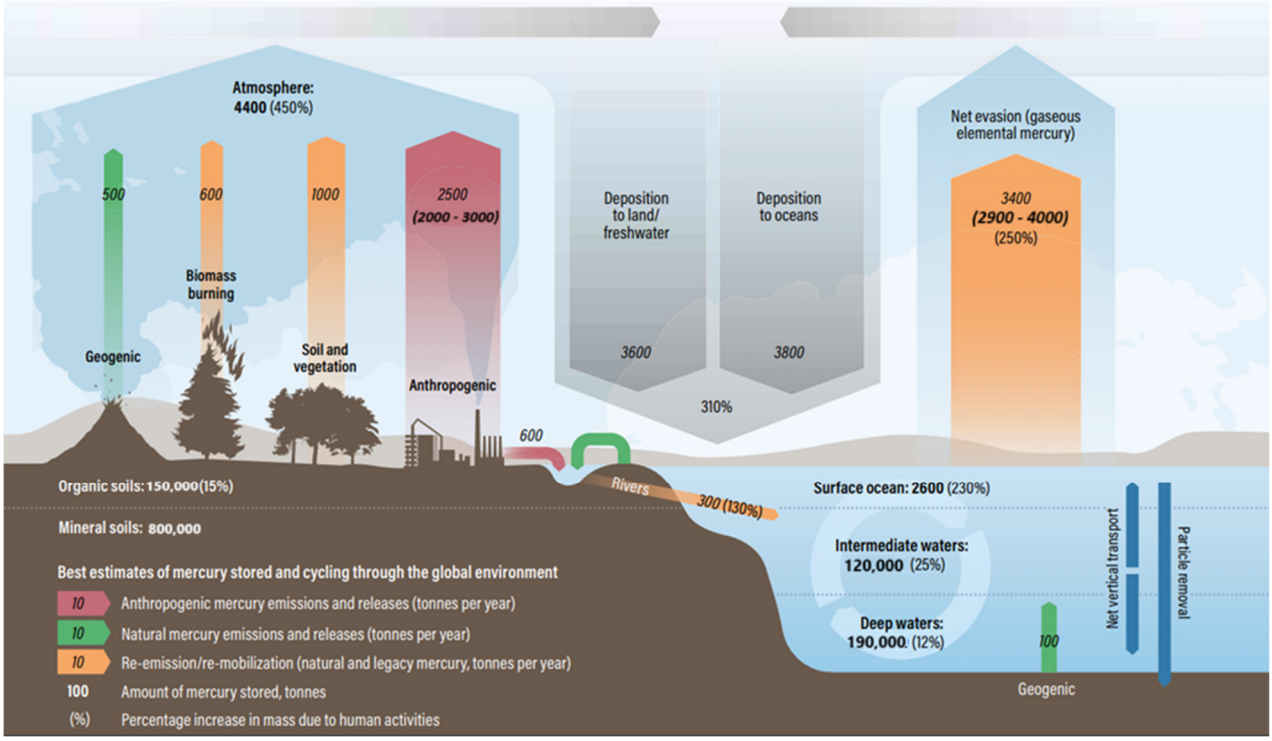

Figure 1. The global Hg budget for emissions, anthropogenic influence on the mercury cycle, and temporary storage in the atmosphere, soils, and aquatic environments [16].

Amotaey and Baawain [17], in a global review of the impact of metal pollution on aquatic biota, observed Hg bioaccumulation in fish muscles, eggs, ovaries, and zooplankton biomass. La Colla et al. [14] reiterated the significant health risk of THg accumulation in fish muscles along an anthropogenically impacted southeast Argentina's Bahía Blanca

estuarine ecosystem. Aquatic MeHg concentrations and biomagnification above acceptable limits in fish communities (732–918 ng/g), frogs (1.075 ng/g), and riparian spiders (347–1140 ng/g) in tropical highland aquatic systems in southwest Colombia have also been reported [18–20]. In addition, Lino et al. [21] observed that artisanal and small-scale gold mining (ASGM) and deforestation were the primary sources of THg and MeHg in Brazil's Tapajós River basin. In the Gambia River flowing through the Kedougou region in eastern Senegal, pollution of stream sediments was in the magnitude of 2–6 mg/kg THg [22] but recently reduced to 1.16 mg/kg THg and 3.2 ng/g MeHg [23].

Streets et al. [24] globally observed a 1.4 Tg cumulative release of Hg between the year 1510 and 2010 period, of which 23% was atmospheric and 77% dissipated into aquatic and terrestrial environments. Furthermore, the authors noted that North America and Europe contributed a cumulative 413 Gg and 427 Gg in this period. With the increased ASGM activities in Africa and the Middle East, about 72% of cumulative atmospheric Hg0 was released [25]. Additionally, ASGM was the largest source of global Hg emissions (775 Mg) in 2015. The aquatic and terrestrial environments that accumulated over 83% of the atmospheric THg were Africa, the Middle East, and Oceania, which contributed 77%, while up to 89% came from South America. Streets et al. [25] further documented an increase in annual Hg emissions from 2188 Mg to 2390 Mg (+1.8%) between 2010 and 2015, where emissions increased in Eastern Africa (>4%), South Asia (>4.6%), and Central America (>5.4%).

In 2011, the ASGM industry employed over 6 million miners globally, who extracted 380–450 tonnes of gold, and by 2018, over 44.67 million people worked in the ASGM sector [16,26]. In sub-Saharan Africa, approximately 1.322 million people work in the ASGM sector, where 27,200 kg of gold was produced in 2014 [16,27]. According to UNEP [16], global Hg emission sources ranged from 40 kg in the ferrous metal industries to 52 kg from biomass burning, 162 kg from waste products, 313 kg from non-ferrous metal production, and 838 kg from ASGM. In 2015, ASGM contributed nearly 1220 tonnes of Hg to global water and terrestrial ecosystems from mining activities in sub-Saharan Africa (8%), East and Southeast Asia (36%), and South America (53%) [16]. The increased use of Hg in ASGM has contaminated aquatic ecosystems. Mercury transforms into highly toxic MeHg, which bioaccumulates in aquatic biota, threatening aquatic productivity and the health of aquatic resource users [28,29]. Furthermore, the ASGM communities risk exposure to inhalation of gaseous Hg, ingestion of contaminated water and food, and dermal contact, resulting in health problems, including neurological disorders [30,31]. For example, communities near ASGM sites in countries like Indonesia [32–34] and Ghana [35–37] have reported both environmental impacts and health issues associated with mercury exposure.

Additionally, Hg used in ASGM enters the global Hg cycle following atmospheric release during gold amalgams, contributing to long-range transport and deposition thus impacting ecosystems globally [38,39]. In aquatic ecosystems, Hg bioaccumulation threatens aquatic biodiversity, particularly in ASGM-intensive areas [40]. For instance, studies in the Amazon basin reported high Hg levels in fish, impacting aquatic ecosystems and human health [41,42]. Although ASGM is often a source of livelihood for marginalised communities, it poses environmental and health risks associated with Hg use, which further undermines the health and productivity of ASGM communities.

In October 2013, the UNEP-led Minamata Convention on Mercury, enforced in August 2017, targeted, among other interventions, the elimination of Hg use in ASGM [43]. Parties to the Convention were obliged to conduct enabling assessments under the Minamata Initial Assessments (MIA) and generate country profiles on Hg status [43]. According to Anan and Toda [44], analysis of country priorities from MIA reports shows that most African countries prioritised three key areas for reduction of Hg release into the environment (Article 8), including Hg waste management, eliminating Hg in products such as cosmetics and dental amalgam (Article 4), and adopting Hg-free gold processing in the ASGM industry (Article 7) (Figure 2). The identified priority area later formed the basis for developing National Action Plans (NAP) to enforce the Minamanta Convention. Furthermore, Anan and Toda [44] identified 16 SSA countries that had prioritised the phasing out of Hg-added

products and the safe handling of Hg wastes to reduce environmental contamination. Similarly, 14 country MIA reports highlighted total elimination or reduction of Hg use in ASGM. Waste incineration, open burning of mercury wastes, and uncontrolled waste damping release approximately 132,776kg (23.2%) and 229,681 kg (40.1%) Hg, respectively. The application, use, and disposal of Hg-added products and dental amalgam contribute 54,521 kg (10%) of Hg, whereas the ASGM sector, dominated by the use of Hg amalgamation during gold production accounts for 156,350 kg (27.3%) of Hg releases. Cumulatively, the implementation of these action areas would reduce approximately 573,328 kg of Africa's contribution to global Hg emissions [44].

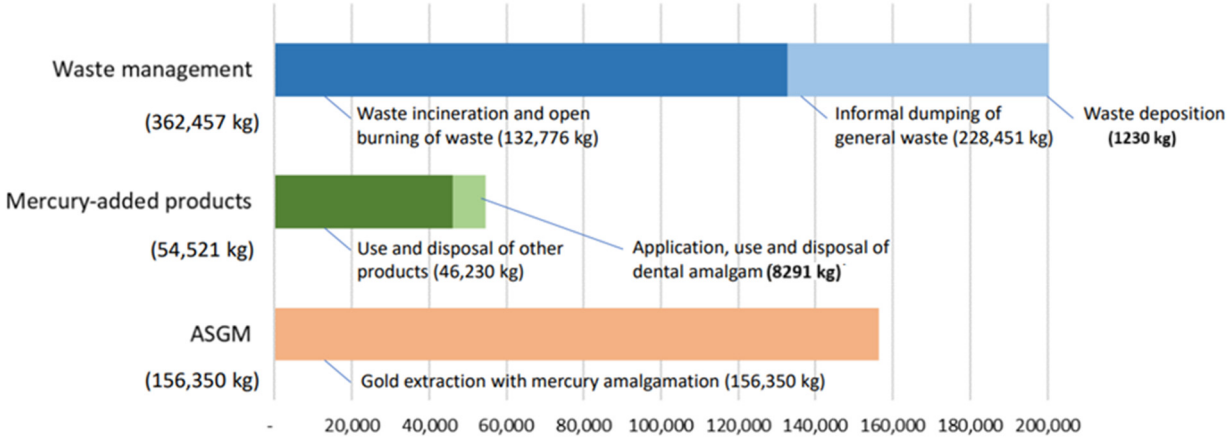

Figure 2. Mercury releases from ASGM, mercury-added products, and waste management sectors from 17 MIA reports from countries in Africa [44].

From the above statistics, it remains clear that the environmental presence and use of Hg in the ASGM sector and industrial products exposes the biosphere to toxicity from Hg interaction with air, land, and water and consumption of Hg-contaminated food, moreso in SSA aquatic systems [16,44]. To address the Hg intoxication problem, there is a need to establish the present status, environmental impacts, and existing interventions to address this global and continental problem, particularly aquatic Hg pollution. The ASGM sector remains a critical contributor to aquatic Hg in SSA [5,45,46]. However, few studies have attempted to establish the magnitude and impact of aquatic Hg pollution from the SSA perspective but have not entirely focused on the contribution of the ASGM sector [47–49]. Other studies have reviewed the impacts of Hg contamination of aquatic environments from ASGM at the country level, including in South Africa [50], the Lake Victoria basin, Eastern Africa [51], and Ghana [35]. However, regional comparative studies on Hg aquatic pollution and related environmental impacts and interventions across and from sub-regional ASGM activities across SSA that provide regional interventions are missing. Consequently, the review focuses on (1) establishing the current status of aquatic Hg pollution, (2) exploring the environmental impacts of Hg pollution on aquatic ecosystems in sub-Saharan Africa, and (3) highlighting proposed interventions and identifying gaps for further research on the management of aquatic Hg pollution from ASGM in SSA.

2. Methodological Approach

We considered primary research and reviews published in English between 2000 and 2023 and the latest annual reports from relevant institutions, such as the UNEP Minamata Convention on Mercury (https://minamataconvention.org (accessed on 18 October 2023)), country-based Minamata Initial Assessment (MIA) reports (https://minamataconvention.org/en/parties/minamata-initial-assessments (accessed on 21 October 2023)), the UNEP 2018 Global Mercury Assessment (GMA) report (https://wedocs.unep.org/handle/20.500.11822/29830 (accessed on 27 October 2023)), UN Environment Global Mercury Partnership (UNGMP) (https://www.unep.org/globalmercurypartnership (accessed on

4 November 2023)), and the Global Environmental Facility (GEF) (https://www.thegef.org (accessed on 8 November 2023)). The articles were retrieved from SCOPUS, Google Scholar, and institutional databases. We further conducted a citation search on the documents retrieved to identify additional relevant studies. Different combinations of keywords were used to access the relevant literature, including "environmental", "impacts", "aquatic", "ecosystems", "small-scale", "artisanal", "gold mining", "mercury", "pollution", and "country" ("country name"). Publications from South America and Asia were also accessed for a comparative assessment of aquatic ASGM pollution in the southern hemisphere. We retrieved 151 documents, 119 primary research articles, and 32 from secondary data (Figure 3).

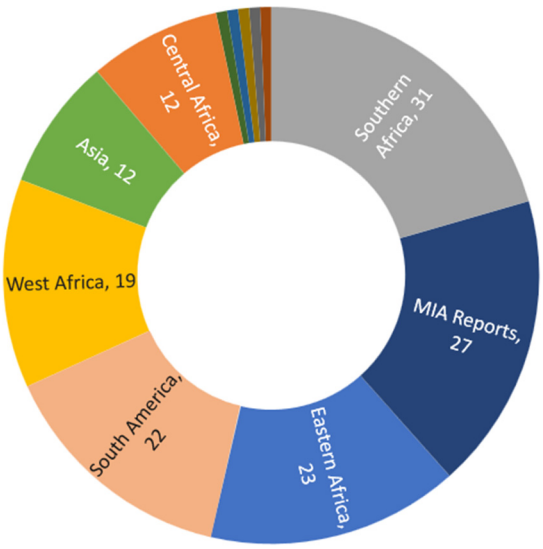

Figure 3. Number of publications between 2000 and 2023 per region on aquatic Hg pollution from ASGM and processing.

3. Mercury Pollution in Sub-Saharan Africa: Trends and Impacts

ASGM has recently intensified in SSA, driven by its potential to provide livelihoods and alleviate poverty in resource-rich but economically disadvantaged localities [47,52]. However, the expansion of ASGM in SSA has accelerated Hg pollution with severe environmental impacts on air, water, land, and human health. The use of Hg in gold processing, often informal and unregulated, severely threatens the aquatic ecosystems of SSA. The release of this toxic element into aquatic systems not only endangers the health of aquatic biota but also the well-being of the riparian community at local and global scales [16]. Several studies have documented the environmental impacts of aquatic Hg pollution across the sub-regions of SSA: Eastern, Central, Western, and Southern, as discussed below.

3.1. Mercury Pollution to Air, Land, and Aquatic Ecosystems: MIA Synthesis

This section presents an account of Hg pollution in air, terrestrial, and aquatic environments in Eastern, Southern, Central, and West Africa from the three key sources, which are primary metal production (PMP), production of other materials and metals (OMM), and extraction and use of fuel/energy sources (FES) listed in the MIA reports (https://minamataconvention.org/en/parties/minamata-initial-assessments (accessed on 21 October 2023). Twenty-seven MIA reports from sub-Saharan African countries were synthesised (Figure 3). Generally, THg emissions were 962,827 kg/yr, of which a total of 261,765 kg/yr (27.2%) was emitted to air, 150,908 kg/yr (15.7%) to water, and 550,154 kg/yr (57.1%) was emitted to land from three major contributors, namely, primary metal production, minerals and other materials, and emissions from the extraction and use of fuel/energy (Figure 4) (MIA, 2017–2023). Burkina Faso and Sudan were the main contributors of THg, with 335,698 (34.9%) and 320,038 (33.2%) kg/yr, respectively. Ghana, South Africa, Senegal,

and Zambia contributed between 30,665 (3.18%) and 65,249 (6.78%) kg/yr THg, while the remaining countries accounted for 114,728 kg/yr (11.92%) THg releases in SSA (MIA, 2017–2023).

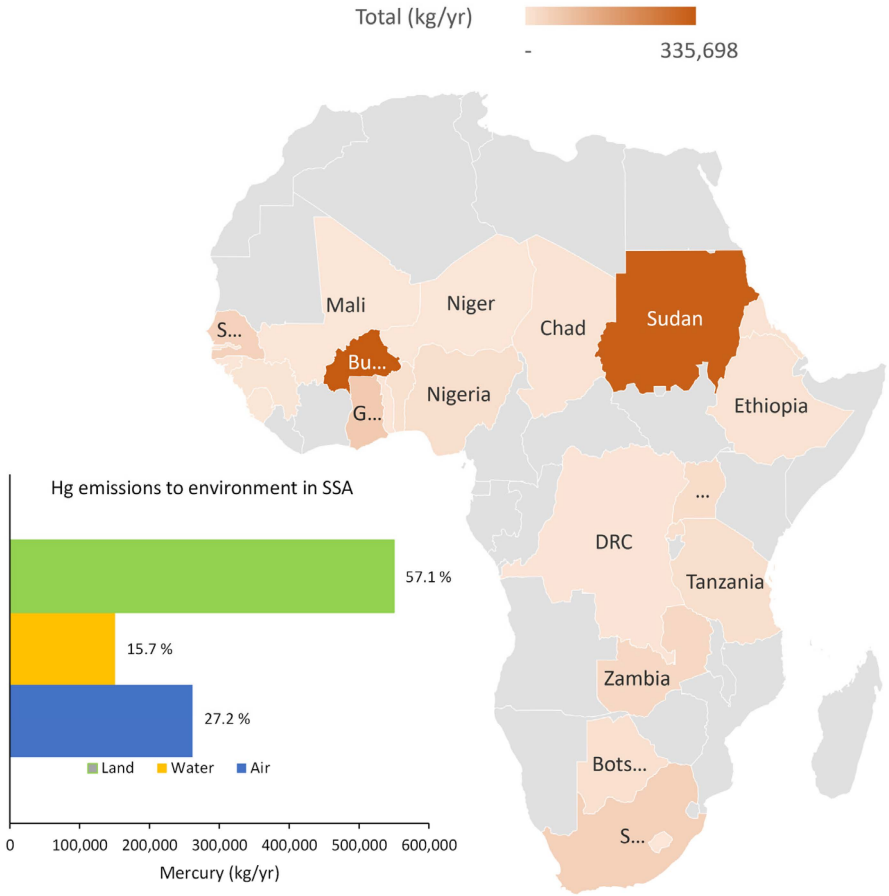

Figure 4. Contribution to total Hg pollution from extraction and consumption of fuel and energy sources and exploitation of primary metals, other minerals, and raw materials in sub-Saharan Africa (data source: MIA, 2017–2023 reports).

3.1.1. Eastern Africa

According to the MIA, between 2017 and 2023, atmospheric Hg emissions in Eastern African countries (kg/yr) increased in the order Eritrea (45.1) < Rwanda (77.4) < Sudan (237) < Tanzania (970) < Ethiopia (5739) < Uganda (12,138) (Figure 5). Annual land THg pollution from the extraction of core metals, such as Au and diamond, from ASGM in the region was predominant in Tanzania (9363), Rwanda (13,193), Eritrea (4106 kg/yr), and Uganda (3333 kg/yr). The extraction of OMM contributed to atmospheric THg emissions of 31.4 kg/yr (Rwanda) and 645 kg/yr (Tanzania), totalling 1646.25 kg/yr. Primary metal production was a significant source of aquatic THg in Ethiopia (375 kg/yr) and Sudan (103,622 kg/yr).

3.1.2. Southern Africa

Only three country MIA reports were available in Southern Africa: Botswana, South Africa, and Zambia; the latter are major sub-Saharan African mining countries. Primary metal production accounted for 65% (19,781 kg/yr) of THg in South Africa, 49% (14,705 kg/yr) in Zambia, and 8% (69 kg/yr) of atmospheric THg emissions. Additionally, 8275 kg/yr of THg was released to aquatic environments in South Africa, 1719 kg/yr in Zambia, and only 44.4 kg/yr in Botswana. Zambia was the highest emitter of THg on land (139,976 kg/yr), followed by Botswana (10,598 kg/yr) and South Africa (2183 kg/yr) (Figure 6).

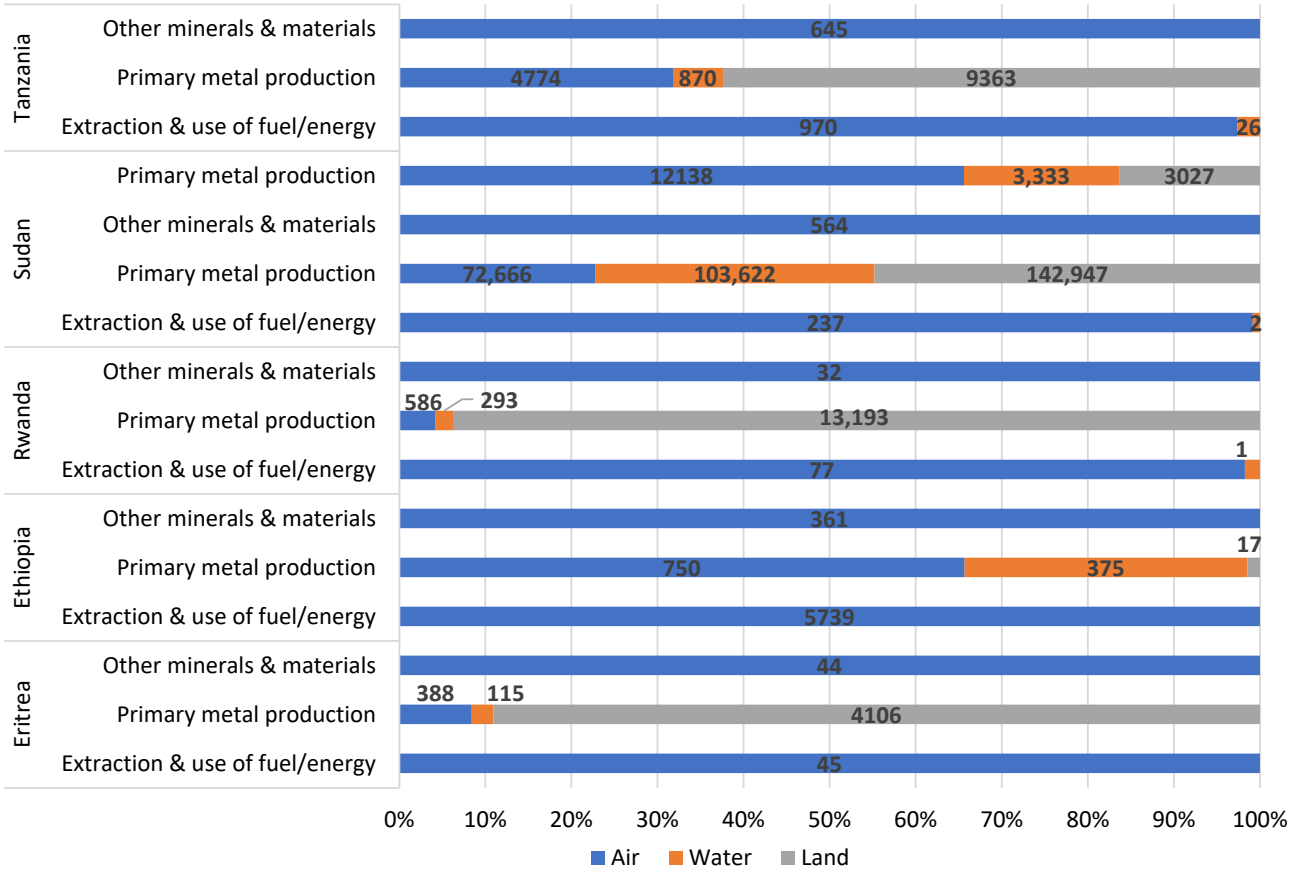

Figure 5. Total Hg emissions to air, water, and land in Eastern Africa from the three main contributors (data source: MIA, 2017–2023 reports).

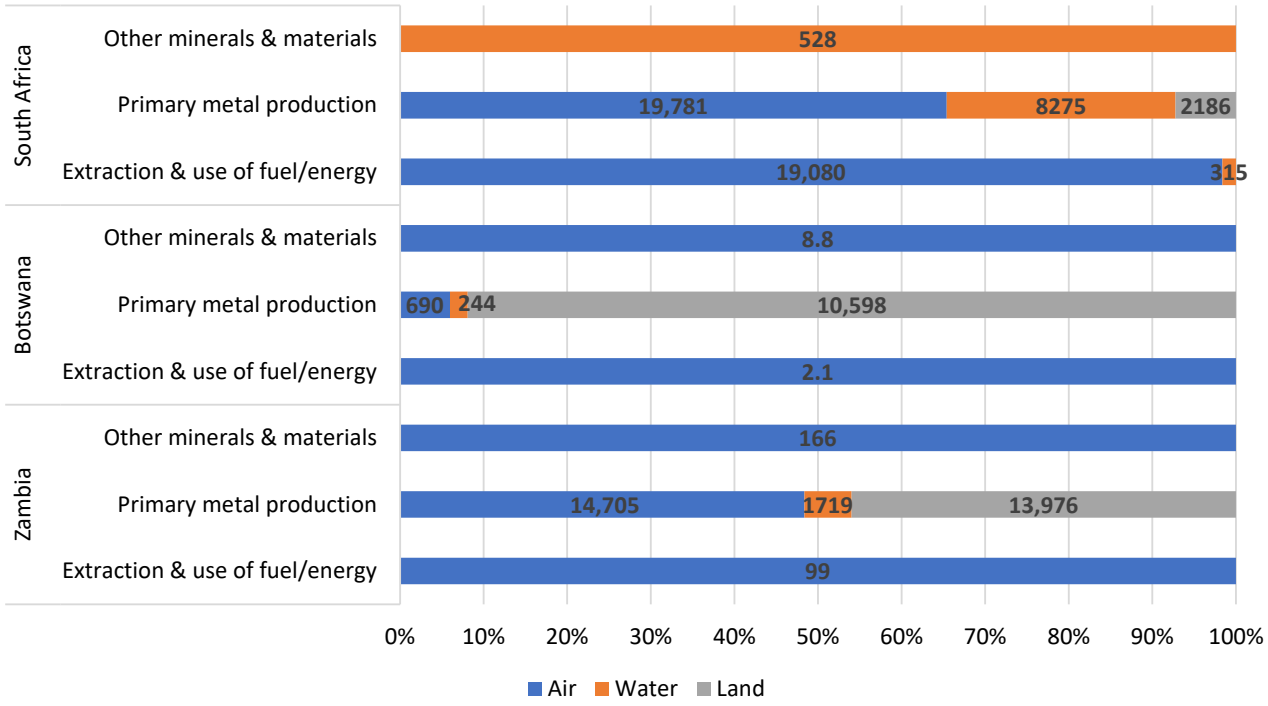

Figure 6. Emissions of THg to air, water, and land in Southern Africa from the production of primary metals, other minerals and materials, and extraction and use of fuel/energy (data source: MIA, 2017–2023 reports).

3.1.3. West Africa

From Figure 7, atmospheric THg pollution was mainly from the extraction of fuel and other energy sources from Nigeria (2370 kg/yr), Ghana (1228 kg/yr), Burkina Faso (286 kg/yr), Senegal (260 kg/yr), Togo (144.2 kg/yr), and Sierra Leone (118 kg/yr). Primary metal processing in West Africa contributed significantly to atmospheric THg, particularly from Burkina Faso (36,996 kg/yr), Ghana (33,344 kg/yr), Nigeria (4396 kg/yr), and Cameroon (2000 kg/yr). The PMP sector also released large amounts of THg to aquatic systems in Benin (3286 kg/yr), Ghana (6527 kg/yr), and Senegal (7266 kg/yr). The West African terrestrial ecosystems equally received alarming quantities of THg from Burkina Faso (287,881 kg/yr), Ghana (6075 kg/yr), Nigeria (6730 kg/yr), and Senegal (21,752 kg/yr).

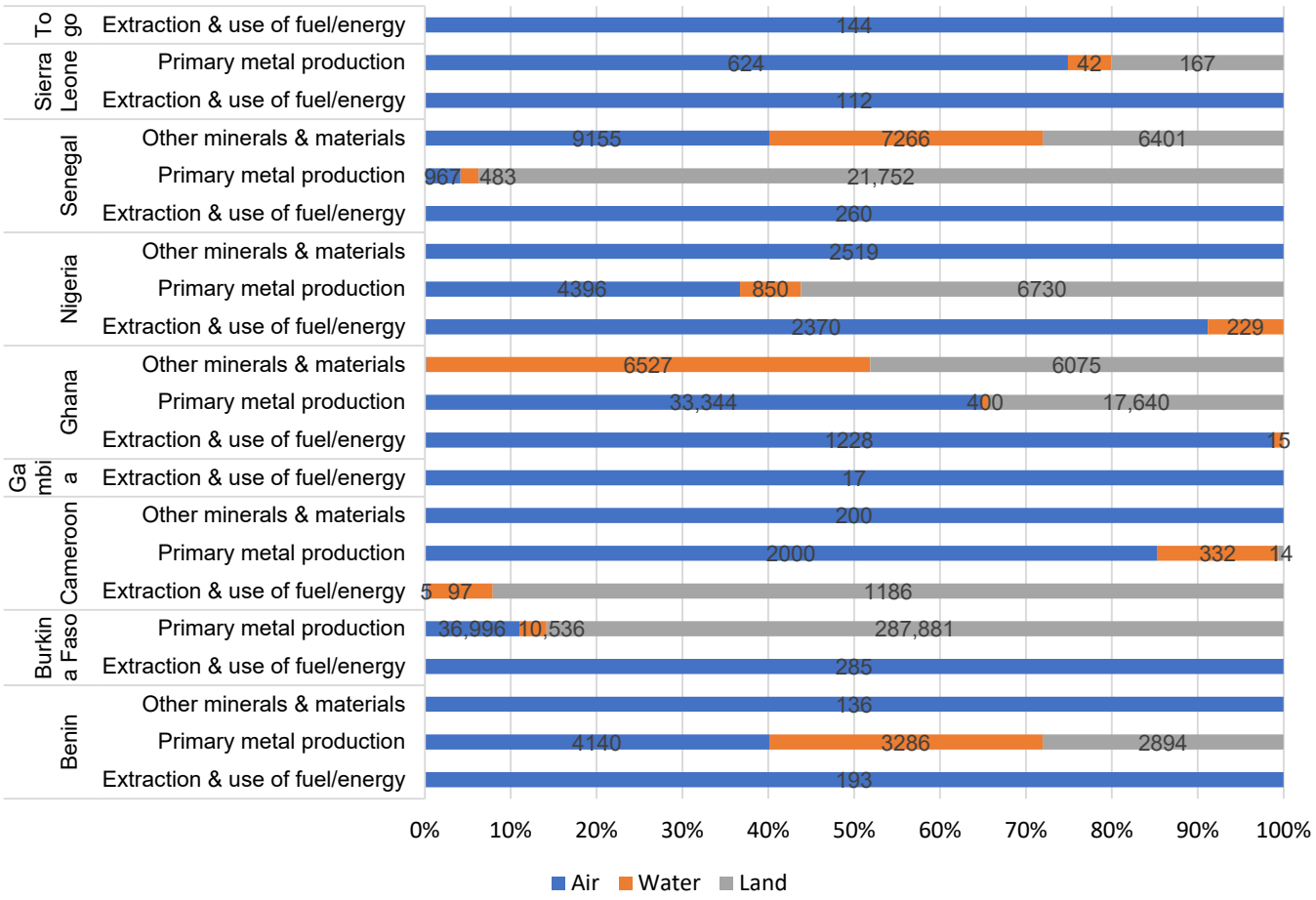

Figure 7. Mercury emissions to air, water, and land in West Africa from the extraction and processing of minerals and fuel/energy resources (data source: MIA, 2017–2023 reports).

Extraction and use of fuel and other energy sources contributed a cumulative 1683 kg/yr to atmospheric THg, approximately 1186 kg/yr to land, and another 326 kg/yr to water bodies in the sub-region.

3.2. Regional Patterns of Aquatic Hg Pollution from ASGM

In SSA, the western Africa region is richly endowed with mineral and natural fuel energy resources compared to the rest. Consequently, as depicted in Figure 8, based on THg emissions from three key sectors, primary metal production, mining and processing of secondary metals and other mineral resources, and extraction of fuels and other energy sources, West Africa was the highest contributor to environmental THg pollution (50.2%), followed by Central Africa (39.6%), Southern Africa (9.6%) and Eastern Africa (0.5%). The implications of these emissions to the aquatic environmental and potential health risks

from the utilisation of water and water resources (e.g., fish) in the different sub-regional locations are described in Section 3.2.1 below and summarised in Table 1 for clarity.

3.2.1. Eastern Africa

Uganda

In the Okame River basin of Eastern Uganda, River Omanyi was the most contaminated from ASGM by Hg (0.0191 mg/L), followed by Nankuke (0.0163 mg/L) and Nabewo (0.0158 mg/L) [53]. Omara et al. [54] investigated THg contamination in water, sediments, and fish from the Namukombe stream in Uganda's Busia gold mining district. THg concentrations in water were up to 1.21 mg/L; fish muscle contained 0.11 µg/g; and sediments had 0.14 µg/g. In the Western Uganda Rwizi River ecosystem, sediments had 0.01–0.4 µg/g, while surface water contained 0.01–0.3 µg/L of Hg traced to ASGM [54]. However, the health risk from drinking water in the Rwizi River was considerably low [55]. In the Napoleon and Winam Gulfs of Uganda and Kenya, respectively, THg ranged from 1.7 to 5.8 ng/L, while MeHg levels ranged between 0.2 and 1.0 ng/L in the L. Victoria waters and were considerably higher than Hg levels in temperate lakes [56].

Tanzania

Earlier studies by Ikingura and Akagi [57] and Ikingura et al. [58] in the L. Victoria goldfields of Tanzania revealed low Hg in fish (7.0 µg/g), sediments (4.19 µg/g) and soils (3.39 µg/g) within the ASGM locations. However, Hg concentrations in urine samples (2.6 ng/mL) and human hair (947 ug/g) from miners exposed to Hg vapour during amalgamation were significantly higher [57,58]. In the Mugusu mine, Hg concentrations in stream sediments varied from 0.5 to 6.0 mg/kg, while tailings from the Mwagamaza mine had 165–332 mg/kg THg [59]. In Nungwe Bay, however, the low Hg concentrations (2–23 µg/kg) in fish were linked to background levels. Furthermore, the tailings released high MeHg concentrations (629–710 ng/g) [56]. Chibunda [60], in a bioassay to determine the bio-uptake and toxicity of mercuric chloride ($HgCl_2$) from ASGM activities on aquatic biota of L. Victoria basin goldfields, observed that assay concentrations ranging from 8 µg/L in the freshwater shrimps (*Caridina nilotica*) to 68 µg/L in freshwater snails (*Bulinus forskalii*) and 162 µg/L in fish (*Hypochromis nubilus*) exhibited biotoxic effects. Taylor et al. [61] comprehensively assessed the environmental impact of Hg release from ASGM in the Rwagamaze gold mine region of the Geita district in Tanzania. In that study, Hg concentration increased from 0.01 to 1.6 mg/kg in stream sediments and 0.006–3.5 mg/kg in fish from Lake Victoria; these values exceeded the WHO limits (0.5 mg/kg) for human consumption and the WHO maximum allowable limit (0.2 mg/kg) for vulnerable groups.

Kenya

The environmental contamination from ASGM Hg release in the Migori Gold Belt in the L. Victoria basin, Kenya, has been extensively documented. According to Ogola et al. [62], stream sediments at the gold sites carried 0.28–348 mg/kg, and tailings at the panning sites released 0.46–1920 mg/kg Hg. Findings from that study estimated that about 150–200 kg Hg/month was used for Au processing, of which 40% and 60% were lost during panning and amalgamation, respectively. Odumo et al. [63] investigated Hg concentrations in gold ores and sediment from four ASGM areas within the Gold Belt (Osiri A and B, Mikei, and Makalda) and reported 16.1–149.9 mg/kg Hg. Ngure et al. [64] also observed significant Hg concentrations in water (0.36–52.1 µg/L), soil (0.51–1830 mg/kg), and fish (0.26–355 mg/kg), which were above the WHO/FAO maximum acceptable limits. In the same period in the Migori-Transmara ASGM region, high Hg was detected in sediment (430 µg/kg), soil (140 µg/kg), and tailings (8900 µg/kg) and was associated with wet and dry depositions [65]. In recent investigations, Tampushi et al. [66] reported 0.66 mg/L in surface water and 24.63 mg/kg Hg in sediments, positively correlated with ASGM ore and tailings contamination sources in the Lolgorian mining region of southwestern Kenya. In Kakamega and Vihiga counties, soil samples contained Hg levels about 49% above the

USEPA standards with 1–72% bioaccessibility. Metal concentrations in 25% of water sources exceeded the WHO (10 µg/L) limit, which increased the risk of non-carcinogenic health effects in humans [67].

Sudan

In sub-Saharan Africa, Sudan was ranked as the largest Hg importer between 2008 and 2015, accounting for an average of 43.25 tonnes of Hg annually, mainly used for gold extraction in ASGM [68]. The use of Hg in gold extraction, particularly when miners employ rudimentary techniques, contaminates aquatic ecosystems. For instance, improper handling and disposal of Hg-laden tailings releases this toxic element that ultimately leaches into aquatic ecosystems [69]. Ahmed et al. [70] assessed the consequences of Hg use in ASGM processes on the surface water quality of the Alebedia area in the River Nile State, Sudan. In the study, the average Hg concentration in water ranged between 0.001 and 0.005 mg/L, attributed to ASGM activities that used mercury amalgamation for gold processing. Hg levels in stream sediments from five regions of the Dar-Mali gold mining area in Sudan's Nile State were lowest in the eastern part (0.001 mg/kg) and increased in the northern (0.002 mg/kg), southern (0.004 mg/kg), and western (0.005 mg/kg) parts [71]. Another study by Mubarak and Ali [72] investigated Hg content among other metals in two fish species, Nile perch (*Lates niloticus*) and Nile tilapia (*Oreochromis niloticus)* of Lake Nubia, Sudan. It was noted that Hg levels ranged from 0.017 to 0.094 mg/kg in *O. niloticus* and 0.085–0.172 mg/kg in *L. niloticus*, indicating bioaccumulation in fish, thus posing health risks to consumers.

3.2.2. Southern Africa

South Africa

South Africa is a significant coal and Au producer in SSA and an important source of Hg pollution globally, contributing about 46.4 tonnes of Hg in 2018 [73,74]. For instance, atmospheric Hg emissions and deposition to the aquatic environment are significantly elevated in South Africa from activities such as coal combustion, ASGM, and industrial gold mining [47]. South Africa is the second-highest emitter of atmospheric Hg from coal-powered energy production plants, which supply ~64% of energy, releasing 0.02–0.16 g Hg per ton of coal burned [75]. South Africa is also the second largest producer of Au, and 70–80% of Hg emissions emanate from Au mining, far higher than coal combustion, while the remaining 20–30% is deposited onto terrestrial and aquatic environments [76]. Additionally, 50 ng/g THg and 1.3 ng/g MeHg were reported in sediment cores and surface sediments from South Africa's Berg River [77], up to 68 ng/g in the Olifants River [74], and up to 0.036 µg/L in the Ga-Selati River [78].

Hg contamination of aquatic systems by coal-fired power generation in the Upper Vaal and Olifants and ASGM in the Inkomati catchment has been observed from fish, water, and sediment analyses [50]. According to Lusilao-Makiese et al. [79], Hg released from ASGM activities in abandoned gold mines in Randfontein, west Johannesburg, release up to 10 µg/g to sediments, 2 ng/L in surface water, and 223 ng/L in groundwater, negatively impacting the Krugersdorp Game Reserve ecosystem. Mine tailings and sediments have been reported to release significant Hg (837–867 µg/kg) to surface waters, of which 90% occur as toxic MeHg [80]. In another study, the variability in MeHg concentration (~13 µg/kg) and IHg (~8480 µg/kg) in sediments in low flows was influenced by seasonality [81]. Verhaert et al. [82] investigated THg in water, surface sediments, aquatic biota, and the trophic transfer dynamics of Hg in the Olifants River basin. The biomagnificative property of THg was noted in fish that accumulated between 0.1 and 6.1 µg/g and trophic magnification factor (TMF) > 1, mostly desorbed from sediments (0.001–0.078 µg/g THg), with potential risk from consumption from fish in the basin.

Zimbabwe

van Straaten [45] compared Hg contamination from ASGM activities in Zimbabwe and Tanzania, where 70–80% was lost to the atmosphere and 20–30% to terrestrial and aquatic ecosystems. While the THg released in Tanzania's Lake Victoria goldfields ranged between 3 and 4 tonnes and above 3 tonnes in Zimbabwe, approximately 1.2–1.5 g of Hg was also released to the environment during Au processing, corresponding to the global 1–2 g Hg loss per gram of Au produced [83]. Green et al. [84] reported aquatic sediment Hg levels between 6 and 154 mg/kg, which positively correlated with organic content but negatively correlated from the source along a four-stream system draining the Farvic Gold Mine area, southeast of Bulawayo, Zimbabwe. In a study to determine the ecological impacts of illegal ASGM on freshwater crabs (*Potamonautes* sp.) and quantify Hg levels in 49 river sampling sites across three land use categories in Chimanimani, Eastern Zimbabwe, Dalu et al. [85] reported Hg levels in stream water from 0 to 0.1 mg/L in communal lands, up to 0.3 mg/L in the national parks, and up to 0.06 mg/L in the timber plantations. Furthermore, the national parks had strong-to-extreme contamination and extremely high Hg enrichment. However, the Hg levels in surface water did not influence the distribution or abundance of crabs. In contrast, Makaure et al. [86] compared Hg contamination and trophic dynamics of fishes between the protected Chivero and ASGM-impacted Mazowe reservoirs in Zimbabwe and revealed significant THg bioaccumulation in Mazowe with trophic magnification slopes (TMS) of 0.28. About 75% of the fish exceeded the 0.5 µg/g THg UNEP recommended threshold, potentially exposing humans and higher trophic fauna to health risks from fish consumption.

3.2.3. Central Africa

Mercury pollution in the lotic systems of Central Africa poses a growing environmental concern, primarily driven by ASGM activities [87]. Artisanal gold miners in Central Africa employ rudimentary processing techniques, often involving Hg [88,89]. The improper handling and disposal of this toxic element has led to substantial contamination of aquatic systems, endangering aquatic life and impacting the livelihoods of local communities [90]. According to UNEP [87], mercury pollution from ASGM in Central Africa is widespread across the region's water bodies, with far-reaching ecological and health consequences. In the south Kivu and some Ituri Basins in Butuzi, eastern DRC, atmospheric Hg emissions account for 29% of THg release from ASGM. In comparison, 71% is lost in mine wastes, of which nearly 50% is transported to streams via surface runoff, exerting adverse impacts on aquatic biota [87].

In the Kienke and Tchangue Basins of the Togo Gold District in Southern Cameroon, Hg levels of 0.106 mg/Kg in river sediments exceeded the WHO limits [91]. However, there was low sediment contamination (CF = 0.17) and low potential aquatic ecological risk (ERF = 4.24) from exposure to Hg in both basins. Additionally, Pascal et al. [92] investigated the influence of gold panning in nine rivers in the Fizi catchment of south Kivu, DRC. Hg levels ranged from 7.8 to 10.7 ng/L in rivers Kimuti, Mandje, and Kuwa, 12.9–18.10 ng/L in Kacumvi, Lubichako, Eto, and Makungu, and 20.3–41.3 ng/L in Misisi and Kambi, which were most polluted [92]. Similarly, Pascal et al. [93] noted Hg concentrations (mg/Kg) in stream sediments of nine rivers in the order Kimbi (89.8) > Misisi (41.1) > Makungu (36.9) > Eto (33.7) > Lubichako (30.1) > Kacumvi (25.3) > Kuwa (20) > Mandje (17.1) > Kimuti (13.6). Furthermore, the higher enrichment of stream sediment with Hg (ER = 24.5) implied a high ecological risk to aquatic biota (PERI = 539.5) in the Fizi catchment [93]. Ngueyep et al. [94] evaluated the effect of AGSM on the surface water quality of the Kadey River system in Batori, east Cameroon, and noted higher Hg concentrations up to 0.02 mg/L, exceeding the 0.001 mg/L WHO limits. Ngounouno et al. [95] evaluated the impact of gold mining on the Lom River of Wakaso, Adamawa, and Cameroon and the efficiency of drumstick tree (*Moringa oleifera*) seeds in bioremediating metal-polluted wastewater. Among other metallic contaminants, Hg concentrations for water (0.01–1.83 mg/L) and sediment (2–25 mg/kg) were both above the WHO limit (0.001 mg/L) and (1 mg/kg), respectively, in all the sampling points. This could

be attributed to gold processing involving mercury amalgamation and burning [96]. Bella Atangana et al. [97] investigated the seasonal variability of Hg contamination of stream water in the Lom gold basin from ASGM, where the dry and wet season mean concentrations were 0.007 and 0.008 mg/L, respectively. In contrast, Ayiwouo et al. [98] observed a higher dry season mean value (0.005 mg/L) and a lower wet season mean value (0.004 mg/L) for Hg concentration in the Lom River, Gankombol region.

3.2.4. West Africa

Ghana

Rajaee et al. [99] evaluated the impacts of human and ecological Hg exposure and spatial distribution in the ASGM in Kejetia, Gorogo, and Bolgatanga, Upper East Ghana. The findings indicated elevated hair, urinary, and household soil Hg concentrations of 0.967 μg/g, 5.18 μg/L, and 3.77 μg/g, respectively, but low concentrations in sediment (0.005–0.248 μg/g; mean 0.036 μg/g) and fish (0.024–0.22 μg/g; mean 0.07 μg/g). Donkor et al. [36] reported seasonal variabilities of Hg in sediments from Ghana's Pra River Basin at 0.018–2.92 mg/kg in the rainy season and 0.01–0.043 mg/kg in the dry season. The high sediment enrichment with THg indicated severe contamination of streams in the Pra Basin. Further studies by Donkor et al. [37] in the basin revealed elevated seasonal Hg sediment concentrations between 0.265 mg/kg (rainy) and 0.019 mg/kg THg (dry), and 0.021 mg/kg (rainy) and 0.001 mg/kg MeHg (dry) from AGSM.

Recently, Affum et al. [100] also correlated the 0.18–0.56 μg/L Hg in water and 1.13–1.21 mg/kg Hg in sediments of the Bonsa River to gold mining and processing. The above Ghana EPS/WHO guideline value (0.001 mg/L) and Hg levels (0.045–0.061 mg/L) in River Bonsa water were also recently confirmed by Obiri-Yeboah et al. [101] and attributed to increased ASGM in the basin. However, Tulasi et al. [102] also attributed Hg methylation in Ghanaian river systems to cyanide (CN)-based Au mining activities. The authors correlated the increase in solubility and sediment transport of MeHg in the Apepe (4.58–14.82 ng/g) and Ankora (0.24–1.21 ng/g) rivers in southwest Ghana with elevated CN concentrations. A health risk assessment by Kortei et al. [40] on Hg toxicity in Ankobrah and Pra Rivers indicated 0.006–0.0093 mg/l in water and 0.4–0.6 mg/kg in fish tissue, with a corresponding target hazard quotient (THQ) > 1, demonstrating potentially harmful health effects.

Senegal

AGSM in Senegal is predominant in the southeastern Kedougou region, along the Mali-Guinea border, which hosts the 230 km^2 Sabodala Belt, the largest gold deposit (~400 tonnes) in West Africa [103]. Gold mining in the Gambia River, draining the Kedougou basin and characterised by THg levels above the sediment quality and probable concentration thresholds, has negatively impacted the basin's aquatic ecosystems. For instance, results from THg analysis of nine freshwater fish species indicated concentrations of between 0.03 and 0.5 mg/kg THg and between 0.5 and 1.05 mg/kg THg in two species of shellfish in the Gambia River, which were above the WHO guideline value of 0.5 mg/kg [22]. In the same basin, higher concentrations of up to 1.5 mg/kg, 0.4 mg/kg, and 0.32 mg/kg THg were detected in human hair in Bantako, Tinkoto, and Samekouta towns, respectively, of the Kedougou region [22]. Niane et al. [104] recently indicated a decrease in THg contamination in the Gambia River stream sediments from 9.9 mg/kg in 2014 to 1.16 mg/kg, with potential toxicity to aquatic biota. Another study by Gerson et al. [105] evidenced that ASGM in Kedougou contributed 4.2 ng/g and 22 ng/L THg in sediment and water, respectively.

Nigeria

In Nigeria, ASGM-related Hg contamination in the Manyera River in Niger State ranged between 0.014 and 0.025 mg/L in water and up to 0.021 mg/kg in sediment. Additionally, fish (*Heterotis niloticus*) from the river bioaccumulated 0.008 mg/kg [106].

In the northwest Anka ASGM region, 2.12 and 1.25 µg/g Hg were recorded from stream sediments and tailings, respectively [107]. Sani et al. [108] recently assessed ASGM pollution of three water sources around the Igade mining area in Niger State, where the Hg levels for the well (0.01 mg/L), borehole (0.005 mg/L), and river water (0.012 mg/L) were above the WHO and Nigeria recommended standards for potable water.

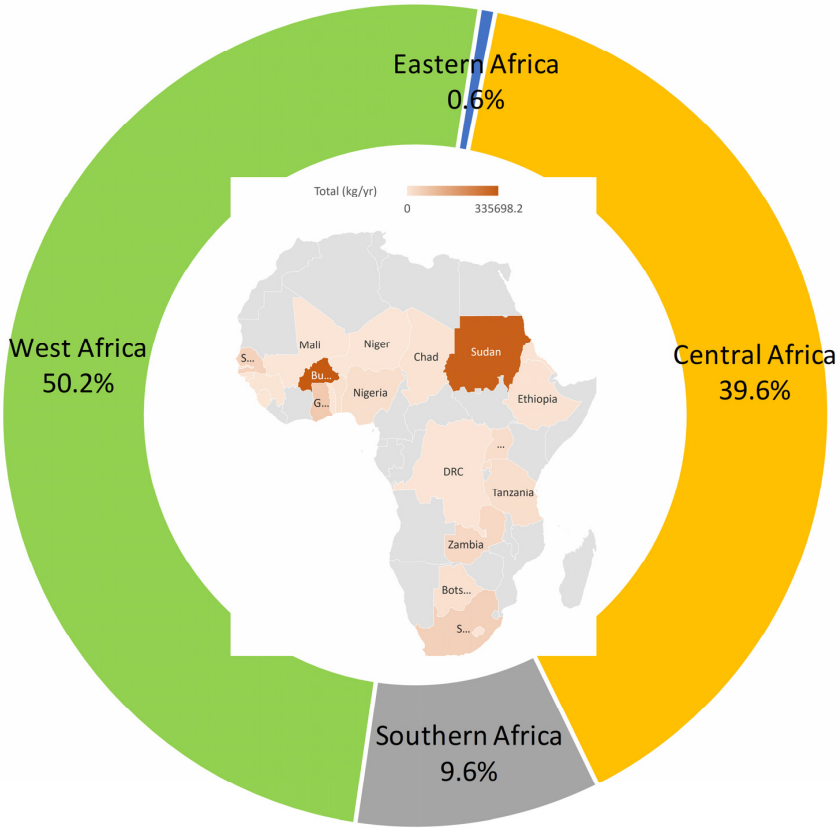

Figure 8. Contribution of THg in Eastern, Central, West, and Southern Africa showing the proportion of THg emissions in SSA from production of primary metals, other metals and minerals, and the extraction of fuel and other energy sources (data source: MIA, 2017–2023 reports).

Table 1 summarises the environmental occurrence and concentration of the different categories of Hg in aquatic ecosystems of the Eastern, Southern, Central, and Western sub-regions of SSA with evidence of ASGM-related impacts.

Table 1. Aquatic pollution in water, sediment, and biota in the Eastern, Southern, Central, and Western sub-regions of SSA from selected studies.

Region and Country	Aquatic Matrix	Hg Category and Value	References
1. Eastern			
Uganda	Okame River	Hg: 0.019 mg/L (Water)	[55]
	Nankuke River	Hg: 0.0163 mg/L (Water)	
	Nabweo River	Hg: 0.0158 mg/L (Water)	[56,57]
	Namukombe stream	THg: 0.11 µg/g (Fish, *Oreochromis niloticus*); 1.21 mg/L (Water); 0.14 µg/g (Sediment)	
	Rwizi River	Hg: 0.01–0.1 ug/g (Sediment); 0.01–0.3 µg/L (Water); 0.04 µg/g (Fish, *Barbus altianalis*); 0.09 µg/g (Fish, *Brycinus sadleri*)	[58]
	Lake Victoria	THg: 1.7–5.8 ng/L; MeHg: 0.2–1.0 ng/L (Water)	

Table 1. *Cont.*

Region and Country	Aquatic Matrix	Hg Category and Value	References
Tanzania	Lake Victoria Goldfield streams	Hg: 7.0 µg/kg (Fish, *Tilapia* sp.); ug/g (Sediment)	[58–61,63]
	Mugusu mine streams	Hg: 0.35–6.0 mg/kg (Sediment)	
	L. Victoria, Nungwe Bay	Hg: 2–35 µg/kg (Fish, *Tilapia* sp.; *Lates niloticus*; *Protopterus* sp.)	
	Rwamagasa Gold mine region streams	Hg: 0.01–1.6 mg/kg (Sediment); 0.006–3.5 mg/kg (Fish, *Lates* sp., *Oreochromis* spp., *Clarias* sp.)	
Kenya	Migori Goldbelt, Lake Victoria Basin	Hg: 430 µg/kg–149.9 mg/kg (Sediment) Hg: 0.36 µg/L–0.66 mg/L (Water); 0.26–355 mg/kg (Fish, *Rastrineobola argentea*)	[64–68]
Sudan	River Nile State Albenda region streams	Hg: 0.001–0.005 mg/L (Water); 0.017–0.094 mg/kg (Fish: *Oreochromis niloticus*); 0.085–0.172 mg/kg (Fish: *Lates niloticus*)	[72,74]
2. Southern			
South Africa	Berg River	THg: 50 ng/g (Sediment); MeHg: 1.3 ng/g (Sediment)	[76,79–81,84]
	Olifants River	MeHg: 68 ng/g (Sediment); THg: 0.1–6.1 µg/g (Fish, *Clarias* sp.; *Hydrocynus* sp., *Labeo* sp., *Schilbe* sp., *Labeobarbus* sp., *Oreochromis* sp.); 0.001–0.078 mg/g (Sediment)	
	Ga-Selati River	MeHg: 0.036 µg/L (Water)	
	Randfontein, West Johannesburg stream	Hg: 10 µg/g (Sediment); 2 ng/L (Surface water); 223 ng/L (Ground water)	
Zimbabwe	Farvic Gold mine area streams, Bulawayo.	Hg: 6–154 mg/kg (Sediment); 0.06–0.4 mg/L (Water)	[86–88]
	Chimanimani, East Zimbabwe	Hg: 0.1–0.3 mg/L (Water)	
	Mazowe and Chivaro Reservoirs	THg: Above 0.5 µg/g (Fish)	
3. Central			
Cameroon	Togo Gold District, Kianke, and Tchangue Basins	Hg: 0.106 mg/kg	[93]
	Kadey River, East Cameroon	Hg: 0.02 mg/L (Water)	[96]
	Lom River, Adamawa	Hg: 0.01–1.83 mg/L (Water)	[97]
	Lom Basin	Hg: 0.007–0.008 mg/L (Water)	[98]
	Lom River, Gankombol	Hg: 0.004–0.005 mg/L (Water)	[99,100]
Democratic Republic of Congo	Fizi Basin River systems, south Kivu	Hg: 7.8–41.3 ng/L (Water); 17.1–89.8 mg/kg (Sediment)	[94–96]
4. West			
Ghana	Kejetia Gorogo and Bolgatanga ASGM area streams, Upper East Ghana	Hg: 0.05–0.248 µg/g (Sediment); 0.024–0.22 µg/g (Fish; species unidentified)	[101]
	Pra River Basin	Hg: 0.01–2.92 mg/kg (Sediment) THg: 0.019–0.265 mg/kg (Sediment)	[36]
		MeHg: 0.001 mg/kg (Sediment)	[37]
	Bonsa River	Hg: 0.18 µg/L–0.061 mg/L (Water); 1.13–1.21 mg/kg (Sediment)	[102,103]

Table 1. *Cont.*

Region and Country	Aquatic Matrix	Hg Category and Value	References
4. West			
	River Apepe and Ankora	MeHg: 0.24–14.82 ng/g (Sediment)	[104]
	Ankobrah and Pra Rivers	Hg: 0.006–0.0093 mg/L (Water); 0.04–0.6 mg/kg (Fish, *Oreochromis niloticus*; *Clarias angularis*)	[40]
Senegal	Gambia River	THg: 0.03–0.5 mg/kg (Fish); 0.5–1.05 mg/kg (Shellfish); 4.2 ng/g–9.9 mg/kg (Sediment); 22 ng/L (Water)	[106,107]
Nigeria	Manyera River, Niger State	Hg: 0.014–0.025 mg/L (Water); 0.021 mg/kg (Sediment); 0.008 mg/kg (Fish—*Heterotis niloticus*)	[108]
	Northwest Anka ASGM Region	Hg: 2.12 mg/g (Sediment)	[109]
	Igade mining area, Niger State	Hg: 0.01–0.012 mg/L (Water)	[110]

3.3. Regional Summary and Intercontinental Hg Pollution from ASGM

Table 2 reflects the overall trend in countries in sub-regions of sub-Saharan Africa, South America, and Asia where evidence of ASGM contributing to aquatic Hg pollution has been documented. Hg concentration in Eastern Africa's aquatic systems ranged from 5.8 ng/L in the Napoleon Gulf, L. Victoria, to 1.21 mg/L in the Namukombe stream, Uganda, and from 0.36 µg/L in the L. Victoria Basin rivers to 0.66 mg/L in the Lolgorian region in Kenya [54,64,66]. In the Alebedia area in River Nile State, Sudan, Ahmed et al. [70] reported 0.001 to 0.005 mg/L Hg in surface water. Sediments in Uganda's Namukombe stream contained Hg levels from 0.14 to 0.4 µg/L [54]. Campbell et al. [51] reported 629 ng/g Hg in sediments of L. Victoria, while Ikingura et al. [59] documented maximum Hg concentrations of 6 mg/kg in stream sediments around the Mugusu mine of the L. Victoria Basin of Tanzania. In Kenya, Tampushi et al. [66] investigated Hg release into stream sediments at the Lolgorian ASGM site, where maximum Hg concentrations reached 24.6 mg/kg. In Sudan's Dar Mali gold mining region, stream sediment Hg concentrations ranged between 0.001 and 0.005 mg/kg [71]. Hg levels of environmental concern have also been reported in Eastern Africa. For instance, evidence of fish contamination with Hg was reported in Uganda at 0.11 µg/g [54] and 2.0 µg/g to 3.5 mg/kg in Tanzania [61].

In South Africa, in the Ga-Selati and Berg Rivers (in Limpopo basin) and Phongolo, Olifants, and Upper Vaal Rivers, concentrations of 0.036 µg/L in surface water, 50 ng/g to 1.3 µg/g in sediments, and 0.001 to 6.1 ng/g Hg in fish tissue were reported for several studies [50,74,77,78,82]. Elevated Hg concentrations ranging between 6 and 154 mg/kg were reported in stream sediments of the Farvic Gold mining area in Bulawayo, Zimbabwe [84], and between 0.006 and 154 mg/kg in the tropical reserve area in Zimbabwe [85]. In central Africa's DRC, in the Fizi catchment of South Kivu, Hg release to water from gold production ranged from 7.8 to 41.4 ng/L and 13.6–89.8 mg/kg in sediments [93], while in the Kienke and Tchangue basins of Cameroon, sediment Hg levels reached 0.106 mg/kg [91]. In West Africa, Hg levels in the range 0.18 ug/L–0.0093 mg/L were reported by Affum et al. [100] and Kortei et al. [40] in the surface waters of Bonsa, Anrobrah, and Pra Rivers, respectively, in Ghana. Fish accumulated up to 0.6 mg/kg Hg in the Ankobrah-Pra River systems [40]. In Senegal, freshwater fish accumulated THg concentrations ranging between 0.03 and 1.05 mg/kg in the Gambia River [22]. In Nigeria's Manyera River, ASGM-produced Hg was detected in tissues of fish (*Heterotis niloticus*) up to 0.008 mg/kg.

Similarly, Hg pollution trends have been documented in Latin American and Asian ASGM environments. In Asia, Hg levels in surface water ranged from 0.002 µg/L in Myanmar [109] to 8 µg/L in the Philippines [110]. Murphy et al. [111] recorded con-

tamination of sediments up to 64 ng/g in Cambodia; bioaccumulation of Hg in fish was between 90 ng/g and 50 µg/g. Abraham et al. [112] reported that bottom sediment contained 2.7 µug/g–0.02 mg/kg Hg in the Zamora River, Ecuador, while tailings from ASGM released 89–1535 µg/g Hg as mining effluents. In the Madeira River, Brazil, in Latin America, the THg accumulated up to 1242 µg/kg in fish [113]. Hg contamination was higher (0.12–1.92 mg/kg) in fish communities of the ASGM in the Cuyuni River Basin of Venezuela [114]. Hacon et al. [115] assessed the potential ecotoxicological risks of THg to trophic guilds of fish in 18 sites in five regions of the Amapá State territory in the Brazilian Northern Amazon region. Carnivorous fish had a mean concentration of 0.4 µg/g; omnivorous fish (*Pimelodus ornatus*) accumulated 1.8 µg/g Hg; and herbivorous fish, e.g., *Mylesinus paraschombourgkii* ("flaviano"), had unexpectedly high Hg levels (1.0 µg/g). At the same time, another herbivore, *Myloplus ternetzi* ("pacu"), bioaccumulated up to 0.85 µg/g Hg. The highest Hg levels were detected in carnivorous fish species (2.1 µg/g), including *Boulengerella cuvieri* ("pirapucu"), followed by *Cichla monoculus* ("tucunaré") and *Hoplias aimara* ("traírão"). The high Hg levels present a potential risk from local fish consumption in the region. A similar study in the western Amazon Basin Triple Frontier monitored the impact of THg on commercial fish [116]. In that study, carnivorous fish species had the highest concentrations of THg (e.g., *Hoplias malabaricus* with a THg of 0.205–2.818 µg/g; *Hoplerythrinus unitaeniatus* with a THg from 0.97 to 1.873 µg/g THg) above the maximum allowed by the Brazilian guidelines (1.0 µg/g), while the THg in the herbivores (e.g., *Pterygoplichthys pardalis*, with 0.092–0.279 µg/g THg) was below the acceptable limit. In the southeastern ASGM region of the Peruvian Amazon, Hg levels in lake and river sediments ranged between 64 and 86 ng/g and 20–53 ng/g, respectively [117]. Additionally, 5% of the piscivorous fish bioaccumulated Hg concentrations above the 500 ng/g limit recommended for human consumption (e.g., locally known as "chambira", "palomata", and "huasaco", bioaccumulated up to 1215, 80, and 500 ng/g, respectively). Some ASGM-impacted rivers in the ASGM regions, such as Quebrado Yarinal and Middle-Malinowski, had no fish during that study.

Table 2. Contribution to aquatic Hg from ASGM in SSA countries from 2000 to 2023 and selected studies from Asia and South America.

Sub-Region	Country	Environmental Compartment			References
		Water	Sediment/Tailings	Biota	
Eastern	Uganda	5.8 ng/L–1.21 mg/L	0.14–0.4 µg/g	Fish: 0.11 µg/g	[53–55]
	Tanzania		629 ng/g–6 mg/kg	Fish: 2 µg/kg–3.5 mg/kg Shrimp: 8µg/L Snail: 68 µg/L	[51,59–61]
	Kenya	0.36 ug/L–0.66 mg/L	430 ug/kg–1920 mg/kg (tailings) 0.001–24.6 mg/kg (sediment)	Fish: 0.26–355 mg/kg	[62,63,65,66]
	Sudan	0.001–0.005 mg/L	0.001–0.005 mg/kg (sediment)	Fish: 0.017–0.172 mg/kg	[70,72,118]
Southern	South Africa	0.036 µg/L	50 ng/g–1.3 mg/g	Fish: 0.001–6.1 ng/g	[50,74,77,78,82]
	Zimbabwe		0.06–154 mg/kg	Fish: 17–32% with Hg > 0.2 µg/g	[84–86]
Central	DRC	7.8–41.3 ng/L	13.6–88.8 mg/kg		[92]
	Cameroon	7.8 ng/L–0.83 mg/L	2–25 mg/kg		[91,93,94,97,98]
West	Ghana	0.18 µg/L–0.0093 mg/L	0.005 µg/g–2.92 mg/kg	Fish: 0.024 µg/g–0.6 mg/kg	[36,37,40,100,102,119]
	Senegal	22 ng/L	4.2 ng/g–9.9 mg/kg		[105]
	Nigeria	0.01–0.05 mg/L	2.12 ug/g–0.021 mg/kg	Fish: 0.008 mg/kg	[106–108]

Table 2. *Cont.*

Sub-Region	Country	Environmental Compartment			References
		Water	Sediment/Tailings	Biota	
Asia	Indonesia	0.7–9.9 µg/L			[34]
	Myanmar	0.002–0.008 µg/L			[109]
	Philippines	0.009–80 µg/L			[110]
	Thailand	0.7–6 µg/L			[120]
	Cambodia		64 ng/g	Fish: 90 ng/g–50 µg/g	[111]
Latin America	Ecuador		Sediment: 2.7 µg/g–0.02 mg/kg Tailings: 89–1535 µg/g		[112,121]
	Brazil		100 ng/g–1207 mg/kg	Fish: 100 ng/g–1242 µg/kg	[113,122,123]
	Venezuela	4.60 µg/L		0.12–1.92 mg/kg	[114]
	Brazil			Fish (Carnivorous 0.4 µg/g; Omnivore-*Pimelodus ornatus*, 1.8 µg/g; Herbivore-*Mylesinus paraschombourgkii*, 1 µg/g; *M. ternetzi*, 0.85 ug/g Hg)	[115]
	Brazil, Colombia, Peru			Fish (Carnivore, *Hoplias malabaricus*, 0.21–282 µg/g; Herbivore-*Pterygoplichthys pardalis*, 0.09–0.28 µg/g THg)	[116]
	Peru		Lake sediment: 64–86 ng/g River sediment: 20–53 ng/g	Fish(“chambira”, 1215 ng/g: “palomata”, 80 ng/g; “Huasaco”, 500 ng/g)	[117]

4. Socioeconomic, Environmental, and Human Health Impacts of ASGM in SSA

According to Hilson [124,125], ASGM is a significant economic driver in rural SSA, providing direct employment to more than 10 million miners in rural communities. For instance, in Ghana and Tanzania, more than 1 million people are directly employed in the ASGM sector, and at least 0.2 million of the ASGM community in Mali are women [124]. Furthermore, ASGM is a source of capital development beyond direct employment by diversifying livelihoods and micro-economies in rural SSA mining communities, thereby providing indirect employment to over 4 million people [126,127]. Therefore, across the sub-regions of SSA, the socioeconomic contribution of the ASGM sector to the rural transformation of the socioeconomic status and livelihoods of millions of people cannot be underestimated [128].

However, the largely informal organisation of the ASGM sector in SSA competes against the socioeconomic gains among mining communities across the region. Hilson et al. [129] noted that the formalisation of ASGM is a difficult undertaking regardless of the locality of the mining landscape and described the situation as a created and perpetual informality in the ASGM mining space. The biggest drawback to this is the imbalanced working conditions, such as the intensive labour demands involved with gold processing, higher prostitution levels, and abuse of drugs such as narcotics [124]. Competing interests between rural communities and ASGM entrepreneurs have frequently led to gang-related violence, thefts, and related vices. For instance, Mkodzongi [130] reported a dramatic increase in gang-related violence in the Shurugwi mining area of Zimbabwe’s Midlands Province, with cases of robbery of cash, gold, and ore from miners and businesses. In addition, most ASGM entities operate under hazardous conditions, impacting the health and well-being of the predominantly poor rural communities [127,131].

ASGM miners are continuously exposed to gaseous Hg during the processing of gold by Au-Hg amalgam, which involves heating to vaporise the Hg. Hg is also released into aquatic systems during amalgamation processes and washed off during rain and flood events, becoming an important route for human exposure, primarily to MeHg (Figure 9). MeHg can bioaccumulate up the food chain, resulting in human exposure risks. Hence, communities within the ASGM regions that use Hg for gold processing may have a higher exposure through fish consumption, intoxication through inhalation, and physical contact, causing increased disease burden from elevated MeHg burden. For instance, in 2016, Steckling et al. [132] reported health impacts on 1.22–2.39 million miners globally from exposure to IHg. A critical factor determining the level of human exposure to MeHg is the interaction with the aquatic medium and the occurrence of IHg, which is usually associated with the aquatic environments synonymous with ASGM in SSA [133,134].

Figure 9. Unstructured ASGM and landscape degradation in the Democratic Republic of Congo, Sierra Leone, and Tanzania. Miners are highly exposed to Hg, MeHg, and other toxic elements associated with gold mining. The use of protective gear and proper handling or disposal of Hg in the ASGM industry in sub-Saharan Africa is largely unregulated (photo credits: N. Nyirabihogo, A. R. Thomas, and H. Nachilongo).

ASGM also exacerbates deforestation and soil erosion in many SSA countries [135–137]. The direct impact of ASGM is more focused on tropical countries in the global south, particularly SSA. According to Fisher et al. [138], several factors may increase the potential of exposure to Hg from ASGM, including (1) high concentrations of Hg in soils, tailings, and stream sediments; (2) a lack of employment or alternative livelihoods in many rural areas, which promotes low-level employment occupations such as the ASGM; (3) the availability and affordability of Hg required for gold processing and a lack of government control on Hg importation and unregulated use in the ASGM sector; and (4) the high relative market price of gold, which pushes the demand for Hg as a "quick" extraction method.

Additionally, reservoirs constructed for electricity generation in most river basins of SSA are potential convertors of Hg into toxic MeHg in the aquatic environment. Hg cycling in reservoirs typically increases MeHg production due to the ecological, biogeochemical, and hydrological changes in aquatic environments [139]. For instance, Hall et al. [140] observed elevated MeHg output and bioaccumulation from the deposition of organic matter during flooding that increased microbial decomposition and net MeHg retention in reservoirs in northwestern Ontario, Canada. In the boreal Canadian reservoirs, MeHg levels increased 3 to 6 times post-impoundment flooding and remained high several decades later [141]. In the tropics, reservoirs have been observed to increase MeHg production from Hg-laden surface sediments, which bioaccumulate to harmful levels in organisms [142]. In

that study, THg accumulation ranged from 50 to 200 ng/g in reservoirs with a surface area between 80 and 400 km^2.

5. Considerations for Interventions and Remediation

5.1. Mitigation and Remediation Strategies

The Minamata Convention, enforced in 2017, aims to "protect the human health and the environment from anthropogenic emissions and releases of mercury and mercury compounds" [28,43,143]. Article 8 of the Convention focuses on controlling and/or reducing THg emissions to the atmosphere. Article 9 addresses efforts to prevent and/or reduce THg releases to land and water from point sources. To minimise exposure to Hg in the ASGM environment, capacity building, adoption of alternative methods, and technology transfer are addressed under Article 14 of the convention [43]. At the country level, Article 7 guides actions to "...reduce, and where feasible eliminate, the use of mercury and mercury compounds, and the emissions and releases to the environment of mercury from sources such as mining and processing" [43].

5.2. Minamata Convention Parties' Commitment in SSA

The Minamata Convention, initially signed by 76% of SSA countries, was established in line with Article 23 of the convention and is governed by the Conference of the Parties (COP) of the UNEP. The COP supports the implementation of the Convention through continuous evaluation and development. In the SSA, 4% of the parties ratified the convention in the 2014–2015 period, 39% in the next 4 years following the initial ratification, and an additional 15% had the convention officially binding in the 2020 to 2023 period. Presently, 58% of sub-Saharan countries have ratified the convention (Table 3). This is expected to positively impact the achievement of Article 19 through the promotion and adoption of Hg-free technologies in the ASGM sector.

Table 3. Participation of the SSA countries in accession and ratification of the Minamata Convention (data source: Minamata Convention Parties 2023).

No.	Action	Year	Party	% of SSA
1	Signature	2013–2014	Benin, Burkina Faso, CAR, Côte d'Ivoire, Djibouti, Gambia, Kenya, Malawi, Mali, Niger, Nigeria, South Africa, Togo, Uganda, Tanzania, Zambia, Ethiopia, Mozambique, Angola, Burundi, Cameroon, Chad, Congo, Gabon, Ghana, Guinea, Guinea-Bissau, Liberia, Senegal, Sierra Leone, Sudan, Zimbabwe	76
2	Accession	2014–2017	Botswana, Equatorial Guinea, Eritrea, Eswatini, Lesotho, Namibia, Rwanda	15
3	Ratification	2014–2015	Djibouti, Chad	4
		2016–2019	Benin, Burkina Faso, Côte d'Ivoire, Gambia, Mali, Niger, Nigeria, South Africa, Togo, Uganda, Zambia, the DRC, Ghana, Guinea-Bissau, Senegal, Sierra Leone	39
		2020–2023	CAR, Kenya, Malawi, Tanzania, Burundi, Cameroon, Zimbabwe	15

5.3. Towards Mercury-Free ASGM Technologies: Selected Case Studies

Article 19 (g) of the Minamata Convention commits all parties to actively and corporately collect relevant information and research on the "technical and economic availability of Hg-free products and processes and on best available techniques and best environmental practices to reduce and monitor emissions and releases of Hg and Hg compounds." Hg-free gold metallurgy technologies represent a crucial shift in the ASGM sector, aiming to mitigate the severe health and environmental impacts of using Hg [144]. The technologies are categorised into physical metallurgy (gravity, magnetic, and flotation), chemi-

cal/hydrometallurgy (chemical-based cyanidation, halide leaching, and use of alternative lixiviants), and pyrometallurgy (smelting, roasting, and calcination) [145].

Earlier interventions towards the sustainable development of Hg-free ASGM technologies in SSA were supported by the Canadian-based Artisanal Gold Council (AGC) in collaboration with the African Mining Development Council [146]. In Burkina Faso, the government supported the development, production, and establishment of chemical-free ASGM technology. The 1998–2004 "PRECAGEME" Project installed the equipment in 8 pilot-scale mining sites, each with 75–85% efficiency of extracting gold from rocks and 90–95% efficiency of free gold extraction [146]. In the Manica Province of Mozambique, a chemical-free small-scale gold mining technology using centrifugation and magnetic separation of Au was adopted in 2012 at the Clean Tech Mine [147]. Briefly, basins were used to collect mineral material from centrifuge drains, ball mill pipes, and centrifuges, which were water-panned, leaving a mixture of Au, Fe-minerals, and Fe-shavings. A magnet was repeatedly passed over the basins to trap magnetic material until 89–93% pure Au was retained.

The use of sodium borax in the Namayingo and Mubende districts, Uganda, is another alternative to Hg-free ASGM [148]. Sodium borax was used to remove impurities from gold concentrate. The method displayed was more efficient after gravitation and yielded higher gold quantities. The gold concentrate was placed in a plastic container. Equal amounts of borax and a few drops of water were then added to a clay bowl, which was then heated with a gasoline burner or acetylene flame to melt the mixture, after which the molten gold was deposited in the bottom of the bowl for collection. Gold has a melting point of 1063 °C. Borax, when heated, melts and lowers the melting point of the mixture, which then enables all the minerals to melt down and separate. As the process continues, the borax causes further oxidation and breakdown of the other minerals, except Au. Au is unaffected by this reaction and sinks to the bottom of the mixture intact for retrieval.

Other miners used the charcoal and blower method, which took about 30 min. The concentrate and borax mixture were placed in a plastic bag and into a clay bowl filled with charcoal. The charcoal was ignited and kept at high temperatures using a mechanical or hand-operated blower to melt the Au concentrate. The melted Au coalesced at the bottom of the bowl and was then retrieved. Separately, a two-stage gravity separation with a direct smelting method was successfully implemented in Buhere, Namayingo District, Uganda, to increase Au recovery in a Hg-free work environment [144].

In Ghana, a UNIDO-led Hg-free gold processing initiative in 2000 promoted the use of glass retorts for the extraction of Au from the concentrate [149]. However, this technology was not widespread due to the relatively longer processing time (~2 h), higher energy requirements, and the fragile nature of the retorts in the rugged mining environment. Styles et al. [150] identified direct smelting as the most preferred Hg-free Au processing method for ASGM in Ghana for processing small batches of Au concentrate. The technique involved smelting using crucibles containing concentrate and flux mixtures (e.g., potassium or sodium carbonate, silica sand, and borax) at 1200 °C on charcoal, gas, or palm-kernel shell fuel stoves. Smelting was advantageous over amalgamation since no Hg was used, thereby safer, cost-effective and non-technical.

The studies above show that the potential of achieving a Hg-free mining environment is apparent, provided efforts are tailored towards non-technical, cost-effective, time-efficient, and robust technologies applicable in the rugged SSA ASGM terrain [144,150].

6. Conclusions and Future Perspectives

Aquatic Hg pollution is rising due to the rapid expansion and intensification of ASGM in SSA. In general, West Africa reported the highest contribution to aquatic Hg pollution (50.2%), followed by Central Africa (39.6%) and Southern Africa (9.6%), while Eastern Africa contributed below 1%. Contamination of freshwater ecosystems was evident in the ASGM regions, from surface and groundwater, stream sediments, bioaccumulation in aquatic biota, and riparian vegetation. The subsequent environmental health risks to

humans from fish consumption, water use, and exploitation of other water resources from Hg-contaminated aquatic ecosystems were also significant.

From the MIA report synthesis, the following gaps need urgent action to enhance the effective management of aquatic Hg pollution from ASGM in SSA: (1) limited documentation and information of mercury availability, quantification, use, and safe disposal; (2) inadequate capacity and resources to monitor and regulate Hg-related ASGM; (3) unregulated and illegal Hg use in the gold mining sector; and (4) poor implementation and low uptake of Hg-free alternative ASGM technologies.

We recommend the following options as a way forward for the management and control of Hg pollution in aquatic ecosystems in SSA: (1) the regulation and reduction of Hg use in ASGM through the development of alternative Hg-free gold mining technologies, including the physical (gravity, magnetic, and flotation), hydrometallurgical (borax, potassium carbonate, silica sand), and pyrometallurgical methods (smelting and roasting); (2) the identification, development, and strengthening of environmental policies and interventions to phase out the importation and use of Hg in the ASGM sector; for instance, the closure of ASGM that use Hg should be accompanied by offering alternative Hg-free livelihoods with an equal or better economic income; and (3) the implementation of health educational programs within the existing health care structures to inform communities within the ASGM regions of the negative health impacts of Hg use.

Implementing and enforcing regulations on the use of mercury in ASGM is essential. Environmental health and public policies should be implemented to balance the socioeconomic benefits and environmental impacts of ASGM in SSA. Governments and international organisations are increasingly recognising the need for stricter regulations. For example, the Minamata Convention aims to regulate and reduce Hg use, particularly in ASGM [43]. Encouraging the adoption of cleaner and more efficient gold extraction technologies is crucial. For example, gravity concentration, cyanide leaching, or other methods that minimise or eliminate the need for Hg can significantly reduce environmental and health impacts [144].

Furthermore, providing training and education to artisanal miners on the hazards of mercury and alternative practices is essential. Educational training would empower ASGM communities to make informed choices about sustainable and environmentally friendly mining practices. There is a need to focus efforts on regulatory measures, community engagement, and the promotion of cleaner technologies to mitigate the adverse effects associated with Hg use in ASGM.

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