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REVIEW PAPER

Review: Artisanal Gold Mining in Africa—Environmental Pollution and Human Health Implications

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Abstract

About nine million Artisanal and Small-scale Gold Mining (ASGM) workers in Africa and people living near ASGM activities are highly exposed to geogenic and anthropogenic potentially toxic elements (PTEs). Despite the hazards and risks posed by ASGM being well characterized, coordinated multidisciplinary environmental characterization with combined public health studies are limited, with often piecemeal and snapshot studies reported, as highlighted by this review. Furthermore, studies are often not connected with efforts to minimize hazards holistically. Given this, we systematically reviewed the scientific literature on human health hazards associated with ASGM in Africa through Google Scholar, Science Direct, and Pubmed databases. One hundred and seventy-three peer-reviewed papers published between 1996 and June 2023 from 30 African countries were identified. Toxicological environmental hazards were reported in 102 peer-reviewed papers, notably As, Cd, CN, Cr, Hg, Pb, respirable SiO_2-laden dust, and radionuclides. Exposure to PTEs in human biomonitoring matrices and associated health impacts were documented in 71 papers. Hg was the most reported hazard. Gaps in research robustness, regulation and policy framework, technology, risk detection, surveillance, and management were found. Despite international and in-country mitigation efforts, ASGM-related hazards in Africa are worsening. This review paper highlights the need for coordinated action and multidisciplinary collaborative research to connect dispersed isolated studies to better characterize the associated disease burden associated with ASGM in Africa and sustainably maximize the wider benefits of ASGM whilst protecting public health and the environment.

Keywords Arsenic · Cadmium · Chromium · ASGM · Lead · Mercury

Introduction

Artisanal and small-scale gold mining (ASGM) presents serious but preventable hazards (Landrigan et al. 2022; WHO 2016). It occurs in over 80 low- and middle-income countries (LMICs), accounts for 20–25% of gold production, and employs 15–20 million people (WGC 2022). The ASGM communities often work without pollution and safety controls and live in heavily polluted environments (Allan-Blitz et al. 2022; Bugmann et al. 2022; Schwartz et al. 2021; Singo et al. 2022a, b; WGC 2022). Africa produced 677–740 metric tons of gold annually between 2017 and 2021 (Sasu 2023). Burkina-Faso, Democratic Republic of Congo, Ghana, Madagascar, South Africa, Sudan, and Tanzania accounted for the most significant production, with 25–100% attributed to ASGM (Jennings 1999; Schwartz et al. 2021; Seccatore et al. 2014; Uganda-NEMA 2019). Across Africa, surface mining, hard rock mining, mechanized cyanidation and hydrometallurgy are the primary techniques used

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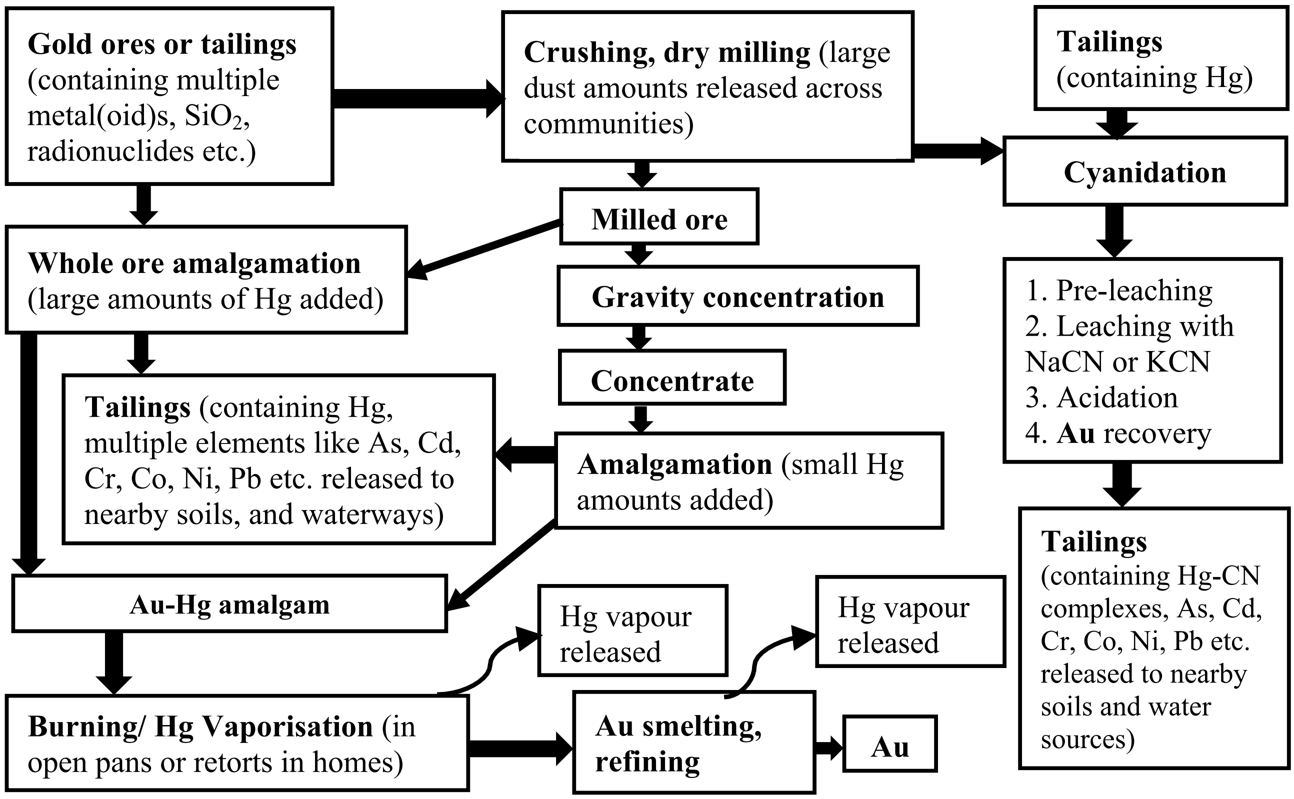
in ASGM depending on the location and value of gold deposits (Table 1). Generally, unsafe working conditions, crude technology, unskilled labour, and poor waste management are significant challenges in ASGM (Basu et al. 2015; Stemn et al. 2021) (Fig. 1) and promoting safer and more sustainable ASGM practices is critical continent wide. The sector has contributed to economic growth and employment in many African nations. For instance, in Ghana, the gold mining industry contributed 7% of the national gross domestic product (GDP) in 2019, with ASGM accounting for 35% (Afrifa et al. 2019; Bakia 2014; Macdonald et al. 2014; Spiegel and Viega 2006; Taux et al. 2022). In Uganda, 7.1 t per year, equating to 90% of the annual gold production, comes from ASGM (Uganda-NEMA 2019). However, limited regulation, inappropriate ASGM technologies, and long gold value chains have resulted in limited economic benefits (WGC 2022) and significant environmental damage and health burdens at the local level (Basu et al. 2015, 2011; Dooyema et al. 2012a; Landrigan et al. 2022; Plumlee et al. 2013; Rajaee et al. 2015a; Ralph et al. 2018) as ASGM activities rapidly expand (WHO 2016).

Detrimental environmental effects, injury, disease, and premature deaths in ASGM are significant issues in Africa (Bose-O'Reilly et al. 2008a; Dooyema et al. 2012b; Gibb and O'Leary 2014; Ismawati 2016; Nyanza et al. 2019; Steckling et al. 2011), a continent severely affected by climate change and strained health infrastructure (Landrigan et al. 2022). The key but neglected hazards to human health in ASGM are potentially toxic elements (PTEs) and physical hazards, most notably airborne dust, gaseous emissions, overexertion, physical injuries and related deaths, excessive noise, excessive heat, and poor ventilation inside the mines. Additional hazards include violence, prescription drugs, alcohol, illicit drug addiction, and a higher risk of infectious diseases, including HIV/AIDS and respiratory ailments (Basu et al. 2015; Singo et al. 2022a, b; WHO 2016; Mbuya et al. 2023). Over nine million workers still directly engage in hazardous ASGM activities in Africa (WGC 2022), putting their lives and those of others at risk. Regulations in the sector are lacking, evolving, or not enforced continent wide (Fritz et al. 2018b; Mallo 2012; Plumlee et al. 2013; Rajaee et al. 2015a; Schwartz et al. 2021; Wireko-Gyebi et al. 2022), leading to unabated degradation of land, waterways, food sources, and air, leading to human exposure to multiple toxic hazards (Bose-O'Reilly et al. 2020; Dooyema et al. 2012b; Keita et al. 2018; Nyanza et al. 2019; Plumlee et al. 2013; WHO 2016).

Multiple toxic hazards, primarily PTEs such as As (arsenic), CN (cyanide), Cr (chromium), Cd (cadmium), Hg (mercury), and Pb (lead); silica (SiO_2); and physical hazards, mainly airborne dust, radionuclides, accidents, and the high risk of infectious diseases are of great public health concern in ASGM across the African continent. They affect

Table 1 ASGM techniques across Africa

Mining method	Location of ore deposit	Equipment used	Value	References
1. Surface mining	Alluvial gravels, sands, sediments, and topsoil in beaches, lakes, streams, and river banks and channels	Buckets, pans, shovels, locally made sluice boxes	Minimal returns per day as small ore quantities are processed	Antabe et al. (2017); Barasa et al. (2016); ELAW 2010); Hagos et al. (2016); Rakotondrabe et al. (2018)
2. Hard rock mining	Gold-bearing veins up to 4500 m below the earth's surface	Deep risky mineshafts dug	Not economical for large-scale mining companies	Arthur-Holmes (2021); Mengistu et al. (2019); Singo et al. (2022a, 2022b)
3. Mechanized cyanidation and hydrometallurgy ("cyanide revolution")	Large rocks are broken using explosives	Compressor pumps, backhoes, river dredges, and high-pressure cannons An alkaline CN leaching process	Greater gold returns as larger volumes of material are processed	Hilson and Monhemius (2006); Knoblauch et al. (2020); Mensah et al. (2022); Razanamahandry et al. (2018); Veiga and Fadina (2020); Verbrugge et al. (2021)



(Abdelaal et al. 2023; Afrifa et al. 2019; Basu et al. 2011; Black et al. 2017; Dooyema et al. 2012b; Gerson et al. 2018a; Lassen et al. 2016; Mambrey et al. 2020; Nsambu et al. 2020; Omara et al. 2019b; Pascal et al. 2020; Plumlee et al. 2013; Rajaee et al. 2015a; Tomicic et al. 2011).

Fig. 1 Summary of ASGM processes across Africa

both ASGM workers and residents living in exposed areas (Basu et al. 2015; Dooyema et al. 2012a; Ismawati 2016; Mambrey et al. 2020; Mtetwa and Shava 2003; Rajaee et al. 2015b; Rakete et al. 2022; Sako and Nimi 2018). Therefore, this review aims to provide a coordinated assessment of environmental and public health studies associated with ASGM in Africa, with the following objectives: (1) Evaluate the documented literature on toxic environmental hazards, related human exposure and health impacts; (2) Characterize the toxic health risks; and (3) Identify continent-wide strategies for mitigating hazards that improve the sustainability of ASGM by reducing the impact on environmental quality and human health.

Methods

The Google Scholar, Science Direct, and Pubmed databases were used with the following predefined search terms: Africa; artisanal small-scale gold mining; artisanal gold mining; environmental pollution; heavy metals; human exposure; health impacts; and names of African countries where ASGM is known to occur. One hundred seventy-three articles that reported multiple toxic environmental hazards in ASGM, most notably PTEs, like As, Cd, CN, Cr, Hg, Ni, and Pb, amongst others; respirable SiO_2-laden dust and radionuclides; related human exposures; associated health effects; and biomarkers and biomonitors of toxic exposures amongst people working and living in ASGM areas in Africa were included. Seventy-seven articles that documented malaria, cholera, and hepatitis; malnutrition; heat stroke; and traumatic hazards, including cave-ins, burns, animal attacks, falls, and weapon-inflicted wounds, were excluded (Moher et al. 2009).

The following variables were extracted from articles and reports that met the inclusion criteria: date of the publication; study area and country; report on toxic hazards in the environment (soil, water, sediment, air, plants, food); report on the toxic hazards identified by human biomonitoring matrices (blood, hair, nails, urine, breast milk, saliva); the number of samples; report on study participants/population; report on interventions or treatment provided and outcomes; particular toxic hazard or risk; and documented health effects.

Results and Discussion

One hundred seventy-three studies published from 1996 through June 2023 (Supplementary Tables 1–5) across 30 different African countries, as presented in Fig. 2, were evaluated. The ASGM activities reported in these publications are spatially concentrated in West, South, East, and Central Africa (Fig. 2). One hundred and two evaluated studies reported toxic environmental hazards (Supplementary Tables 1–3). The human biomonitoring matrices data evaluated in 71 studies present both occupationally ($n = 3{,}749$ subjects) and inadvertently ($n = 3{,}815$ subjects) exposed subjects and associated documented health effects (Table 4; Supplementary Tables 4 and 5). Most residents, non-ASGM workers, farmers, and fishermen were classified as non-occupationally or inadvertently exposed. In contrast, most occupationally exposed subjects were miners, ore processors, and gold traders, who were anticipated to become increasingly exposed due to the nature of their work. Concentrations of PTEs in the blood ($n = 2418$ samples), breastmilk ($n = 120$ samples), hair ($n = 1{,}599$ samples), nails ($n = 329$ samples), and urine ($n = 2{,}948$ samples) were used to estimate exposure. More commonly, environmental concentrations of PTEs in soils, food, water, and air are used to estimate human exposure through predictive models and the associated hazards to health, including cancer risk.

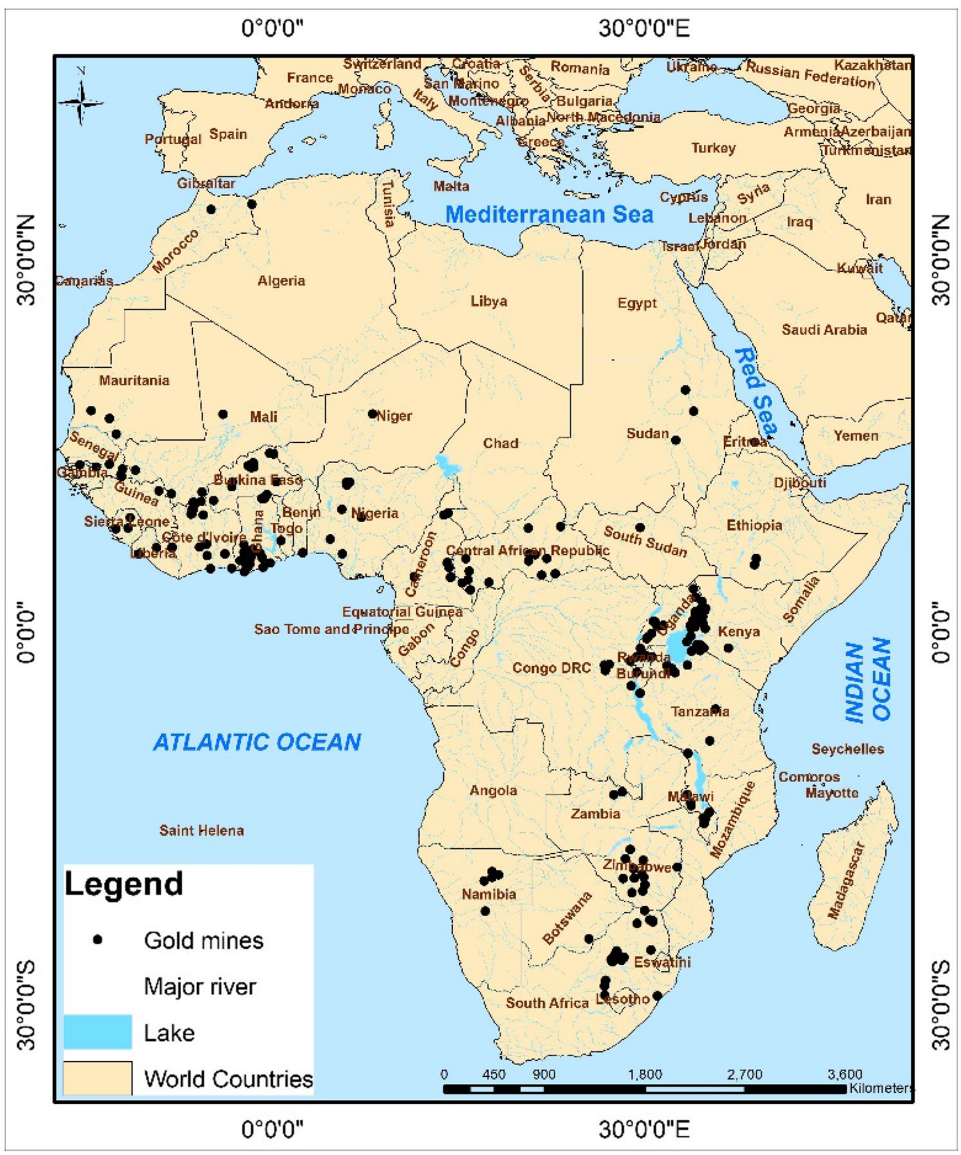


Fig. 2 Map of sampling sites of studies on toxic environmental hazards in artisanal and small-scale gold mining, related human exposure, and health impacts in Africa. (*Map produced using Arc Map 10.4.1, Esri, 2016, using data from the reviewed studies*)

Toxic Environmental Pollution in Artisanal and Small-Scale Gold Mining in Africa

Artisanal and small-scale gold mining negatively impacts the environment during ore exploration and mining, ore processing, gold recovery and purification, and waste dumping (Basu et al. 2015; Haidula et al. 2011; Ngole-Jeme and Fantke 2017; Plumlee et al. 2013). One hundred and two studies reported multiple toxic environmental hazards in ASGM in 30 countries, as presented in Supplementary Tables 1, 2, and 3 whilst summarized in Table 2 for selected PTEs. Exceedance of threshold concentrations of multiple toxic hazards, most notably, potentially toxic metals, As, CN, SiO_2, and radionuclides are given for African examples for soils, sediments, surface and ground waters,

Table 2 Concentrations of potentially toxic elements in environmental matrices in artisanal and small-scale gold mining across Africa

Matrix	Soils	Sediments	Tailings	Wild plants	Food crops	Fish	Drinking water
Units	mg/kg	mg/kg	mg/kg	mg/kg	µg/g	µg/g	µg/L
N samples	1758	810	173	136	95	353	1096
As							
n studies	20	12	12	1	8	3	20
Min.–max	0.01–73,497	0.03–5705	0.03–5830	0.5–798	0.03–19,700	20–2370	0.01–32,556
Mean min.–max	0.4–3199	13–3536	37–793	19.1–91			0.1–6843
Threshold	12 (US EPA)	10 (EU)	12 (US EPA)			0.5 (FAO/WHO)	10 (WHO)
Cd							
n studies	13	3	2	2	1	3	12
Min.–max	0.01–511	ND–25	0.07–9.1	0.1–1.5	1900–10,100	1900–10,100	0.01–4900
Mean min.– max	0.01–24.9	3–14	0.1–5.4	0.2–0.3		–	0.04–534
Threshold	10 (CCME)	2.3 (EU)	10 (CCME)	–	0.2 (FAO/WHO)		3 (WHO)
Cr							
n studies	10	7	2	2	5	–	11
Min.–max	0.7–905	27–1550	13–150	5.1–63.7	44.3–287,000		0.03–20,900
Mean min.– max	62–542	69–1614	2.8–85	11.3–21.9	175–129,000	–	0.1–2480
Threshold	64 (CCME)	81 (EU)	64 (CCME)	–			50 (WHO)
Hg							
n studies	27	10	8	3	22	19	19
Min.–max	0.0002–1830	ND–422	0.001–220	0.1–1920	0.001–355,000	0.01–355,000	0.01–134,000
Mean min.– max	0.02–141	2–5889	0.6–20.5	0.4–0.43	0.003–133		0.1–211,310
Threshold	1 (US EPA)	0.15 (EU)	1 (US EPA)	–	0.5 (FAO/WHO)	0.5 (FAO/WHO)	1 (WHO)
Ni							
n studies	12	7	3	2		–	8
Min.–max	0.08–11,200	9–1187	7.6–766	6.3–36.3			4–1,212,700
Mean min.– max	3.5–7.3	78–831	3.1–229	9.5–18.1		–	10–2370
Threshold	50 (CCME)	21 (EU)	50 (CCME)		67.9 (FAO/WHO)		20 (WHO)
Pb							
n studies	25	13	4	2	4	2	21
Min.–max	0.01–330,000	2–5859	3–11,075	3.2–103	12.4–13,100	400–13,100	0.01–317,000
Mean min.– max	2.4–62,036	29–3220	0.8–1016	24.6–120	16.9–6500		0.05–190,270
Threshold	400 (US EPA)	120 (EU)	400 (US EPA)		0.3 (FAO/WHO)		10 (WHO)

Abdelaal et al. (2023); Achina-Obeng and Aram (2022); Addai-Arhin et al. (2022); Adewumi et al. (2019); Adimado and Baah (2002); Adounkpe et al. (2021); Agaba et al. (2018); Ali et al. (2017); Asante et al. (2007); Babut et al. (2003); Barasa et al. (2016); Bitala et al. (2009); Cobbina et al. (2011); Dooyema et al. (2012); Getaneh and Alemayehu (2006); Green et al. (2019); Haidula et al. (2011); Idris et al. (2018a, 2018b); Ikingura and Akagi (1996); Kamunda (2017); Keita et al. (2018); Khafouri et al. (2021); Kortei et al. (2020); Kpan et al. (2014); Lusilao-Makiese et al. (2013); Magodi (2017); Marriott et al. (2023); Meck et al. (2006); Naicker et al. (2003); Ngure et al. (2014, 2015); Nsambu et al. (2020); Nyanza et al. (2014a); Nyanza et al. (2014b); Odumo et al. (2011, 2014, 2018); Ogola et al. (2002); Ondayo et al. (2023); Pascal et al. (2020); Plumlee et al. (2013); Podolský et al. (2015); Porgo and Gokyay (2017); Rakotondrabe et al. (2018); Razanamahandry et al. (2018); Sako and Nimi (2018); Serge et al. (2019); Ssenku et al. (2023); Thiombane et al. (2023); Uriah et al. (2013); Weleabzgi et al. (2021); Wilson et al. (2017)

fish, food crops and wild plants, and air (Black et al. 2017; Gyamfi et al. 2020).

Before ASGM activities commence, trees and vegetation cover are cleared, and large portions of agricultural land are often destroyed (Pancrace et al. 2022; Rajaee et al. 2015a). Miners typically use traditional methods, primarily indigenous knowledge, to explore gold deposits and break ores into smaller pieces. The ores are ground using locally fabricated ball mills to a fine powder, dispersing dust onto nearby vegetation, food crops, soils, houses, and surface waters. Ground ore is wetted and sluiced to concentrate gold particles. Sluice cloths are then washed in water buckets to remove concentrated gold. Panning separates gold-associated sediment particles, to which liquid Hg is added and kneaded to amalgamate gold in order to separate it from the sediment matrix. Continued panning and amalgamation may result in loss of Hg into discharged water or sediments. However, the Hg–Au amalgam is burnt to vaporize Hg and obtain pure gold, creating a highly mobile and toxic route of Hg exposure (Fig. 1). Sometimes, the Hg is added to the mined ore before or during crushing, a process called complete ore or whole ore amalgamation (Fig. 1) (Afrifa et al. 2019; Lassen et al. 2016).

Arsenic and Pb mainly occur in gold-sulphide deposits as minerals arsenopyrite (FeAsS) and galena (PbS). Other PTEs, most notably Ag (silver), Be (beryllium), Bi (bismuth), Cd, Co (cobalt), Cr, Cu, Fe, Hg, Ni, Mn (manganese), Os (osmium), Pd (palladium), Pt (platinum), Re (rhenium), SiO_2, Sn (tin), and Zn, also occur naturally with gold ores (Doyi et al. 2016; Khafouri et al. 2021; Netshitungulwana 2011; Ondayo et al. 2023; Plumlee et al. 2013; Thiombane et al. 2023). These minerals are relatively stable under natural conditions, but mining and other ASGM activities expose them to oxygen and water, which dissolve and oxidize the metals to less stable and more reactive species (Kaninga et al. 2019; Ogola et al. 2002; Plumlee et al. 2013). Elemental Hg and CN are introduced during ore processing (Clifford 2017; Kristensen et al. 2014; Nyanza et al. 2014a, b; Ogola et al. 2002). Mercury released during amalgam burning can be inhaled or dispersed more widely into the environment. Surface run-offs and wind are important migration routes for Hg and other PTEs from the ASGM process into nearby waters and soils (Nyanza et al. 2014a; Veiga and Hinton 2002; Veiga and Baker 2004). Microorganisms biotransform elemental and inorganic Hg into methyl mercury (MeHg) in waterways. This neurotoxin (MeHg) bioaccumulates in fish and other aquatic animals and often biomagnifies in higher trophic food chain levels, posing risks to fish-consuming communities and persons consuming other contaminated animals and animal products, such as milk, eggs, and meat (Abdelaal et al. 2023; Adimado and Baah 2002; Gerson et al. 2018b; Niane et al. 2015; Telmer and Veiga 2009).

Potentially toxic metals ($n=102$ studies) are the most studied environmental hazard in ASGM, with few studies reporting radionuclides ($n=5$) (Ebongue and Njock 2018; Kamunda 2017; Kamunda et al. 2016; Klubi et al. 2020; Rwiza et al. 2022; Wanyama et al. 2020), silica ($n=3$) (Bråtveit et al. 2003; Gottesfeld et al. 2015; Moyo et al. 2021), airborne Hg vapours ($n=2$) (Black et al. 2017; Gyamfi et al. 2020), and CN ($n=4$) (Knoblauch et al. 2020; Obiri et al. 2006; Porgo and Gokyay 2017; Razanamahandry et al. 2018). Subsequently, Hg is the most documented metal pollutant associated with ASGM (Further detail in Supplementary Tables 1–3).

Across the continent, hazardous wastes generated by ASGM processes are often poorly managed. Tailings with residual Hg and other PTEs; exhausted wastes from cyanidation plants; dust laden with SiO_2 and other PTEs from ore crushers, inside mine shafts and tunnels; and wastewater and gases, including volatile Hg, are often released into the atmosphere, soils, water systems, and food sources untreated (Black et al. 2017; Ngole-Jeme and Fantke 2017; Omara et al. 2019a, b; Podolský et al. 2015; Talla and Moandjim-Me-Bock 2018; Tibane and Mamba 2022). For instance, there are increasing concerns about the extensive drinking water contamination and soil pollution caused by leaching from waste heaps and spillages from tailings storage areas and solution ponds (Basu et al. 2015; Bitala et al. 2009; Hilson and Monhemius 2006; Khafouri et al. 2021; Pascal et al. 2020). Additionally, occuptional exposure through use of CN and its complexes present severe hazards CN for workers and nearby communities (Knoblauch et al. 2020; Porgo and Gokyay 2017). Whilst CN degrades naturally in the environment, high concentrations of CN are acutely injurious to the environment and human health (Razanamahandry et al. 2018). Chemical properties and toxicity of CN depend on various factors, including exposure to light, air, and other metals. In ASGM, Hg-CN complexes formed when Hg-contaminated tailings are reprocessed with CN pose more significant health risks exponentially as Hg becomes readily methylated and more bioavailable (Hilson and Monhemius 2006; Veiga et al. 2009). Thus, the Minamata Convention on Mercury bans the application of CN to Hg-containing tailings and recommends the legal use of CN in gold mining by organized and trained miners in compliance with chemical management protocols (Minamata-Convention-on-Mercury 2021b; Stapper et al. 2021).

Migration Pathways and Routes of Exposure to Multiple Toxic Hazards Amongst ASGM Workers and Nearby Populations

The review found that ASGM is a source of constant high-dose exposure to multiple toxic hazards amongst workers and populations living nearby. The human biomonitoring

Table 3 Potentially toxic elements concentrations in human biomonitoring matrices in artisanal and small-scale gold mining across Africa

Exposure type	Inadvertent exposure					Occupational exposure				
Matrix	Blood	Breastmilk	Hair	Nails	Urine	Blood	Breastmilk	Hair	Nails	Urine
Units	µg/L	µg/L	µg/g	µg/g	µg/g	µg/L	µg/L	µg/g	µg/g	µg/L
n samples	1489	42	682	32		929	78	917	285	
As										
n studies	0	0	2	2	3	14	0	2	0	7
Min.–max			0.1–0.9	0.1–0.7	3.7–280	0–218		0.2–		5.7–700
Median min.–max			0.3–0.4	0.2–0.4	200	2–136				6.8–260
Threshold/ BE					6.4 (Hays et al. 2010)					6.4 (Hays et al. 2010)
Cd										
n studies	0	0	2	2	3		0	0	0	2
Min.–max			0.07–0.6	0.1–3	0.3–0.4					0.1–11.4
Median min.– max			0.2–0.3	0.1–0.7	0.4					0.4–0.6
Threshold/ BE					1.2 (Hays et al. 2008)					1.2 (Hays et al. 2008)
Cr										
n studies	0	0	2	2	1		0	0	0	2
Min.–max			1.6–15.3	2–6.8	20–31					5.7–58.6
Median min.– max			1.1–4.6	3–4.5	25					21–24.2
Threshold/ BE										
Hg										
n studies	11	1	10	1	9	14	1	14	0	21
Min.–max	0.2–1960	0–248	0.01–21	0.01–1	0.03–86.9	0–248	0–10.5	ND–53	0.13–22.9	0.02–3493
Median min.– max	1.1–1689	1.2	0.2–3	0.4	1.4–10.2	2–136	1	0.6–106	0.7–3.5	8.5–70.8
Threshold/ BE	0.58 (So et al. 2021)		1.9		0.16 (So et al. 2021)	0.58 (So et al. 2021)		1.9		0.16 (So et al. 2021)
MeHg										
n studies	0	0	0		0		0	1	0	0
Min.–max								ND–5.3		
Median min.– max										
Threshold/ BE										
Ni										
n studies	0	0	4	2	0		0	0	0	0.17 (So et al. 2021)
Min.–max			2.9–19	2.2–19.2						1.1–25.7
Median min.– max			6.7–7.6	5.4–5.9						5.4
Threshold/ BE										

Table 3 (continued)

Exposure type	Inadvertent exposure					Occupational exposure				
Matrix	Blood	Breastmilk	Hair	Nails	Urine	Blood	Breastmilk	Hair	Nails	Urine
Units	µg/L	µg/L	µg/g	µg/g	µg/g	µg/L	µg/L	µg/g	µg/g	µg/L
n samples	1489	42	682	32		929	78	917	285	
Pb										
n studies	3	0	4	2	1	3	00	0	0	2
Min.–max	36.5–612		17.1–172	8.2–336	1–3.1	0–652				0.2–10.2
Median min.– max	108–3686		29.8–74	17.7–90	1.8	12.7–215				1.1–4.1
Threshold/ BE			1.9 (NHANES)					1.9 (NHANES)		
Zn										
n studies	0	0	4	2	1			0		2
Min.–max			53–271	22.7–214	333–697					64–2089
Median min.– max			88–156	42.8–140	557					437–648
Threshold/ BE	6017 (Poddalgoda et al. 2019)				439 (Poddalgoda et al. 2019)	6017				439

BE biological equivalent

Astolfi et al. (2020); Abrefah et al. (2011); Adewumi et al. (2019); Adimado and Baah (2002); Afrifa et al. (2017); Agaba et al. (2018); Asante et al. (2007); Basu et al. (2011); Bose-O'Reilly et al. (2008a, b; 2010, 2020); Dooyema et al. (2012); Gottesfeld et al. (2019); Harada et al. (1999); Ikingura and Akagi (1996); Kwaansa-Ansah et al. (2010, 2019); Mensah et al. (2016); Niane et al. (2015); Nyanza et al. (2019); Oosthuizen et al. (2010); Paruchuri et al. (2010); Rabiu et al. (2019); Rakete et al. (2022); Ralph et al. (2018); Tayrab et al. (2016); Tomicic et al. (2011); Wanyana et al. (2020)

studies evaluated ($n = 71$) reported significant body burdens of PTEs above thresholds in the blood ($n = 27$ studies), breast milk ($n = 2$ studies), nails ($n = 9$ studies), hair ($n = 28$ studies), urine ($n = 30$ studies), and inhaled air drawn from ASGM workers and nearby populations across Africa as fully detailed in Supplementary Table 4 and summarized in Table 3. Urine, hair, and blood are the most widely used biomonitors, whilst Hg is the most studied hazard amongst ASGM workers and local communities, followed by Pb.

Several critical migration routes and pathways of human exposure to PTEs in ASGM exist. Firstly, there is a common occurrence of incidental ingestion of soils, especially by young children and pregnant women that exhibit pica (Dooyema et al. 2012b; Gottesfeld et al. 2015; Moyo et al. 2021; Nyanza et al. 2014b; Plumlee et al. 2013). For instance, high incidences of geophagy were found in 203 out of 340 pregnant women aged 15–49 years in ASGM areas in Tanzania. The consumed soil was heavily contaminated with various PTEs, including As, Cd, Cr, Hg, Mn, and Ni, posing a severe risk to foetuses (Supplementary Table 3) (Nyanza et al. 2014b). Secondly, inhalation of airborne pollutants, most notably metallic Hg vapours during amalgam burning and respirable crystalline dust containing silica and other PTEs (Afrifa et al. 2017; Black et al. 2017; Gyamfi et al. 2020; Moyo et al. 2021; Tayrab 2017), is a significant pathway in ASGM. The third major exposure route is the ingestion of contaminated water, fish, and other foods (Addai-Arhin et al. 2022; Asante et al. 2007; Niane et al. 2015; Nyanza et al. 2019, 2014a; Rakete et al. 2022; Rakotondrabe et al. 2018; Wanyama et al. 2020). Fourth, in addition to utero exposures, children can be further exposed by consuming PTE-contaminated breast milk from their exposed mothers (Bose-O'Reilly et al. 2008a, 2008b, 2020; Nyanza et al. 2019). For example, in a study, young mothers (15–42 years) living and working in ASGM were found to expose their children to Hg and MeHg through breastfeeding (Bose-O'Reilly et al. 2008b, 2020). Therefore, pregnant women, new mothers, and women who might become pregnant should be particularly aware of the potential dangers of exposure from ASGM and take precautions by halting their participation in ASGM, avoiding geophagy, and seeking medical advice (Bose-O'Reilly et al. 2020; Nyanza et al. 2019). Fifth is the direct contact with PTEs, notably Hg, CN, and contaminated ores and wastes from ASGM processes, including tailings and Au–Hg amalgam washing pond waters (Chetty et al. 2021; Duncan 2020; Laker 2023; Ngole-Jeme and Fantke 2017; Talla and Moandjim-Me-Bock 2018). Detailed investigations linking specific migration routes and pathways of human exposure to particular toxic hazards in ASGM are still limited throughout the African continent.

Human exposure in ASGM varies depending on factors, such as occupation, Personal Protective Equipment (PPE) use, gold extraction technologies, geography, geological characteristics, personal behaviour, and individual biological characteristics, such as age, sex, immunity, and genetic makeup amongst others (Abebil et al. 2023; Afrifa et al. 2017; Bose-O'Reilly et al. 2010; Dooyema et al. 2012b; Godebo et al. 2019; Gottesfeld et al. 2015; Gottesfeld et al. 2019; Tomicic et al. 2011). A relatively high proportion of African women (50–60% of the workforce) engage in ASGM compared to the global average for ASGM (10%). In terms of gender, a high proportion of women are often responsible for ore processing (ore crushing, grinding, transport, sluicing, panning, and amalgam burning), whilst men traditionally explore, prospect, excavate gold ores, and distribute the income from the sale of gold. Women also have a role in supplying mine workers with food, drinks, apparatus, and equipment onsite (Hinton et al. 2003; Wall 2010) and are indirectly exposed to ASGM activities. In some ASGM sites, children are involved in all hazardous ASGM stages: ore extraction, milling, sluicing, amalgamation, and Hg–Au amalgam burning without personal protective equipment (PPE) (Bose-O'Reilly et al. 2007). The reviewed studies reported over 3,000 children (0–17.9 years) that were both occupationally and inadvertently exposed to As, Cd, Hg, and Pb in ASGM (Afrifa et al. 2017; 2019; Bose-O'Reilly et al. 2007; Nyanza et al. 2019; Ralph et al. 2018).

The ASGM activities are often not physically segregated from the communities but rather occur near housing units and other social and economic activities. Thus, even residents of ASGM areas that do not participate in the activities are exposed to similarly significant concentrations of PTEs as the ASGM workers (Astolfi et al. 2020; Bose-O'Reilly et al. 2008b; Bose-O'Reilly et al. 2020; Dooyema et al. 2012b; Niane et al. 2015; Nyanza et al. 2019; Rabiu et al. 2019; Rakete et al. 2022). This is of particular concern since it is estimated that for every active ASGM worker, there are likely to be upwards of ten non-mining family and community members at risk of exposure to PTEs (Harada et al. 1999; Kamunda 2017; Ralph et al. 2018; Steckling et al. 2014b; Tayrab 2017; Tomicic et al. 2011). For example, there were generally no significant differences between recorded exposures for miners and non-miners in a study comparing Hg in urine drawn from miners (mean 3.6 μg/L; range 0.5–9.4 μg/L) and non-miners (mean 4.3 μg/L; range 1.1–12 μg/L) living in Takwa-Ghana and non-miners (mean 3.1 μg/L; range 1.4–5.5 μg/L) residing in Accra. Likewise, in Dunkwa-on-Offin in Ghana, reported mean Hg concentrations in hair drawn from small-scale gold miners (2.1 mg/kg) and non-small-scale miners (2.4 mg/kg) did not significantly vary (Kwaansa-Ansah et al. 2010).

Human Health Impacts of Artisanal and Small-Scale Gold Mining in Africa

Forty-nine studies across Africa have linked premature mortalities and non-communicable diseases. For example, neurological and behavioural disorders, asthma, congenital disabilities, liver, lung, heart, and kidney diseases, blood disorders, skeletal disorders, suppressed immunity, stroke, and cancers in children and adults working or living in ASGM areas. Exposure to toxic hazards, most notably heavy metals, As, CN, and respirable crystalline silica, could be both acute and chronic, as fully detailed for health implications in Supplementary Table 5 and summarized in Table 4. Health effects associated with heavy metal exposure are the most widely studied ($n = 39$ studies) continent wide.

Overall under-studied toxic hazards in ASGM, including radionuclides (Kamunda 2017), respirable SiO_2 (Moyo et al. 2021; Ross et al. 2010; Steen et al. 1997), airborne Hg vapours (Black et al. 2017; Gyamfi et al. 2020), and CN (Knoblauch et al. 2020; Obiri et al. 2006; Porgo and Gokyay 2017) pose significant risks to human health. For instance, a study found that amalgam burners were exposed to higher airborne Hg (702,676,857 mg/m^3) compared to bystanders (141,272,870 mg/m^3) and the 100-mg/m^3 Permissible Exposure Limit (PEL). The 8-h time-weighted average (TWA) readings for 82% of amalgam burners exceeded the PEL,

Table 4 Human health effects of selected toxic hazards in artisanal and small-scale gold mining across Africa

Toxic hazard	Health effectss	Country	References
As	Respiratory infections	Burkina Faso, Ghana	Porgo and Gokyay (2017); Cobbina et al. (2011)
	Skin infections); wounds); Buruli ulcer	Burkina Faso, Ghana	Duker et al. (2006); Porgo and Gokyay (2017)
CN	Respiratory infections	Burkina Faso	Knoblauch et al. (2020); Porgo and Gokyay (2017)
	Skin infections); wounds	Burkina Faso	Porgo and Gokyay (2017)
	Neurological effects	Burkina Faso	Knoblauch et al. (2020)
Hg	Hg intoxication	Burkina Faso, Ethiopia, Ghana, Sudan, Tanzania, Uganda, Zimbabwe	Abebil et al. (2023); Afrifa et al. (2017); Agaba et al. (2018); Mensah et al. (2016); Tayrab (2017); Tayrab et al. (2016); Tomicic et al. (2011); Bose-O'Reilly et al. (2008a, b; 2010, 2017); Steckling et al. (2014a, b); Porgo and Gokyay (2017); Harada et al. (1999)
	Mortalities	Burkina Faso, Cameroon	Tomicic et al. (2011); Ralph et al. (2018)
	Kidney damage	Ghana, Tanzania, Zimbabwe, Ethiopia	Abebil et al. (2023); Afrifa et al. (2017); Bose-O'Reilly et al. (2008a, b; 2010, 2017); Steckling et al. (2014a, b)
	Respiratory problems	Ghana, Cameroon, Sudan, Uganda	Afrifa et al. (2017); Agaba et al. (2018); Mensah et al. (2016); Ralph et al. (2018); Tayrab et al. (2016); Wanyana et al. (2020)
	Musculoskeletal problems	Ghana, Cameroon	Afrifa et al. (2017); Mensah et al. (2016); Ralph et al. (2018)
	Thyroid dysfunction	Sudan	Tayrab (2017)
	Neurological effects	Tanzania, Zimbabwe	Bose-O'Reilly et al. (2008a, b, 2010, 2017); Steckling et al. (2014a, b); Harada et al. (1999)
Hg, Pb	Hypertension	Cameroon	Ralph et al. (2018)
MeHg	Neurological effects (Minamata disease)	Tanzania	Harada et al. (1999)
Pb	Musculoskeletal problems and hernias	Cameroon	Ralph et al. (2018)
	Respiratory problems	Cameroon, Ghana	Ralph et al. (2018); Cobbina et al. (2011)
	Mortalities	Cameroon, Nigeria	Dooyema et al. (2012); Ralph et al. (2018)
	Neurological effects in over 10,000 children	Nigeria	Dooyema et al. (2012)
	Pb intoxication	Nigeria	Dooyema et al. (2012)
SiO_2	Silicosis, tuberculosis, Chronic lung diseases, HIV	Botswana, Ghana, Malawi, Tanzania, Zimbabwe	Abeid et al. (2022); Mbuya et al. (2023); Moyo et al. (2021, 2022); Ohene et al. (2021); Steen et al. (1997); Ross et al. (2010); Rambiki et al. (2020)

with 11% having TWA values that exceeded the Immediately Dangerous to Life and Health (IDLH) level of 10,000 mg/m^3. In addition, the TWA in 86% of ASGM workers at the burn points and 59% of control workers exceeded the recommended exposure limit. The detectable peak air Hg concentration was from 0 to 19, 999 mg/m^3 (Black et al. 2017). Besides, the risk of silicosis, lung cancer, tuberculosis, autoimmune diseases, and deaths is increasing amongst ASGM workers and local community members exposed to respirable crystalline SiO_2-ladden dust in Botswana, Ghana, Malawi, South Africa, Tanzania, and Zimbabwe (Abeid et al. 2022; Moyo et al. 2021; Ohene et al. 2021; Rambiki et al. 2020; Ross et al. 2010). However, the data collected do not accurately reflect the actual burden of the disease since diseases persist or manifest even after workers quit ASGM (Steen et al. 1997). Furthermore, predispositions and positive associations between dust exposure and incidences of cancer and infectious diseases such as COVID-19, HIV, and tuberculosis (TB) have been established in ASGM. Silicosis and HIV infection additively increase the risk of TB infection more than fifteen times (Moyo et al. 2021; Ross et al. 2010) (Supplementary Tables 5).

Once PTEs reach human bodies, their toxicities and subsequent health effects depend on the elemental oxidation state, chemical species, dosage consumed, length and frequency of exposure, age, and behavioural and biological characteristics of the recipient, amongst others. Through various mechanisms of action in exposed subjects' cells, tissues, and organs, PTEs can induce carcinogenicity, cardiovascular toxicity, genotoxicity, hepatotoxicity, immunotoxicity, nephrotoxicity, neurotoxicity, reproductive and developmental, and skin toxicities (Mitra et al. 2022). Health effects occur even at low quantities, acute, and chronic PTE exposures and are either reversible or largely irreversible, ranging from subtle, subclinical changes in function to symptomatic and life-threatening intoxication in the human body. Generally, susceptible sub-populations that need to be aware of health protection measures in ASGM areas are those that are more sensitive to the toxic effects of PTEs (like the foetus, the newborn, children, and sick individuals) and persons exposed to higher PTEs concentrations (like the Hg–Au amalgam burners and ore millers) (Abadin et al. 2007; Chou and Harper 2007; Dooyema et al. 2012a; Fashola et al. 2016; Mitra et al. 2022; Risher 1999; Tayrab 2017). As explicitly discussed in this review, the relative scales of the short- and long-term effects of various toxic hazards in ASGM have not been wholly clarified in Africa.

Neurological Health Effects

Studies ($n = 14$) in ASGM across Africa document neurological effects associated with As, CN, Hg, MeHg, and Pb exposures (Table 4; Supplementary Table 5). Arsenic is known for cognitive impairment of the central nervous system as detailed in Table 5 (Thakur et al. 2021). Studies documented As exposure levels that are potentially detrimental to ASGM workers and residents' health in Ghana (Abrefah et al. 2011; Asante et al. 2007; Basu et al. 2011; Mensah et al. 2020), Kenya (Ondayo et al. 2023), and Tanzania (Ikingura and Akagi 1996; Nyanza et al. 2019, 2014b) (Tables 2 and 3; Supplementary Tables 1–4). Similarly, a few ($n = 4$) studies found Cd concentrations that can potentially have adverse health effects (Adewumi et al. 2019; Asante et al. 2007; Basu et al. 2011; Rakete et al. 2022). No reported studies investigated shorter- and longer-term neurotoxic health effects or As and Cd biomarker effects in ASGM in Africa, contrary to available global evidence (Table 5).

Though limited ($n = 2$), findings of studies on the neurological health effects of CN use in ASGM in Africa (Knoblauch et al. 2020; Porgo and Gokyay 2017) complement the existing broader literature on neurological health effects of CN (Table 5) (Isom and Borowitz 2015). Neurological health effects due to Hg ($n = 25$ studies) and Pb exposure ($n = 14$ studies) are the most widely studied in Africa (Table 4; Supplementary Tables 4 and 5). Mercury (Hg) is known to damage the brain and the nervous systems as described in Table 5 (Zhu et al. 2022). The Hg exposures reported amongst ASGM workers and residents in Burkina Faso (Tomicic et al. 2011), Ghana (Mensah et al. 2016), Tanzania (Bose-O'Reilly et al. 2010; Harada et al. 1999), Uganda (Wanyana et al. 2020), and Zimbabwe (Bose-O'Reilly et al. 2008a; Steckling et al. 2014b) were statistically significantly associated with the neuro-psychological symptoms notably ataxia, dizziness, headaches, excessive salivation, numbness, thoracic pain, Minamata disease, and mortalities (Supplementary Table 5; Table 4), corroborating existing literature.

Besides, poisoning Pb clinically manifests as seizures, encephalopathy, headaches, cerebral palsy, and confusion and can be fatal as Pb exposure increases (Table 5) (Axelrad et al. 2022; Ortega et al. 2021), as reported amongst children in Zamafara, Nigeria (Dooyema et al. 2012b). Existing global literature also links Cu, Cr, Fe, Mn, and Zn to neurological complications, but these health effects are not documented in the reviewed ASGM studies across Africa (Mitra et al. 2022; Tinkov et al. 2021).

Cancer Effects

Clinically Established Carcinogenic Effects

As widely established in the literature (Basu et al. 2015; Landrigan et al. 2022), various cancers are linked to exposure to As (skin, bladder, lung, liver, and kidney cancers); Cd (lung, kidney, and prostate cancers); Ni (lung and nasal

Table 5 Known health effects of toxic element exposure in the global literature

Known health effect	Hazard(s)	Mechanism	Symptoms/ manifestation	References
Cancers	As	Disrupt DNA synthesis and repair); induce cellular injuries and cell death); cause DNA damage and genomic instability); and induce reactive oxygen species(ROS) generation	Skin, bladder, lung, liver, and kidney cancers	Chou and Harper (2007); IARC (2021); Landrigan et al. (2022); Mitra et al. (2022)
	Cd		Lung, kidney and prostate cancers	
	Cr, (hexavalent), Ni, and SiO_2		Lungs and upper respiratory cancers	
	Pb		Lung, stomach, and urinary bladder cancers	
Cardiovascular health effects	Cd	Cd induces Hypertension at low-moderate levels	Hypertension); diabetes); carotid atherosclerosis); peripheral arterial disease); myocardial infarction); stroke, heart failure); increased risk of cardiovascular death	Mitra et al. (2022); Zhang et al. (2022); Zhu et al. (2022)
	CN	CN stimulates biogenic amine release causing pulmonary and coronary vasoconstriction	Pulmonary oedema and heart failure	Zhu et al. (2022)
	Co	Exposure to Co induces cardiomyopathy	Cardiomyopathy); heart failure); fatalities	Mitra et al. (2022); Zhang et al. (2022); Zhu et al. (2022)
	Hg	Hg induces hypertension even at low doses); inactivates paraoxonase); and progresses atherosclerosis	Hypertension); changes in endothelial function); increased risk of coronary heart disease, cardiovascular disease, acute myocardial infarction, and carotid artery stenosis	Mitra et al. (2022); Zhang et al. (2022); Zhu et al. (2022)
	Pb	Increases ROS, reduces NO); increases vasoconstrictor prostaglandins, alters the renin-angiotensin system, lowers vasodilator prostaglandins); disrupts vascular smooth muscle Ca^{2+} signalling); increases inflammation and endothelium-dependent vasorelaxation); and adjusts the vascular response to vasoactive agonists. Chronic Pb exposure increases arterial pressure	Arteriosclerosis and hypertension, thrombosis, atherosclerosis, and cardiac disease	Mitra et al. (2022); Simões et al. (2021)
Dermal effects	As, CN, Cr, and Hg		As poisoning (arsenicosis)); skin hyperkeratosis, hyperpigmentation, Bowen's disease, early skin cancer, and potentially malignant lesions	Mitra et al. (2022); Thakur et al. (2021)
Genetic health effects	Cd	Impairs neurogenesis and inhibits neuron gene expression	Epigenetic effect and endocrine disruption	Gonçalves et al. (2021); Mitra et al. (2022)

Table 5 (continued)

Known health effect	Hazard(s)	Mechanism	Symptoms/ manifestation	References
Hepatotoxic health effects	Cd	Cd changes the cellular redox balance, resulting in oxidative stress and hepatocellular damage	Liver failure and liver cancer	Mitra et al. (2022)
	Cr(VI)	Cr(VI) causes steatosis of hepatocytes); parenchymatous degeneration and necrosis); elevated ROS levels, lipid peroxidation, suppression of DNA, RNA, and protein synthesis); DNA damage); decrease of antioxidant enzyme activity); and mitochondrial dysfunction and liver cell death	Liver damage and liver failure	Mitra et al. (2022)
	Cu	Cu increases oxidative stress	Wilson's disease and cholestatic liver diseases lead to Cu accumulation in the liver	Mitra et al. (2022)
	Pb	Pb increases oxidative stress and causes glycogen depletion and cellular infiltration	Liver damage	Mitra et al. (2022)
Immune suppression	Hg (organic)	Toxicity action is not yet established	Inflammation without mitogens	Pollard et al. (2019)
	Respirable SiO_2	SiO_2 triggers immunological dysfunction and macrophages impairments and increases oxidative–nitosative stress	Chronic inflammation and fibrosis in the lung and other organs	Carneiro et al. (2022); Rupani (2023)
	Pb	-Acute Pb exposure induces multiple immune responses-Pb initiates the production of B and T cells, MHC action, influences cellular and humoral responses, and modifies the role of T cells	Allergies); infections); autoimmune diseases); and cancer, notably lung, stomach, and bladder cancers	Mitra et al. (2022); Zhu et al. (2022)
	Cr, Be, Cd, and Au	varry	Suppressed immunity	Mitra et al. (2022)

Table 5 (continued)

Known health effect	Hazard(s)	Mechanism	Symptoms/ manifestation	References
Nephrotoxic health effects	Inorganic Hg	Acute Hg exposure induces tubular necrosis	Renal dysfunction, a dyspnoea, altered mental status, abdominal pain, excessive salivation, tremors, vomiting, chills, hypotension, proteinuria, and membranous nephropathy	Mitra et al. (2022)
	Cd	Cd alters miRNA expression, affects the proximal tubular epithelium of the kidneys, impairs renal tubular phosphate reabsorption, and, a high Cd dose can cause kidney failure	Chronic kidney disease	Gonick (2008); Mitra et al. (2022)
	Pb	Pb impacts kidneys the greatest and tar	Proximal tubular dysfunction and Fanconi-like syndrome (acute Pb)); Chronic Pb leads to to hyperplasia, interstitial fibrosis, atrophy of the tubules, renal failure, and glomerulonephritis	Gonick (2008); Mitra et al. (2022)
	CN	Fixes cobalt and the ferric (Fe^{3+}) ion of cytochrome oxidase, causing 'histotoxic hypoxia' and lactic acidosis	Kidney damage, renal failure, and associated health problems	Isom and Borowitz (2015); Kirman et al. (2018)
	Cr, Li, and Th	varry	varry	Markowitz et al. (2000); Mitra et al. (2022)
Neurological health effects	As	Cognitively impairs the CNS); induces death of brain cells	Neurodegenerative diseases, pricking sensation in hands and legs	Thakur et al. (2021)
	Cd, Pb	Impairs motor function and cellular activity of the PNS and CNS); induces neural cell death); Pb substitutes Ca^{2+}	Neurodegenerative defects, peripheral neuropathy, neurological disturbances, impaired motor skills and hearing, learning disabilities, mental retardation, behavioural changes, headaches, headaches, seizures, death	Axelrad et al. (2022); Gonçalves et al. (2021); Mitra et al. (2022); Simões et al. (2021)
	CN	Induces neuropoisoning); inactivates respiration); and inhibits cellular energy production	Severe metabolic acidosis); symptoms of acute exposure to CN are convulsions, unconsciousness, and death	Isom and Borowitz (2015)
	Hg	Brain and the nervous system damage	Memory loss, muscle weakness, skin infections); headaches); poor mental function); tremors); emotional changes (mood swings, irritability, nervousness, excessive shyness, insomnia)); neuromuscular changes (muscle atrophy, weakness, and twitching)); and death	Zhu et al. (2022)

Table 5 (continued)

Known health effect	Hazard(s)	Mechanism	Symptoms/ manifestation	References
Reproductive and developmental health effects	Ag, Al, As, Cd, Cr, Co, Hg, Pb, U, and V	Various	*Stunted growth); impaired reproductive function); stillbirths); birth defects in children*	Clarkson et al. (1985); Goutam Mukherjee et al. (2022); Mitra et al. (2022)
Respiratory infections	Al, Be, Cd, CN, Cr, Cu, Fe, Hg, Mn, Ni, Pb, Ti, and Zn	Various	CN induces shortness of breath, chest pain, coughing, and death As, Cd, and Ni cause lung diseases, including asthma, COPD, nasal, and lung cancers	Isom and Borowitz (2015); Mitra et al. (2022); Nemery (1990); Zhou et al. (2022)
	SiO2	Induces pulmonary toxicity); exacerbates the predisposition to tuberculous infection	Lung diseases, including asthma, COPD, nasal, and lung cancers	Patrick et al. (2023); Rupani (2023)
Skeletal health effects	Al, As, Cd, Cr, Cu, Fe, Hg, Ni, Pb, Ti, and Zn		Bone and other musculoskeletal diseases	Reyes-Hinojosa et al. (2019); Rodríguez and Mandalunis (2018)

CNS central nervous system, *PNS* peripheral nervous system, *COPD* chronic obstructive pulmonary disease, *MHC* major histocompatibility complex, *NO* nitric oxide, *ROS* reactive oxygen species

cancers); SiO^2 (lungs and upper respiratory cancers); hexavalent Cr (lungs and upper respiratory cancers); and Pb (lung, stomach, and urinary bladder cancers) (Table 5) (IARC 2021). In the reviewed studies, As, Cd, Ni, and Pb had the most data available using reliable biomarkers (Supplementary Tables 4 and 5). Further research is critical to establishing if reported exposures may be causing cancer in ASGM communities since, to our knowledge, no clinical data exist on cancer rates in ASGM settings in Africa (Supplementary Tables 1–5).

Overall Risk Assessments of Cancer Hazards and Non-cancer Health Effects

Studies ($n = 10$) conducted health risk assessments for cancer and non-cancer hazard indices as results of ASGM operations amongst ASGM workers and local communities (Cobbina et al. 2011, 2013; Gyamfi et al. 2021; Kamunda 2017) (Supplementary Table 5). The cancer risk is generally increasing amongst children from ASGM communities based on the concentrations of toxic hazards detected, most notably heavy metals, As, CN, and radionuclides. For example, a hazard assessment of environmental radionuclides and heavy metals in the Westwits ASGM area in Gauteng, South Africa, found elevated heavy metal concentrations and radionuclides in soils, edible plants, and drinking water. Significant mean activity concentrations (Bq/kg) for radioactive uranium (238U), thorium (232Th), and potassium (40 K) in soil (238U 574 ± 39.5; 232 Th 49.4 ± 8.5; and 40 K 425 ± 129), plants (238U 17.4 ± 3.1, 19.7 ± 1.6; and 232Th 147 ± 9.2), and water (238U 0.7 ± 0.03, 232Th 0.56 ± 0.03, and 40 K 7.4 ± 0.6) were recorded. It was estimated that the heavy metals and the radionuclides posed an increased cancer risk to communities in the ASGM area (Kamunda 2017). Furthermore, a study evaluated human health risks from using CN in gold extraction amongst children and adults in Bogoso, Ghana and attributed most unexplained deaths experienced in the communities to accidental ingestion and dermal contact with CN water (Obiri et al. 2006). From the findings, about 230 and 43 resident adults were likely to suffer diseases related to CN intoxication via ingestion and dermal routes, respectively (Obiri et al. 2006). Findings of a study in western Kenya revealed an increased risk of non-cancer health effects (97) and cancer in adults (4.93×10^{-2}) and children (1.75×10^{-1}) potentially exposed to As, Cd, Cr, Ni, and Pb in 19 ASGM villages in Kakamega and Vihiga counties, Kenya (Ondayo et al. 2023).

Respiratory Problems

Few studies which were limited in range and scope reported respiratory problems linked with exposure to As, Cd, CN, and Pb ($n = 2$ studies), Hg ($n = 6$ studies), and SiO_2 dust in

ASGM in Africa ($n = 6$ studies) (Supplementary Table 5). High amounts of SiO_2-laden dust common in hard rock ASGM mines and SiO_2 exposure are risk factors for silicosis, lung cancer, Chronic Obstructive Pulmonary Disease (COPD), asthma, and death. Silica particles in the lung may trigger tuberculous infection (Patrick et al. 2023; Rupani 2023), as detailed in Table 5. Studies ($n = 6$) reported a high burden of silicosis, pneumonoconiosis, and tuberculosis among ASGM workers despite generally short exposure and latent durations (Supplementary Table 5) (Armah et al. 2021; Mbuya et al. 2023; Moyo et al. 2022; Ohene et al. 2021; Ross et al. 2010), augmenting existing literature (Table 5). Additionally, existing literature strongly and exhaustively links various respiratory problems to Al, Be, Cr, Cu, Fe, Mn, Ni, Ti, and Zn exposure (Nemery 1990; Zhou et al. 2022) (Table 5), which are not widely documented in ASGM contexts in Africa.

Other Health Effects

Studies found skin and wound infections amongst populations exposed to As and CN (Table 4; Supplementary Table 5). Skin and wound infections associated with Cr and Hg exposure (Mitra et al. 2022) have not been studied in African ASGM settings (Supplementary Table 5).

Limited studies that documented kidney damage due to exposure to Hg, Cd, and CN in ASGM continent-wide (Afrifa et al. 2017; Bose-O'Reilly et al. 2008a, 2010, 2017) (Supplementary Table 5). They are consistent with the broader existing literature summarized in Table 5. Health effects of Cr, Lithium, and Thallium on the kidneys are not documented in ASGM across Africa (Markowitz et al. 2000; Mitra et al. 2022).

Tayrab (2017) studied the impact of Hg exposure on thyroid function in African ASGM workers, augmenting existing literature (Table 5), although limited to defining an outcome for thyroid function. These health effects require further comprehensive evidence to define possible links to Hg or ASGM activities.

Findings on Hg and Pb and hypertension in ASGM Africa (Ralph et al. 2018) augment existing literature on health effects of Pb and Hg (Table 5). However, cardiovascular health effects associated with Cd, CN, and Co (Mitra et al. 2022; Simões et al. 2021; Zhang et al. 2022; Zhu et al. 2022) are not reported in ASGM in Africa.

Reproductive and developmental health effects are strongly linked with Ag, Al, As, Cd, Co, Cr, Hg, Pb, U, and V (vanadium) in the broader global literature (Table 5) (Clarkson et al. 1985; Goutam Mukherjee et al. 2022; Mitra et al. 2022). These are not widely studied in ASGM in Africa, except for a few studies ($n = 10$) that reported neurodevelopmental effects of PTEs in ASGM (Supplementary Table 5). The burden of reproductive and developmental health effects associated with toxic exposure in ASGM, notably in Africa, is not documented.

The broader global literature documents the immune-suppressing effects of Pb and Hg (Table 5) (Mitra et al. 2022; Pollard et al. 2019; Zhu et al. 2022), not widely and exhaustively studied in ASGM in Africa. A study reported frequent autoimmune rhinitis in 125 out of 174 Pb- and Hg-exposed miners in Batouri Gold District, Cameroon. However, rhinitis prevalence was not statistically significantly linked to Pb and Hg exposure (Ralph et al. 2018) (Supplementary Table 5).

Documented silica dust and inhaled respirable crystalline silica in ASGM in Africa (Armah et al. 2021; Gottesfeld et al. 2015) point to the potential risk of associated autoimmune diseases, notably scleroderma, rheumatoid arthritis, systemic lupus erythematosus, and some of the small vessel vasculitides with renal involvement (Carneiro et al. 2022; Hoy et al. 2022; Parks et al. 1999) although there are no studies to evidence this link. Even though studies on immune suppression effects are limited in ASGM in Africa, the prevalence of HIV (average 2%) amongst ASGM workers diagnosed with silicosis and increased tuberculosis (TB) (6766 per 100,000 cases) with the severity of SiO_2 dust exposure in Zimbabwe suggested immune suppression (Moyo et al. 2022, 2021). Similar to adverse immune-suppressing effects of Cr, Be, Cd, and Au (Mitra et al. 2022), links between high-dose exposure to respirable silica dust and chronic inflammation, and fibrosis in the lung and other body organs (Carneiro et al. 2022) (Table 5) have not been explored in ASGM in Africa. Any further study would require a comprehensive inclusion of dietary and nutritional status alongside lifestyle and work activities.

Only a few studies ($n = 4$) in ASGM in Africa established musculoskeletal effects, notably low back pains, body pains, myalgia, severe fatigue, and hernias amongst ASGM workers and residents exposed to Hg and Pb (Afrifa et al. 2017; Mensah et al. 2016; Ralph et al. 2018; Tayrab et al. 2016) (Supplementary Table 5).

Risks Characterization of ASGM in Africa

The ASGM risks in Africa are complex and influenced by scale, techniques, regulatory environment, and PPE usage (Afrifa et al. 2017; Landrigan et al. 2022). Thus, risks should be characterized based on context. Reviewed data revealed similar dynamics of potentially toxic metals, As, CN, radionuclides, and SiO_2 contamination in soil, dust, sediment, water, food, and air, with identical migration routes in ASGM across Africa (Table 2; Supplementary Tables 1–3). The ASGM workers and community members were exposed to significant concentrations of PTEs in the reviewed countries (Table 3; Supplementary Table 4). Most studies documented Hg, Pb, and As exposures and related health effects at low to moderate concentrations. The health effects generally included cell, tissue, system and organ damage, and metabolic disorders amongst exposed individuals and populations (Table 4; Supplementary Table 5). Exposures and risks to human health from under-studied respirable crystalline SiO_2 dust, radionuclides, inhalation of airborne Hg vapours, CN, and other critical heavy metals in ASGM in Africa were underreported (Supplementary Tables 1–5). In order to reduce ASGM-related exposures, wet ore crushing, and milling, mechanization, extended sluice channels, and non-toxic alternatives, like borax and retorts, amongst others, have been developed and deployed in some African countries (Appel and Jonsson 2010; Aslam et al. 2022; Barasa et al. 2016; Mitchell et al. 2021; Steckling et al. 2014a; Stoffersen et al. 2019). However, adoption rates of these alternatives for ASGM in the field is low throughout the continent. This is attributed to technical issues, such as development process and complexity, know-how transfer, and adaptability of new technologies in changing environments; ASGM workers' level of organization, responsiveness to ASGM workers' varying needs; and the extent of supply chain collaboration (Keane et al. 2023).

This review highlights gaps in African literature compared to global evidence.

Gaps in the Representativeness of Exposure and Health Effects Research in ASGM and Inclusion of Vulnerable Groups

Less focus is put on exposure and health effects research in ASGM in Africa ($n = 173$ studies reviewed across 30 countries). Furthermore, limited studies represented foetus ($n = 3$) and children between 0 and 7 years ($n = 10$) who are most vulnerable to the toxic effects of various toxic hazards. The reviewed studies cover other vulnerable groups, notably young women and highly exposed ASGM workers (Supplementary Tables 4 and 5). Ethical boards, national and local environmental and health authorities, and all relevant stakeholders, including ASGM communities, should be involved in early development and all other research processes and decision-making phases. Uncertainties around involving vulnerable groups should be resolved (von Stackelberg et al. 2022; World-Bank 2020).

Data Availability, Transparency, and Quality Gaps

Similar to past efforts to build secondary data sources (Steckling et al. 2014b), this review faced data availability, transparency, and quality challenges across the African continent. A defined continent-wide research agenda in the ASGM context is critical in line with existing global initiatives, notably the Global Mercury Partnership (Minamata-Convention-on-Mercury 2021a) and the World Bank's agenda, recognizing the 'big global data gap' (Keane et al. 2023; World-Bank 2020). Contrary to Europe (Apel et al. 2017; Černá et al. 2017; Schmidtkunz et al. 2019) and North America (Control and Prevention 2015; Haines et al. 2017; Saravanabhavan et al. 2017), amongst other developing countries, human biomonitoring (HBM) at a national level that includes PTEs outside of an occupational exposure environment is uncommon in Africa (Watts et al. 2021). As there are few or no reference values and biological equivalents for evaluating toxic exposure data in the context of human health in the African population, it was challenging to interpret biomonitoring data in recent studies (Nakaona et al. 2019; Ondayo et al. 2023). Future efforts should be focused on developing these in Africa. There is also a need to practically assess and update existing environmental and biomonitoring limits in order to consider low-level, chronic toxic exposures in Africa since most PTEs, for example, Pb, have been shown to have profound effects even in low to moderate concentrations (Axelrad et al. 2022).

Gaps in Assessing Toxic Hazards and Exposures, Methods Used, and Study Robustness

Highly diverse exposure assessment approaches notably sampling and analysing up to 58 PTEs in environmental (Table 2; Supplementary Table 1–3) and human (Table 3; Supplementary Table 4) media; use of risk indices; and in limited studies, use of biomarkers of effects (Abebil et al. 2023; Afrifa et al. 2017; Bose-O'Reilly et al. 2008a, 2010, 2017; Knoblauch et al. 2020; Tomicic et al. 2011). There is considerable interest in highlighting Hg pollution and its health effects in the reviewed studies. This can be explained by adopting the Minamata Convention on Mercury in 2013 (Minamata-Convention-on-Mercury 2021a). From the reviewed data, it is evident that Hg use in ASGM could be overshadowing other significant toxic exposures and health concerns in ASGM, notably other potentially toxic metals other than Hg, such as As, Cd, Co, Cr, Cu, Mn, Ni, and Zn, amongst others; CN; SiO_2 dust; and radionuclides (Supplementary Table 5). Whilst international literature reports mobility, bioavailability, and toxicities of various toxic hazards (Zhang et al. 2022; Zhu et al. 2022), 90% of ASGM studies in Africa focused on quantifying total PTEs concentrations in various matrices. Few studies focused on elemental Hg vapour from amalgam burning and MeHg in fish, soils, and rice (Black et al. 2017; Gerson et al. 2018a; Gyamfi et al. 2020; Harada et al. 1999; Odukoya et al. 2022) and As speciation in soils (Mensah et al. 2020; Ondayo et al. 2023). It is crucial for future research to explore speciation as it reveals the mobility, bioavailability, and toxicity of elements, ions, and compounds, affecting their reactions and adverse health effects. For example, metallic elements are generally inert, but their ionic salts and chelates have significant bioavailability and toxicity, for example, the carcinogenic potential of various As, Cr, and Ni species (Mitra et al. 2022; Watts et al. 2008; Zhu et al. 2022). The conversion of metallic elements to organic forms makes them more lipophilic, enabling them cross-the-blood–brain barrier, like the case of organic Hg (Zhu et al. 2022).

Studies identifying the contributing role of each PTE from the myriad of other stressors in ASGM are lacking in Africa and globally. A few studies investigated exposures to multiple toxic hazards and linked them to various health effects in ASGM in Africa, but used basic scientific approaches, like hazard indices (HI) (Kamunda 2017; Olujimi et al. 2015; Ondayo et al. 2023; Rabiu et al. 2019; Ralph et al. 2018). However, toxicity mechanisms of multiple elements in a particular human or environmental media can be antagonistic, additive, synergistic, or potentiating (Zhang et al. 2022; Zhu et al. 2022). Thus, the combined health effects of a given mixture depend on individual components, the potencies, and proportions in the mixture. This is a vast knowledge gap both in Africa and globally and enhancing methods and tools for assessing human health risks from combined exposure to multiple toxic hazards, as in the case of most ASGM settings, is critical (Nikolopoulou et al. 2023). Furthermore, dermal exposure to PTEs is an essential pathway in ASGM but has not been studied (Supplementary Table 4).

Gaps in the Health Conditions Investigated, Surveillance, and Associated Burden of Disease in ASGM in Africa

Overall in ASGM in Africa, only one study calculated the burden of disease in 2004, whereby ASGM workers in Zimbabwe experienced 72% chronic Hg intoxication, causing 95,400 Disability-adjusted Life Years (DALYs) in the whole Zimbabwean population (Steckling et al. 2014b). One DALY represents the loss of one year of total health due to premature mortality and prevalent disease cases in a population (WHO 2020). Critical health impacts of toxic exposures, notably genotoxic, hepatotoxic, hepatic, and reproductive effects (Mitra et al. 2022), are not documented in ASGM in Africa (Table 4; Supplementary Table 5). Besides, respective studies did not holistically look at all potential effects of investigated toxic hazards on health (Table 4; Supplementary Table 5). Future research should, therefore, focus on the public health relevance of multiple toxic hazards shown to co-occur in ASGM (Tables 3 and 4; Supplementary Tables 1–5) (Gottesfeld et al. 2015; Kamunda 2017; Knoblauch et al. 2020; Moyo et al. 2022; Ondayo et al. 2023). Few studies ($n=3$ articles) reported communicable diseases, notably malaria, water-borne diseases, tuberculosis, and HIV, amongst other sexually transmitted infections, which are more likely to be prevalent in ASGM given their remote contexts with poor local health systems (Moyo et al. 2022, 2021). Future research should cover associated infections (Moyo et al. 2022, 2021) as these potentially contribute to the systematic health data gap in the ASGM sector at local, national, and regional levels. Furthermore, it leads to insufficient knowledge about the relationship between ASGM activities and the effect of other toxic exposures on human health. Broader international literature shows long-term PTE exposure, chronic disease risks, and spillovers from unmanaged conditions (Allan-Blitz et al. 2022; Landrigan et al. 2022; von Stackelberg et al. 2022; WGC 2022). Mostly in ASGM in Africa, ad hoc surveys reported cancers and other health outcomes amongst ASGM workers, children, and women with no evidence of genetic risks and developmental effects (Supplementary Table 5). Additionally, an evidence gap exists on specific long-term health risks and consequences of each respective toxic hazard, including associated fatality levels in ASGM across Africa.

Gaps in Regional Regulation of ASGM in Africa

The widely informal ASGM sector across Africa operates autonomously without government support (Chupezi et al. 2009), with 70–80% of the sector being illegal (Achina-Obeng and Aram 2022). The remaining 20–30% are legal (Mensah et al. 2022) but often improperly overseen, monitored, and evaluated (Hilson et al. 2018; Keane et al. 2023; World-Bank 2020). For instance, Kenya's Mining Act of 2016 legalizes ASGM nationwide (Fritz et al. 2018b; GoK 2016) but lacks regulations for health, safety, environmental surveillance, and cost–benefit evaluation of ASGM. Considering the evidence of exposures and health effects (Tables 2–4; Supplementary Tables 1–5) in Africa, preventive measures are needed to reduce and eliminate exposures. In contrast, Africa's regional ASGM policies and regulations are critical but lacking (Hilson et al. 2018; Keane et al. 2023; World-Bank 2020). Besides, most ASGM workers and communities are unaware of exposure risks and compensation for risks from ASGM. African countries lack updated compensation criteria for ASGM risks and morbidities. For example, the Medical Bureau and Compensation Commission delayed compensating 200,000 and 700,000 eligible ex-miners in South Africa (World-Bank 2015).

Risk Monitoring and Management Measures in ASGM in Africa

Toxic exposures in ASGM lead to significant health burden-related costs, including reduced work performance, intellectual capacity, behavioural and psychosocial loss, and healthcare costs (Table 4; Supplementary Table 5). These are transferred to future generations, negatively impacting individuals, families, societies, and national, regional, and global economies (Landrigan and Fuller 2015). Regional and global multidisciplinary, multi-sector and multi-stakeholder interventions are crucial for combating Africa's ASGM-related environmental and health risks. Global efforts, including Ramazzini, Minamata Convention, and Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development (IGF) and Collegium Ramazzini, aim to address these and ensure sustainable development. The Minamata Convention urges governments to promote Hg-free gold processing to protect vulnerable populations (Hilson et al. 2018). The IGF supports sustainable mining in 60 countries with minimal adverse environmental, economic, social, and health impacts (Fritz et al. 2018a; Keane et al. 2023). Collegium Ramazzini promotes environmental and occupational hazard reduction in small-scale artisanal mining (Landrigan et al. 2022). Despite all these global efforts, there is still the need for respective in-country, inter-country, and regional multi-sectoral multi-stakeholder interdisciplinary policies and preventive interventions to minimize and eliminate ASGM-related hazards in Africa. In the future, as a region, this paper recommends the following essential action areas:

Research and Systematic Monitoring

Established gaps in toxic hazards and health effects studies between African and broader literature require investment in scientific research and practice improvement across the continent. This is crucial in ensuring an accurate understanding of the environmental and health burdens and risks of ASGM by researchers, regulators, and policy-makers. Updated literature and data will aid in developing comprehensive policies and interventions. Research should focus on critical areas, notably investigating the migration routes and pathways of occupational and non-occupational exposures in ASGM; toxicological studies, including investigations on multiple exposures, biomonitoring of PTEs, and regular medical checks for known associated risks amongst ASGM workers and community members, especially women and children including foetuses and preventing them from harm. Additionally, implementing surveillance systems for ASGM workers, ex-workers, and communities is crucial for best practices (Keane et al. 2023; Landrigan et al. 2022; von Stackelberg et al. 2022; WHO 2016; Wireko-Gyebi et al. 2022; World-Bank 2020).

Improving and Strengthening Legislation, Regulation, and Policy

Governments should acknowledge and provide appropriate support to ASGM. Developing consistent policies addressing poverty alleviation, sustainable rural development, environmental and health impact reduction, productive business environment, and government revenue stability is crucial. These should be consistent for artisanal, small-scale, and large-scale mechanized gold mining (Fritz et al. 2018a; WGC 2022; WHO 2016; World-Bank 2020). Establishing appropriate in-country and regional transparent, non-discriminatory legal and regulatory frameworks for ASGM workers are crucial whilst improving government enforcement and compliance, such as mandatory PPE use and banning child labour, Hg, and other toxic chemical use in ASGM. Governments should also offer regularization incentives. For instance, tax allowances, equipment exemptions, finance, and export assistance for ASGM enterprises (Fritz et al. 2018a; Keane et al. 2023; WGC 2022; WHO 2016; World-Bank 2020). To fully control the ASGM sector, governments must address ASGM workers' legal, organisational, technical, health and safety needs, including cooperatives formation, exposure standards, monitoring, coherent administration, and collaboration with NGOs, donors, and industry (WGC 2022; World-Bank 2020).

Technology Development and Improvement

The ASGM sector is widely informal and unorganized with minimum support or intervention from their governments (Chupezi et al. 2009). Regional multi-sectoral and multi-disciplinary cooperation is needed for investment, improvement, and adoption of affordable, cleaner, safer, and efficient alternative ASGM techniques (Appel and Jonsson 2010; Aslam et al. 2022; Keane et al. 2023; Mitchell et al. 2021; Steckling et al. 2014a; Stoffersen et al. 2019). This includes research and exploration of affordable, cleaner, and more efficient gold recovery alternatives for Hg and NaCN, like the use of borax and retorts; putting in place engineering and mechanical controls to reduce/eliminate occupational and non-occupational dust exposures; and updated technologies for hazard controls, management of wastes in ASGM, medical surveillance and remediation. Further improvements should include increasing access to geological information, adequate management tools, capacity building, and increasing access to finances and appropriate technologies by ASGM workers (Keane et al. 2023; WGC 2022; Zhuwarara 2023). For instance, collective cash and equipment loan schemes aimed at encouraging the formation of groups and the use of required technology in ASGM have been met with little success in Congo, Kenya, Namibia, Zambia, and South Africa (IGF 2017; PlanetGOLD 2020; WGC 2022).

Risk Reduction and Subsequent Elimination

Investing in adequate and proper management of the identified risks is necessary. The first step is identifying and managing risks at the source (Landrigan et al. 2022). This can, for instance, include eliminating PTEs sources in ASGM by substituting Hg, NaCN, and other toxic chemicals used in gold ore processing with less toxic options such as borax and upgrading ASGM technologies used in most countries by adopting the use of retorts and wet milling machines to reduce dust emissions and Hg losses and safe leaching (Appel and Jonsson 2010; Aslam et al. 2022; Mitchell et al. 2021; Steckling et al. 2014a; Stoffersen et al. 2019). Additionally, addressing the low adoption of safer, cleaner ASGM technologies is critical (Keane et al. 2023). The second step is in identifying and managing hazards and risks along the migration pathways (Landrigan et al. 2022; WHO 2016; World-Bank 2020). For example, eliminating the various migration routes and exposure pathways of PTEs through personal protective equipment, traceable mine waste management, and extensive awareness engagement and education amongst ASGM workers and local communities. Informing miners, ore processors, and the community on ASGM policies, PTEs exposures and health risks are also vital. Governments should implement mitigation measures to prevent adverse impacts on public spaces, schools, hospitals, and markets. For example, by resettling communities, relocating schools, remediating contaminated soils, monitoring, and involving ASGM workers and local communities in risk assessments (Smith et al. 2016). Thirdly, identifying and managing risks in ASGM by improving research practice and enhancing legal procedures are critical. Ensuring compliance with occupational, health and safety guidelines, adherence to the recommended limits for respective PTEs exposures, and systematic monitoring of ASGM workers and local community members have significantly reduced and subsequently eliminated risks in developed countries (Allan-Blitz et al. 2022; Smith et al. 2016; WGC 2022).

Detection, Surveillance, and Management of Health Outcomes in ASGM in Africa

African countries should invest in diagnostic capabilities, training, and early disease screening to manage ASGM health burdens effectively. Enhancing healthcare access for ASGM workers, ex-workers, and communities; enhancing surveillance infrastructure; and regionally coordinated health risk collaborations and data exchanges, including malnutrition, mined gold, and illegal transport and purchase of toxic chemicals, like Hg, amongst others, are critical (Smith et al. 2016; WHO 2016; World-Bank 2020; Zhuwarara 2023).

Limitations and Strengths of the Review

Whilst a substantive body of literature was found in the search, this review had limitations; primarily, literature in English was included. This might under-represent some Lusophone (Angola, Equatorial Guinea, Guinea-Bissau, and Mozambique) and Francophone (Burundi, Djibouti, and Togo) countries. Grey literature, which is not available online, was not incorporated. Studies were of variable quality, sometimes old and concentrated in a few countries where established gold deposits were more likely to have been reported widely. The available data in other studies limited our review. Whereas very few studies provided complete datasets to summarize measures of central tendency adequately, most studies lacked information on the distribution and spread of PTEs concentrations or information on the number of samples and subsamples collected and the median. Few studies provided adequate information on data collection and quality assurance checks to provide research transparency and confidence in the study design and sample analyses. Besides, the lack of standard terms for investigated adverse health conditions, such as symptoms of Hg intoxication and Pb intoxication in included studies (Table 4; Supplementary Table 5), may have caused duplication.

However, this review explores environmental and health research in African ASGM communities, offering insights into practices and literature. Additionally, the scientific evidence found for the African continent was adequate to identify and characterize significant ASGM-related toxic hazards to the environment, human exposures, and health risks and allow for comparison with the broader global evidence.

Conclusion

The review reveals extensive ASGM in 30 African countries. The ASGM sector presents major and complex challenges as it is a significant source of widespread environmental pollution and human exposure to toxic hazards, which have detrimental health effects on the ASGM workers and local community members, including fatalities. Thus, there are no quick solutions, as explained in this review. Essentially, there is a continued need for a collective cost–benefit analysis of ASGM in Africa using DALYs calculation and review of legislation, policies, stringent oversight of ASGM operations in the field, and tangible actions to eliminate environmental degradation and human exposure to toxic hazards in ASGM.

In contrast, the overall disease burden of ASGM in Africa remains unknown. This review petitions for country-specific efforts and properly coordinated collaborative continent-wide efforts amongst all countries where ASGM is practised, the World Health Organization, World Bank, the United Nations agencies (UNEP, UNDP, and UNIDO) and Non-Governmental Organizations, academia, and the private sector to identify, design, and implement sustainable solutions for the ASGM sector in individual countries and regionally. The activities are well-documented measures for identifying, assessing, and managing occupational and non-occupational hazards and risks arising from ASGM at the source, along the migration routes and pathways and at the receiving environments, individual human beings and populations as summarized in this review. Similarly, considering the regional magnitude of ASGM practice in Africa, the number of health-related studies in ASGM appears low, with several specific contexts not adequately represented in the existing literature. For instance, twenty African countries have developed National Action Plans for ASGM, focusing on eliminating Hg use and use of CN to reprocess Hg-contaminated tailings. However, apart from Hg and Hg-CN complexes, other toxic hazards of significant public health importance, notably potentially toxic metals, As, crystalline respirable SiO_2 dust exist in ASGM. With concrete holistic actions, addressing the highlighted research and "big data gaps" in ASGM contexts in Africa is possible.

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Declarations

Conflict of interest The authors have no conflicts of interest.

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