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REVIEW

An analysis of the foremost issues with artisanal and small-scale gold mining from Ghana's perspective

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Abstract Ghana has abundant mineral reserves in many of its regions, and gold mining remains one of the country's main sources of revenue. Given Ghana's current position in the global gold market, this review provides insight into the ASGM sector to give an understanding of the pertinent issues in the sector and its role in the socio-economic development of the country. This review assesses the effects of ASGM operations in economic, social, health, and environmental contexts to raise awareness of issues related to ASGM. It evaluates the measures taken to lessen the consequences of ASGM and maintain the sector's long-term viability. This review considers the foremost issues, including continued Hg use in ASGM, recent use of cyanide in ASGM, pollution of water bodies, and toxic metal contamination. It takes into account sustainable measures and remedial techniques that Ghana has implemented to alleviate the negative effects and support best mining practices. The primary factors influencing people to participate in ASGM are the need for quick sources of income, the scarcity of jobs in rural areas, the economic hardship, the need to supplement earnings from other activities like trading, and the comparatively meager profits from agricultural activities. Findings indicated that to gain more traction in addressing the challenges in the ASGM sector, the involvement of the community and direct stakeholders is essential to promoting responsible mining and environmentally sustainable practices. This review will increase awareness and pressure on decision-makers, researchers, and ASGM communities about the relevance of environmental conservation and sustainability.

Keywords Toxic metals · Artisanal and small-scale gold mining · Human health · Remediation · Mercury

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Introduction

Ghana's economy is one of the fastest-growing in the world, but regional trade restrictions, high energy prices, low availability of credit, a high interest rate, low yields from agriculture, a business environment that discourages private sector growth, and a significant amount of government debt are all obstacles to the nation's long-term economic development (USAID, 2022). The rapid growth in Ghana's economy may be due to the diversified sources that influence its gross domestic product (GDP), including services (48.9%), industries (i.e., mining and quarrying sectors including oil and gas) (30.1%), and agriculture (21.0%) (Ghana Chamber of Mines, 2021). The mining industry plays a vital role in the socio-economic development of Ghana because it is the largest tax-paying sector (Ghana Chamber of Mines, 2021; Yeboah & James Nyarkoh, 2022). Over the last two decades, mined gold has accounted for more than 90% of all mineral revenues annually (corporate income tax, mineral royalties, employee income tax, and residual impost revenue) for the Government of Ghana and has a long history that reaches back to the fifteenth century, when Ghana was then called the Gold Coast (Minerals and Mining Policy of Ghana, 2021; Yeboah & James Nyarkoh, 2022). Gold is an essential commodity that contributes to the development of gold-producing countries due to its significance to the global economy (Toroskainen et al., 2018). Gold output increased from 2.82 million ounces in 2021 to 3.74 million ounces in 2022, a 32% increment, making Ghana the lead producer in Africa and overall in 10th position on a global scale (Akorlie, 2023). These earnings have strengthened the international trade position of the country, stabilized the balance of payments, and provided resources that support many commercial activities (World Bank, 2020).

Artisanal and small-scale gold mining (ASGM) has been defined in different countries based on parameters such as the amount of capital put in, the volume produced, the size of the workforce, the level of technology involved, the size of the concession, and the depth of the mine (Malehase et al., 2016). In Ghana, artisanal gold mining is a labor-intensive mineral extraction involving a few groups of often unskilled workers (about four to nine persons) with low capital investment, which uses elementary tools such as shovels, hammers, and pans with low technology on concessions ranging from 3 to 5 acres, while small-scale gold mining involves the use of advanced equipment (more mechanization), including excavators, dredging machines, trucks, and crushers, with medium-sized groups or corporate society in its extraction on concessions not above 25 acres (10 ha) (Aryee, 2001; Bedu-Addo et al., 2019; Brugger et al., 2020; McQuilken & Hilson, 2016; Quarm et al., 2022). Over the years, there has been a substantial move from artisanal mining toward small-scale mining in Ghana due to access to huge capital associated with the entry of local and foreign investors (Brown & Kimani, 2021). In this review, the collective term ASGM will be used to represent both artisanal mining and small-scale mining. Large-scale gold mining could be differentiated from the ASGM sector based on its comparatively high start-up capital requirement, structured operating requirements, advanced technology, conformity to strict regulatory agencies, and higher output (World Gold Council, 2021).

The mining activities in Ghana are governed by the Minerals Commission Act of 1993 (Act 450) and the Minerals and Mining Act of 2006 (Act 703) (as amended by Act 794 of 2010 and Act 900 of 2015 and Act 995 of 2019). The amendments in 2010, 2015, and 2019 were done to manage the adverse effects of small-scale mining and address the payment of royalties (Brugger et al., 2020). Besides these major laws, the environmental issues for all mining activities fall under the Environmental Protection Agency Act, 1994 (Act 490) and the Environmental Assessment Regulations, 1999 (LI 1652) (Bedu-Addo et al., 2019; GHEITI, 2020). The environmental permit of mine operators may be revoked or suspended if there is a breach of any requirement of the regulations or non-compliance with mitigation commitments in an assessment report (Tychsen et al., 2017). Under the Small-Scale Gold Mining Act of 1989, registered and licensed artisanal gold mining operations were legalized and allocated for Ghanaian citizens (Rajaee et al., 2015). Formal ASGM activities are those that are governed by the law (those that have obtained the license and permit), whereas informal ASGM operations are those that are not governed by the law but have the support of influential locals who are not recognized by the law (social license). Although the government issues the license and concession for ASGM operations, a social license is obtained from the traditional landowners, often the chiefs or local leaders who inherited the land from their forefathers (Gatune & Besada, 2020). In Ghana, many ASGM activities are informal and termed *galamsey*, meaning "gather them and sell" (which implies collecting the gold and selling it) (McQuilken & Hilson, 2016; Tulasi et al., 2021). According to Adu-Baffour et al. (2021), the informality of the ASGM sector could also be due to limited finances, a lack of technical support, the likelihood of evading sanctions through bribery, and the limited logistics ability of authorized regulators. Barriers, including difficulties in obtaining a license, land, limited resources, and the perceived longer process to obtain a license (about a year), may be the reason why the majority in the ASGM sector (about 85%) do not have a license to operate formally (Adranyi et al., 2023; Brugger et al., 2020). Thus, the ASGM sector mostly operates outside the authorized framework with little consideration of the impact on the environment and health (Brugger et al., 2020).

In over 80 countries across the world, approximately 15 to 20 million people take part in ASGM and produce about 20% of the recently mined gold supply (World Gold Council, 2022). This encompasses about four to five million women and children and may be how over 100 million people make a living (Keane et al., 2023). In Ghana, the ASGM is carried out in 13 regions among its 16 regions (NAP, 2020). The upsurge in the ASGM sector, especially in rural areas, may be partly due to the few options aside from agriculture (unemployment) and an increasing demand for gold (the high price of gold) (Donkor et al., 2023; Yoshimura et al., 2021). A study identified the main reasons that influence people to take part in ASGM as a quick avenue to generate income, limited jobs in remote areas, economic hardships, to supplement profits obtained from other activities such as trading, and the comparatively low proceeds from agricultural activities (Arthur et al., 2016). The limited job opportunities in Ghana have been reported by the World Bank as a major challenge, as the rate of unemployment is higher when compared to other countries in Sub-Saharan Africa (The World Bank, 2020).

Despite the ASGM's contributions to the economy, the sector faces a lot of challenges environmentally, including water pollution, air pollution, land degradation, and soil contamination. This is because gold is mined from water bodies, forests, alluvial deposits, and underground (Brugger et al., 2020), which perturbs the ability of ecosystem regeneration and vegetation restoration (UNEP, 2001). The activities of this sector involve water (which has led to siltation, suspended solids, and high turbidity in affected streams and rivers) and the use of mercury to extract gold (the amalgamation method), which pose health hazards to miners and people living close to mine sites (Achina-Obeng & Aram, 2022; Brugger et al., 2020; Rajaee et al., 2015). According to Cheng et al. (2023), although there is uncertainty in the data collected, the estimated total annual emission of mercury into the air globally from the ASGM sector (the largest source) has a median value of 892 tonnes (ranging between 640 and 1000 tonnes). The annual Hg used in Africa recorded a median value of 140 tonnes, South and Central America recorded a median value of 272 tonnes, and Asia recorded a median value of 636 tonnes, while contributions from North America, Oceania, and Europe were minor. According to Veiga et al. (2004), Germany and the Netherlands recycle mercury in European waste (i.e., it is cheaper than disposing of it in a hazardous waste facility) and sell it to Asia, Latin America, and Africa. Nonetheless, there has been a ban on the export of Hg from the European Union since 2011 (Friends of the Nation, 2017). The discrepancy between legally imported Hg (Ghana does not produce Hg) and the amount of Hg used is attributed to smuggling (unofficial channels) that end up in the ASGM regions (NAP, 2020). Notably, the ASGM sector accounts for about 80% of Hg emissions from Sub-Saharan Africa (Gyamfi et al., 2021). According to NAP (2020), about 42.5 to 62 tonnes of Hg are used annually by the ASGM sector.

Metals are widespread in the environment, and their concentrations are rising as a result of increased anthropogenic activities, particularly mining. The activities of the ASGM are extractive because they liberate previously uncommon and isolated components from their native matrices in their quest to retrieve the gold and expose them to the environment. Toxic metals (TMs) found above permissible levels have been found in ecological media including soil, water, sediment, crops, and biomarkers in key mining communities. The levels, circulation, and risk of metal contamination in some communities may be related to their proximity to ASGM sites, according to the findings of studies by Bortey-Sam et al. (2015) and Darko et al. (2020). As a result of metal releases and environmental accumulation, mining sites might be thought of as risk areas in relation to metal contamination (Fashola et al., 2016; Rajaee et al., 2015). The complex nature and magnitude of these problems require continuous studies to probe further and eliminate their negative impacts on the ecosystem.

This review gives an overview of ASGM, examines the difficulties facing the sector, and assesses relevant topics, such as the effects of ASGM activity on the environment and people. The review will increase awareness and pressure on decision-makers, researchers, and ASGM communities about the importance of environmental conservation and sustainability.

Gold and Hg amalgamation in ASGM

Ghana's gold deposits can be classified as primary along shear zones in the Birimian gold belts (mesothermal quartz-vein gold deposits) or secondary free gold in conglomerates of the Tarkwaian Banket Formation (paleoplacer deposits) (Milési et al., 1991; Sunkari, 2018). A common method involving an amalgamation stage uses mercury because it is known to be an easy, simple technique that is also not expensive and is accessible. Amalgamation was initially commercialized in Spain and then adapted in 50 A.D. by the Romans (De Lacerda & Salomons, 1998). It is a process of concentration that is done on a table or drum. According to Malehase et al. (2016), the application of mercury to the gold ore or concentrates takes place during the different stages of the extraction process. Mercury may be introduced into a pit to retrieve gold; mercury may be put in ball mills (milling); mercury may be added to a sluice box to facilitate easy capture by agglomeration of little particles (sluicing); mercury may be placed in a pan with black sand (panning); and by rolling and rubbing through the sand to ensure maximum exposure to the gold to form a gold-mercury paste. The amalgam paste is left behind when the sand is washed away in the panning process. Excess mercury may be squeezed out of the amalgam paste with a cloth for reuse at another time. Gold sponge, which is yellowish-brown, is left after heating the amalgam paste with a blowtorch or fire to vaporize the mercury (WHO, 2016). This is then further smelted with borax, a flux that is added to gold concentrate by a miner or at a gold processing facility to eliminate any remaining impurities. This reduces the viscosity and melting temperature of other materials to obtain pure gold when cooled (U.S. Borax, 2018). Figure 1 displays a summary of mining processes.

The majority of the time, ASGM does not employ technological devices to lessen mercury release into the environment. Mercury is often emitted into the atmosphere or discharged along with tailings into drainages. The introduction of an environmentally safe method involving retorts has been poorly patronized in countries including Mozambique, Guyana, Ecuador, Tanzania, and Ghana due to reports that

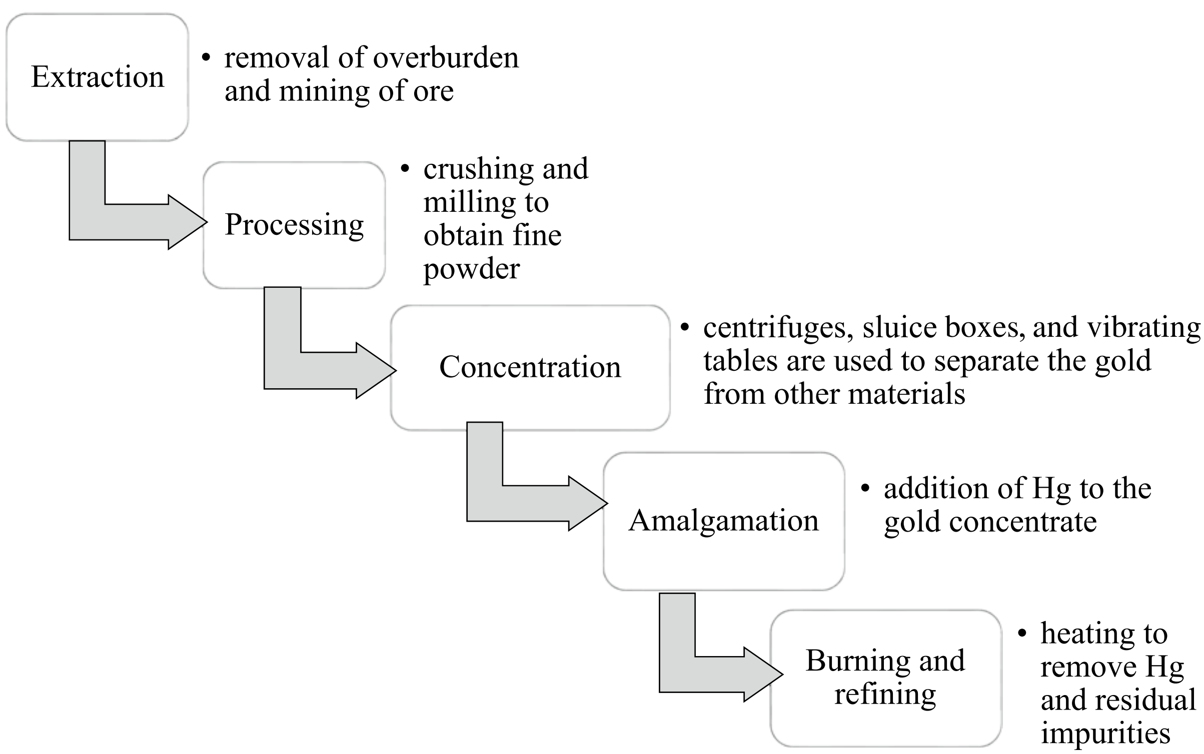

Fig. 1 Summary of the ASGM process, detailing the steps used to obtain gold in Ghana

it consumes a lot of time (slow process); the cost of the retort is fragile (glass), and it has a low capacity (unable to see the gold) (NAP, 2020). Also, it was reported that the gold obtained is brown and affects the price when sold, and gold may stick to the retort when not lined with a thin layer of soot or clay (Veiga et al., 2004). Other negative reports about retorts were stated by Malehase et al. (2016), including decreased production of gold, being cumbersome and not easily accessible on the Ghanaian market and that operating them was not easy. The retort (steel or iron) had been designed to distill off mercury in an enclosed vessel whereby gold is recovered and the mercury vapor condenses back to its metallic state (Richard et al., 2014). This is supported by a study conducted in a mining community in Ghana involving 77 unapproved and 44 approved gold miners, which revealed that 68% of miners did not use retorts but rather an open flame (Rajaee et al., 2015). Thus, mercury is released into the environment in an unrestrained manner. For security reasons, the burning of the amalgam is sometimes done indoors, either in their storerooms or kitchens, and this exposes the household and surrounding residences to mercury vapor. Globally, mercury poses a threat when it is emitted because it has a long atmospheric lifetime and can be transported over long distances before it is deposited (WHO, 2007). According to Veiga et al. (2004), the use of mercury in amalgam by miners could be because miners are not aware of the health risks or have decided to ignore the risk. Also, miners do not readily give information about the quantity of mercury they use in producing the gold, and their activities are intermittent. A study revealed that at an amalgam burning site in an ASGM area, there was a higher concentration of Hg of 10,900 ngm^{-3} and 74,000 ngm^{-3} which was above the 1000 ngm^{-3} WHO guidelines in two different assessments in Myanmar (Soe et al., 2022). In Ghana, Kwaansa-Ansah and Armah (2019) observed that miners were not mindful when handling mercury. This is a concern that needs to be addressed by educating miners about the threat Hg poses to their lives.

Reasons for ASGM

In every continent, with the exception of Antarctica, gold mining takes place usually in remote and underdeveloped locations with minimal infrastructure or alternative kinds of economic activity (World Gold Council, 2021). According to Cossa et al. (2021), artisanal and small-scale mining occurs in about 124 countries: 49 countries in Africa, 35 countries in Asia, 29 countries in Latin America and the Caribbean, 6 countries in Europe, 3 countries in Northern America, and 2 in Oceania. Most low- and middle-income countries (LMICs) have to deal with unemployment and a fast-growing population. According to Brown and Kimani (2021), relatively higher profits are obtained from ASGM operations than from agriculture, hence the conversion of farmlands to mining sites and a decrease in the migration from rural areas to urban areas. This activity is carried out by local or foreign investors who engage some members of the local community in the gold extraction venture to create wealth (Adranyi et al., 2023). Unfortunately, proceeds from ASGM operations are largely invested abroad and in other urban areas, with only a small portion of the proceeds left for the development of host communities (Brown & Kimani, 2021). Hence, the continual dependence on this activity by locals improves their well-being (cyclical poverty). The drive for this activity has been primarily fuelled by universal economic hardship, unemployment, the influence of policies in the sector, and quick alternatives to improve one's livelihood and support their family (Achina-Obeng & Aram, 2022). According to Tychsen et al. (2017), proceeds from mining may be input back into farming activities or used to learn new skills. This is very crucial so that after the end of ASGM operations, miners will have an alternative, sustainable source of revenue. The World Bank has cited the lack of work opportunities in Ghana as a significant issue, as the country has a higher unemployment rate than other Sub-Saharan African nations (The World Bank, 2020). History reveals that the upsurge in ASGM activities due to economic hardship in 1983 was partly due to the implementation of International Monetary Fund (IMF) directives, which also gave access to foreign investment, especially in the mining industry (privatization of mines in Ghana) (Rajaee et al., 2015).

According to Wireko-Gyebi et al. (2020), the complex and cumbersome licensing protocols, corruption on the part of officials, and non-enforcement of laws are causes for the continued illegal mining from the miners' viewpoint. Hence, the government must create an enabling environment that attracts foreign investment and equip the local community to engage in responsible mining practices within the context of the law to ensure sustainable development in the country. Also, an expansion in the informal ASGM sector was recorded in Ghana when the high price of gold attracted foreigners (especially the Chinese), who brought in advanced machines and start-up capital to increase returns (Gatune & Besada, 2020). The registration process is perceived to be costly, prolonged, and demanding, and the low literacy level of miners points to their lack of knowledge of meeting the requirements and the paperwork required to legalize their operations (Adu-Baffour et al., 2021). According to Bedu-Addo et al. (2019), sustainability of the ASGM sector and the maximization of its benefits could be attained if mining is carried out transparently and comprehensively that takes into consideration internationally accepted practices, decreases environmental and health impacts, and safeguards the rule of law. This can be attained by complying with and enforcing the ASGM sector to operate within the Minerals and Mining Act, Regulations, and Environmental Assessment Act (IGF, 2021). Also, a case study in Uganda revealed that a reform in the legal framework resulted in ASGM operating legally (Hinton, 2012). This was achieved when the powers to grant licenses were overseen by the Commissioner of the Department of Geological Survey and Mines (DGSM) instead of the Minister responsible for Minerals, and this ensured that miners were treated fairly (first come, first served) (Hinton, 2012). This coincides with suggestions that the licensing system for the ASGM sector in Ghana should be exempted from parliamentary ratification requirements and the building capacities across the board to improve the sector (Bansah, 2023; NAP, 2020).

Problems associated with the ASGM activities

Nonconformity to legal requirements, limited resources, and limited technical know-how, especially in informal ASGM operations, contribute to environmental and health problems (WHO, 2016). The use of Hg and improper disposal of mine wastes, including tailings (solid wastes), dust, and acid mine drainage (AMD), during the extraction and purification of gold are major problems. The tailings (a mixture of water and finely milled gold-bearing rock) are left behind after the recovery of the gold. According to Fu and Lu (2018), tailings are an eventual contamination source that is extensively generated in mining areas. Also, the reprocessing of these dumps produces dust that affects people in surrounding communities through inhalation and ingestion. Also, air pollution occurs during ore crushing and sieving in the form of solid suspension, in addition to the release of Hg vapor into the air during the burning of the gold amalgam (Eshun, 2005). Asthma, chronic bronchitis, emphysema (an inflammatory and irritable lung disease), pneumoconiosis, especially silicosis, pulmonary tuberculosis (PTB), and asbestosis (lung damage) are common health problems as a result of exposure to dust from mining activities (Yalala, 2015).

Additionally, the extraction of low-grade ores results in the production of mine wastes that contain pyrite and arsenopyrite (FeAsS), which, when exposed to oxygen and water, can oxidize and cause acid mine drainage (AMD) (Anekwe & Isa, 2022). According to Anekwe and Isa (2022), the inflow of acidic water from sulfide-bearing mine wastes and tailings at abandoned and actively mined lands contributes to the contamination of nearby water bodies and soil due to the release of potentially toxic elements at low pH. According to Timsina et al. (2022), AMD was identified in groundwater that was discovered 10 km near a gold mine in South Africa. Moreover, the mine pits and trenches are often abandoned without any remediation strategy to restore the land for other productive uses.

Across the world, Ghana is not a main contributor to the emission of greenhouse gases, although the use of fossil fuels for certain mining activities and deforestation may influence a change in climate, which may negatively affect sectors such as farming, tourism, and fishing (Rajaee et al., 2015). The immediate impact of the ASGM operation is the destruction of ecosystems; however, in the long term, land and forests that naturally act as carbon sinks are affected (Bartrem et al., 2022). According to Bartrem et al. (2022), studies have confirmed that there is an association between mineral extraction, conflict, and climate change (due to changes in temperature that could lead to a decline in food production and a drive toward more ASGM operations). Changes in the rainfall pattern can contribute to the transport of contaminants from mine sites to the surrounding ecosystem.

Alluvial gold deposits found in river sediments have been mined over the years in Ghana and have significantly contaminated major rivers (NAP, 2020). Also, mines are often near rivers or streams because water is needed at different stages for washing, sluicing, panning, and amalgamation. Rajaee et al. (2015) reported poor water quality, noting excessive turbidity, acidic pH values, and nitrate levels that exceed stipulated guidelines in some mining communities in Ghana. Flooding is also a problem in some mining communities, particularly during heavy rainfall, because mining along the banks makes them prone to spilling over (Emmanuel et al., 2018). Indigenous people, especially women, children, and the elderly, living in mining communities may also be exposed to TM transported alongside dust from mining operations by directly inhaling such particles, dermal contact, or ingestion of polluted soils (Kerin & Lin, 2010). It has been found that inhaling arsenic-containing dusts and aerosols increases systemic absorption and has both carcinogenic and non-carcinogenic health effects in mining locations.

When the entry of toxic metals into the body over time exceeds the body's ability to eliminate them through its detoxification pathways, they tend to accumulate in body tissues (Shantakumari et al., 2012). The effects of toxic metal pollution on the health of living things are usually not immediate since they accumulate over time (Briggs, 2003). This has stimulated numerous research projects in this area because of the need to address the effects of metal contamination on ecological media and human health.

Impact of ASGM on miners and residents in mining communities

Although the ASGM sector contributes significantly to the Ghanaian economy, its negative impacts have undermined its advancement, hence the necessity for responsible mining. The fact that ASGM frequently works without a license and with little understanding of the consequences of its unregulated actions has resulted in a variety of problems. The economic, health, social, and environmental effects of ASGM operations are discussed below.

Economic

In 2012, the ASGM sector produced about 34% (1,423,453 ounces) of the total gold (4,313,190.00 ounces) in Ghana (Minerals and Mining Policy of Ghana, 2021). However, output from the ASGM sector fell from 1.175 million ounces in 2020 to 0.098 million ounces in 2021 (91.66%). A decline in the level of gold produced from this sector may affect the economy. This setback was linked to the imposition of a 3% withholding tax on the output of the sector, which was suspected to have caused the exportation of gold through non-official systems (Ghana Chamber of Mines, 2021). It is challenging to estimate the amount of gold generated by informal ASGM operations because not all may be exported through official channels, as some are believed to be smuggled (Hunter, 2020). According to NAP (2020), in Ghana, it is projected that about 1 million people are engaged in ASGM, and indirectly, about 4.5 million are impacted by the sector. Thus, gold sales are used to support miners and other dependents. The proceeds from ASGM activities help the indigenous people support their families and venture into other businesses like trade. According to Hirons (2014), in Ghana, the failure of agriculture to adequately support local communities, a large pool of people looking for work as a result of the entrenchment of the public sector, and low entry requirements readily make the ASGM an option to improve livelihoods. The ASGM sector provides direct work opportunities (to chisel men, engineers, processors, and head potters) and indirect work opportunities (to food and water vendors, drivers, gold dealers, etc.) (Arthur et al., 2016). Also, miners sometimes lose their investment when they mine low-gold-bearing concessions based on trial and error due to a lack of geological information (Friends of the Nation, 2017). This tends to prevent them from backfilling dug pits to restore the land for other productive work. There is a need to improve productivity by employing advanced techniques and responsible mining to achieve a sustainable economy.

Health

The ASGM sector is generally informal, and the workforce may be exposed to unsafe working conditions that may result in injuries, loss of life, and diseases (Minerals and Mining Policy of Ghana, 2021;Siabi et al., 2022 ; World Bank, 2020). In addition, the limited resource setting of the ASGM, along with the low education of miners and the manual operation of equipment, could also contribute to the risk of injuries (Nakua et al., 2019). The health of miners and the local community is exposed to the burning of the gold amalgam or at the gold shop during the melting of gold *doré* (Yoshimura et al., 2021). A study by Donkor et al. (2023) in a mining district of Ghana revealed that about 60 (150 respondents) involved in AGSM operations did not use personal protective equipment (PPE) and attributed it to the high cost of buying PPE in Ghana. Thus, miners and people living close to burning sites may be directly exposed to elemental mercury through the inhalation route during the heating of the gold amalgam (Brugger et al., 2020). This may lead to neurological and behavioral disorders, including emotional instability, memory loss, neuromuscular changes, and tremors (Friends of the Nation, 2017). Also, indirect exposures may occur through dermal contact due to inappropriate handling or storage. The continued illegal ASGM activities imply that more mercury will be emitted into the environment. Also, the ASGM sector requires a lot of manpower and puts stress on the physical body. The economic quandary causes miners to engage in illegal activities at the expense of their health. Diseases reported among ASGM communities include respiratory difficulties, loss of hearing due to vibrations and loud noise, silicosis, and malaria (Brugger et al., 2020). Miners are also at risk of lung disease (silicosis) due to continual exposure to crystalline silica present in some gold dust (Basu et al., 2015). Also, other health impacts identified include accidental falls into pits, cuts from the use of machinery, bruises, and fractures (NAP, 2020). There is a need to improve the well-being of miners and their communities through education and effective monitoring to ensure that health and safety practices are observed during operations (Siabi et al., 2022; World Bank, 2020).

Social

The ASGM sector may be linked with negative social outcomes including violent conflicts, assault, drug abuse, and criminality, although positive social impacts like improving the livelihood of the locals through job creation are also significant (Basu et al., 2015; Quarm et al., 2022). Conflicts over eviction and resettlement arise when sector operations result in the destruction of natural resources and the loss of productive areas (farms). ASGM operators sometimes encroach on concessions belonging to large-scale gold mining companies (LSGM). According to Hunter (2022), the competition for access to land with gold deposits brings about tension. For instance, in some mining areas, LSGM companies have exclusive rights to mine without interference from ASGM operators. This is a contentious issue because, on certain occasions, military troops have been deployed to prevent the invasion of ASGM on concessions belonging to the LSGM companies. Additionally, the locals sometimes strongly oppose ASGM activity due to its negative impact. The expansion of ASGM activities in Ghana's Birim North District has been related to an increase in teen pregnancies and STDs (Basu et al., 2015). In Uganda, the proceeds from ASGM activity are reported to stimulate the sex trade and issues related to HIV/AIDS (Hinton, 2012). Also, some illegal miners engage in substance abuse due to the labor-intensive nature of their operations.

Environment

Globally, the quality of the environment is a major issue of concern because of the increase in anthropogenic activities associated with the demands of a growing population and advances in technology (Artiola et al., 2004). Water and air quality deterioration, land degradation, and soil contamination are some ecological issues pertaining to the ASGM operations in Ghana. Erosion due to the loss of vegetation cover also transports contaminants to nearby water bodies, resulting in siltation (with lateritic materials) and suspended particles in major water bodies. Deforestation and Hg contamination have also been reported. Also, the ASGM operations are not quite limited to a small area, and their widespread use results in the destruction of land. Also, the diversion of rivers, the lowering of the groundwater table due to pumping out water from mine pits during operations, the loss of vegetation, and the conversion of previous farm soil may limit access to safe crops and clean water in ASGM communities (Brown & Kimani, 2021). Protected areas (forest reserves) in Ghana have also been encroached upon, as reported in other countries like Peru and

Mongolia (Barenblitt et al., 2021). According to Dietler et al. (2020), impacts on the environment may be classified under mercury contamination (lack of use of PPE during the burning of gold amalgam in poorly ventilated sheds and spillage into rivers), landscape disturbance (deforestation, improper disposal of tailings and wastes at abandoned mines after the end of operations, uncovered pits that may hold stagnant waters and may serve as a breeding ground for mosquitoes), soil contamination (loss of arable land and contamination of crops), contamination of water (discharge of potentially toxic chemicals such as mercury that may bioaccumulate in fish and discoloration of water bodies), and contamination of air (dust and long-distance transport of gaseous mercury) and physical hazards (noise produced during operations of heavy equipment). A study by Obeng et al. (2019) indicated that respondents identified flooding of farmlands, drying up of rivers and streams, the decline in the quality of water bodies, loss of soil fertility, erosion, and degradation of land as major negative impacts of the ASGM operations in local communities. Key findings from research on the impact of ASGM in Ghana are presented in Table 1.

Foremost issues of ASGM in Ghana

Continued Hg use in ASGM

According to Saim (2021), the intensification of monitoring of illegal mining activities in Ghana and the recent ban on ASGM operations have not significantly reduced Hg usage, as high levels above internationally accepted levels were identified in soil, water, fish, sediment, crops, and mine workers. The underlying factors behind the recurrent use of Hg, irrespective of the above interventions, may be that it is affordable with regard to the price of gold, accessible, and easy to use by individuals in different settings, and miners are accustomed to its use in gold processing (Malone et al., 2023). The continued use of Hg in the ASGM was attributed to the lack of funding to promote the implementation of alternatives through training programs. Moreover, the lack of information about the supply of mercury for miners and the quantitative estimates in ASGM presents a major challenge. According to NAP (2020), Hg may be supplied to miners through informal deals with gold buyers who have an interest in the extracted gold, owners of concessions, and imports from Burkina Faso. A survey

Table 1 Key findings from research related to ASGM operations in Ghana

Source	Finding
Arthur et al. (2016)	Common health issues identified among miners in an ASGM area were asthma, skin rashes, cough, malaria, and pain in the waist and muscles
Bansah (2023)	Nine variables impede the informal ASGM from operating legally. These included political interference in the battle against galamsey, corruption, a lack of effective regulations, a failure to consult stakeholders, resistance from the miners, a failure to recognize the needs of miners, the participation of political leaders in galamsey, a lack of political will, and a lack of understanding of the galamsey sector
Barenblitt et al. (2021)	The collective footprint of the ASGM sector is relatively seven times larger than the few distinct deep impressions left on the landscape by the LSM sector
Dietler et al. (2020)	About 89% (representing 523 out of 588) of miners had little knowledge about the negative health effects of Hg.
Gyamfi et al. (2020)	The level of Hg in the air in the indoor compartments of homes that burned gold amalgam indoors was higher, with an average of 14,800 ngm^{-3}, compared to the homes that did not, with an average of 785 ngm^{-3}.
Gyamfi et al. (2021)	Soils at homes or active mining sites in an ASGM area in Ghana were extremely enriched with Hg, probably from direct spills onto the soil and the burning of an amalgam.
Ovadje et al. (2021)	A study found that there was a 3-fold difference in urine Hg in miners from unregistered sites relative to miners from registered sites.
Sarpong et al. (2023)	The low concentration of metals in surface soil in an ASGM area was attributed to high rainfall in the district, which could have leached the metals into deeper soil layers or runoff into surrounding ecological media.
Yevugah et al. (2021)	Three times higher Hg concentrations in soil were found in intensive mining areas in Ghana in comparison with the non-mining areas, and this was attributed to atmospheric deposition over the years.

in 2019 identified the price for a kilogram of Hg to vary between 875 and 1125 Ghana cedis (175 and 250 US dollars) depending on the demand. However, in Ghana, Hg is applied to concentrate, which does not require as much Hg as in the case of whole ore amalgamation (NAP, 2020).

Also, open burning of gold amalgam in homes for security reasons is a major issue of concern (Keane et al., 2023). In the absence of retorts or personal protective equipment, miners inhale elemental mercury during the melting of the amalgam to obtain gold. Long-term exposure to moderate Hg has been observed to lead to memory loss and tremors (neurological and pulmonary effects); however, deaths associated with acute intoxication are not common (Drace et al., 2016). The erroneous management of Hg and the waste generated is a source of pollution in the environment. The direct release of Hg into the atmosphere is a global problem because of its long lifetime before deposition in aquatic and terrestrial ecosystems, hence the reason the Minamata Convention agreement sought to regulate its manufacture, usage, trade, and consumption (Selin, 2014). However, the continued use of Hg in the ASGM sector in countries including Indonesia, Myanmar, Colombia, Peru, Mongolia, Tanzania, and Ghana may be attributed to poor engagement, weak legislation and enforcement, and a black market supply of Hg (Soe et al., 2022). According to Malone et al. (2023), efforts to discontinue the use of Hg among miners have not been fully realized due to the difficulty in encouraging and keeping up a positive behavioral change, limited resources, and a lack of technical know-how and capacity to shift to alternative methods that take into consideration the complex nature of the various gold-bearing ores.

To implement an integrated measure to replace or reduce the use of mercury in the ASGM sector and ensure safe practices, the government (Ministries, Agencies, and Departments) and other stakeholders (civil society and the private sector) must provide technical support and build the capacity of miners to engage in cleaner techniques, including the use of gravimetric methods, condensing fume hoods, and retorts to manage the emission of Hg in their operations (Schwartz et al., 2021). This would go a long way toward reducing the release of Hg and promoting the safe management of Hg during ASGM operations. The ASGM sector should be encouraged to adopt mercury-free practices through access to finances (GEF, 2020).

Mercury exposure analysis

Mercury is used to get gold out of low-quality ores while leaving behind other impurities. This is because Hg adsorbs on the surface of gold particles (to form $AuHg_2$, Au_2Hg, and Au_3Hg) due to its surface tension being lower than that of gold but higher than that of water, and at low temperatures, Hg forms an alloy with gold by breaking its atomic structural bonds. The lighter gangue material floats on top, whereas the Hg behaves as a medium in which gold sinks (Veiga et al., 2004). Mercury is highly volatile and hence vaporizes into a toxic plume when heated, while gold is left behind. The elemental mercury is circulated in the atmosphere for some time, and then it is oxidized to Hg^{2+} (for example, $HgCl_2$, a water-soluble compound) before deposition onto water and land. This may be converted back to the gaseous form and reemitted, or it may be transformed into methylmercury to enter fish through their skin and gills.

There is the possibility that inappropriate handling, storage, waste management, and direct inhalation will increase Hg exposure in the nearby towns, the general public, and the miners themselves. This is problematic because it could cause damage to the kidneys, the immune system, and the nervous system. For instance, in the 1950s, Japan's Minamata Bay tragedy happened when industrial waste dumped into the bay caused Hg to build up in the fish. High levels of mercury had a detrimental effect on the health of some adults, but the subsequent generation was born with several neurological issues (Harada, 1995). However, Hg is a common air pollutant in communities that engage in intense mining activities (WHO, 2007). Biomarkers for Hg exposure in humans have helped to identify health problems, devise effective healthcare management, and prevent deleterious effects in the future. Table 2 summarizes exposure to Hg due to ASGM operations in communities based on the analysis of human biological specimens including fingernails, blood, hair, and urine. Research outcomes identified that not only miners are exposed to high Hg levels, but the locals in these communities are also at risk (Basu et al., 2015; Markham & Sangermano, 2018). The need to create more awareness and educate miners on the health effects of Hg would help

Table 2 Studies comparing the use of biological specimens in Ghana and other parts of the world

Country	Biological specimen	Finding	Reference
Ghana	Hair, fingernails, and urine	Locals living in the ASGM area were exposed to high levels of Hg, even though the highest exposures were recorded among miners directly involved in the burning of the gold amalgam	Basu et al. (2015); Kwaansa-Ansah and Armah (2019)
Zimbabwe	Blood and urine	A study in an ASGM area identified that out of 207 participants, 92 (33.3%) had Hg levels above the tolerable threshold in at least one specimen, whereas 9 participants (4.3%) had chronic mercury intoxication	Butscher et al. (2020)
Columbia	Urine	A study in two ASGM towns identified that about 67% (25 out of 37 miners) had Hg concentrations in their urine above 5 mg/g of creatinine (the alert level)	Drace et al. (2016)
Indonesia	Hair	The results of a study identified three issues that influence the level of Hg in hair: distance from residence to mining sites, level of education, and distance from residence to the ball mill where they add Hg for processing	Harianja et al. (2020)
Tanzania	Blood	A study identified that about 75% of pregnant women in an ASGM community had blood total Hg above the standard reference of 0.80 $\mu g\ L^{-1}$ while 25% had urinary total arsenic above 15 $\mu g\ L^{-1}$	Nyanza et al. (2019)
Ghana	Blood	Relatively, miners involved in amalgamating the gold, burning the amalgam, and smelting the gold are likely to have higher blood Hg levels than other miners who do not take part in such activities	Saalidong and Aram (2022)
Myanmar and other Southeast Asian countries	Hair	The consumption of Hg-contaminated fish (endogenous) and the adherence of elemental Hg to human hair in ASGM influenced the high Hg concentration in human hair	Soe et al. (2022)
Uganda	Blood, urine	The high median blood Hg level of 136 $\mu g\ L^{-1}$ and urine level of 105.5 $\mu g\ L^{-1}$ of miners in Mubende, an ASGM area, were above the WHO threshold of blood 15 $\mu g\ L^{-1}$ and urine 25 $\mu g\ L^{-1}$, respectively	Wanyana et al. (2020)

reduce and probably eliminate its usage, as projected by the Minamata Convention treaty.

Recent use of cyanide in ASGM

Over the years, the cyanidation method was introduced when sulfide ores were mined because the mercury reacted with sulfur, thus reducing its ability to isolate the gold and making the amalgamation method less efficient. According to Verbrugge et al. (2021), emerging evidence in many ASGM areas like Mali, Burkina Faso, and Indonesia indicates that although the conventional method for processing gold remains mercury, it is being complemented or gradually replaced with the cyanidation technique. High recoveries of residue gold in mine waste are reported for processing with cyanide, whereas mercury tailings from ASGM operations in Ghana contained a considerable amount of unrecovered gold, which may be associated with inefficient grinding as gold was trapped in smaller size fractions (Cobbinah et al., 2021). According to Macdonald et al. (2014), tailings from ASGM are sent through unofficial channels to larger processors or countries like Burkina Faso and Cote d'Ivoire for the application of cyanide. This is because the ASGM sector is not permitted under the current laws to use cyanide or other leaching techniques, although cyanide is used in the northern and eastern regions of Ghana (Friends of the Nation, 2017).

A case study of operations in Burkina Faso detailed the leaching process as dug ponds in fenced fields are used to decant tailings submerged in cyanide and water solutions. According to Drace et al. (2016), cyanidation involves the use of sodium cyanide, which reacts with elemental gold under aerobic conditions to form a complex and is reported to be more efficient than the use of mercury. The gold is solubilized in a basic solution and separated from the gangue material. Merrill Crowe's cementation method, which reduces the gold complex to elemental gold by precipitating the gold on the surface of zinc shavings, or the carbon-in-pulp method, which uses activated carbon to adsorb from the solution, are the two techniques used to separate the gold from a cyanide solution. The complexes comprising gold and cyanide are desorbed at elevated temperatures and pH. Finally, the gold is separated from the solution after being reduced in an electrowinning process (Drace et al., 2016).

According to Malone et al. (2023), in practice, instead of replacing the use of Hg with cyanide (a traditional gold extraction technique in mining industries), the ASGM sector recovers gold residue from mercury-treated tailings in about fifteen countries. The recovery of gold using cyanide on mercury-laden tailings poses a higher health risk as the methylation of mercury renders it more readily available for absorption by organisms (Verbrugge et al., 2021). Hence, the Minamata Convention requires the removal of Hg from sediments or tailings before the use of cyanide and seeks to eradicate such practices (Keane et al., 2023). According to Amara et al. (2022), residual Hg in barren black sand should first be removed by panning before using sodium cyanide (NaCN), activated carbon, and zinc shavings to recover the gold. However, the combination of Hg and cyanide would worsen the risk to the environment and human life. To ensure safety, cyanide must be used with precautions. Also, the use of cyanide to extract low-quality ores is associated with an increase in hydrogen cyanide emissions, tailing production, and global warming (Fashola et al., 2016; Kosai et al., 2023). A study in Ghana by Tulasi et al. (2021) indicated that the reprocessing of Hg-laden tailings with cyanide facilitated Hg mobility and solubility, resulting in a potentially greater rate of methylation in sediments from the River Aprepre. Hence, this technique requires expertise, equipment, and high capital to increase gold output. Through word of mouth, informal learning, and illustrative effects, the transition from the use of Hg to cyanide is expected to cause the ASGM sector to align with best practices that reduce the negative impacts and enhance gold production (Malone et al., 2023).

Pollution of waterbodies

ASGM operations often occur close to water bodies because water is used, especially during the washing stage. A study in an ASGM area in Ghana identified four challenges: mining on the river bed and diversion of the path of the Fena river; potential toxic metal contamination (Cd, Fe, and Pb) of the river associated with the elevated levels of suspended solids; and the subsequent rise in the cost of treating the water as more chemicals are required to purify the water, which may lead to the closure of treatment plants; disruption in the normal flow of the river due to waste rocks and sludge; and a decline in the level of fish caught in the river by fishermen (Duncan, 2020). Also, the heavy reliance on water for the processing of the gold ore, the discharge of mine effluent, and seepage leaching from abandoned tailings are sources of water contamination. These contaminants may make the water unsafe for drinking, irrigation, and other domestic purposes due to a decline in its quality, particularly surface water.

Also, mining along the banks of rivers results in flooding during the rainy season, besides the destruction of the natural environment and aquatic life (Kazapoe et al., 2023). The discharge of untreated effluent containing cyanide and Hg into rivers has polluted waterbodies in the Philippines (Soe et al., 2022). Four reported major impacts of the ASGM activities on water bodies in terms of quality include erosion of riverbanks resulting in sedimentation and contamination of aquatic ecosystems, toxic metal leaching and contamination, contamination from chemicals used in the processing of gold, and acid mine drainage (AMD) (Emmanuel et al., 2018; Timsina et al., 2022). According to Kinyondo and Huggins (2020), the pollution of surface water with fecal matter (poor sanitation) is likely since temporal structures are mounted at ASGM sites, which are often located in rural areas. A study on three main rivers (Pra, Oda, and Offin) in Ghana indicated intense color obliteration and elevated turbidity values, which suggest the presence of suspended materials possibly from the ASGM operations along the river banks and upstream (Nunoo et al., 2022). Thus, effective management of the water used in mine operations and proper treatment of effluents before release into water bodies are crucial.

Toxic metal contamination

The upsurge of unregulated ASGM activities has left behind heaps of scattered mine wastes that are exposed to oxidation and harsh weather conditions (high rainfall and a hot climate in the tropics), leading to a chemical transformation that may increase metal availability and mobility to other surrounding ecological media. According to Rakete et al. (2022), several factors, including the use of chemicals, concentrations of metals in the soil, fish, water, and aerial dust, result in high levels of toxic metals in people living close to ASGM sites or directly involved in ASGM activities. The release of high levels of toxic metals, particularly arsenic (As), cadmium (Cd), and lead (Pb), that occur along with the gold-bearing ores due to the geological formation has been reported in ASGM areas (Fashola et al., 2016; Rajaee et al., 2015). The physical characteristics of some toxic metals, such as As (such as no odor, no color, and no flavor), make the identification and prevention of drinking contaminated water an issue of concern (Marshall et al., 2007). History records mass poisoning in Bangladesh as the largest as a result of the population drinking groundwater that was contaminated with naturally occurring As and was at risk for cancer and organ dysfunction (Smith et al., 2000). Locals in an ASGM area of Ghana who were exposed to elevated concentrations of As in drinking water and food crops were susceptible to Buruli ulcer infections due to arsenic's immunosuppressive effects (Duker et al., 2004). According to Basu et al. (2015), drinking water with an arsenic content of more than 50 μg/L is associated with an increased risk of cancer of the bladder, kidney, liver, lungs, and blood pressure; anemia in pregnancy; obstructive lung diseases; respiratory disease mortality; skin lesions; and problems with neurodevelopment. Lung cancer is an occupational hazard that miners are often at risk of because of inhalation exposure because cadmium is produced during the heating and melting of gold-bearing ores (smelting) (Genchi et al., 2020). Cadmium damages organs like kidneys and bones when it gets into the body and can be detected in urine due to damage to proximal tubular cells (Wuana & Okieimen, 2011). A study found high levels of Cd (13.2 mg/kg) and Hg (2.02 mg/kg) in soil from an ASGM area in Ghana (Wiafe et al., 2022).

Also, exposure to Pb, a neurotoxin, impairs development in children. It was revealed by Cecil et al. (2008) that an adult who was exposed to Pb when they were children had a reduction in their brain volume (grey matter), precisely these parts (prefrontal cortex and anterior cingulate cortex), required for mood regulation, decision-making, and executive function. Dooyema et al. (2012) reported the deaths of children below 5 years of age and high blood concentration in 97% (out of the 204 remaining children) who required chelation therapy as a result of lead poisoning, which was attributed to ASGM activities in Nigeria. Small children are more likely to suffer adverse effects from toxic metals than adults because of how their bodies work. For instance, bone remodeling for skeletal growth during pregnancy and in young children results in the release of Pb stored in the bones into the blood (Barbosa et al., 2005).

TM contamination in soil can also result from atmospheric deposition, which includes precipitation and dust, or direct disposal of waste on the soil (WHO, 2007). This has had a significant impact on the ecological balance due to the decline in bacterial species that facilitate nutrient cycling in soils (Fashola et al., 2016). Previous studies carried out in mining areas have revealed high metal contamination in cassavas (*Manihot esculenta*) grown in mining areas in Ghana (Armah et al., 2014; Bortey-Sam et al., 2015). Ingestion of plants that have an elevated concentration of TM can affect the health of grazing animals. Moreover, amphibians are reported to be affected by TM contamination due to their exposure to aquatic life during the breeding stage, their unshelled eggs, and the permeability of their skin (Markham & Sangermano, 2018). Thus, the loss of habitat and the possible risk of exposure may cause the extinction of some species. The issue of TM contamination due to informal ASGM operations highlights the necessity for environmental protection measures to stop the release of these metals.

Sustainable approaches

According to Schwartz et al. (2021), strategic initiatives to mitigate risk due to ASGM activities should be comprehensive to prevent the release of contaminants, including improved gold ore processing techniques (such as gravimetric methods, retorts, or alternative chemicals), taking into consideration the properties of the ore, available resources, and capacity training of miners to understand the risks from exposure to potential toxic metals to their health and that of the local community. The Minerals Commission in Ghana has established nine district centers in designated mining areas made up of 38 mining committees to ensure the regulation and efficient management of ASGM operations (Friends of the Nation, 2017).

The president of Ghana commissioned 100 gold processing machines (mercury-free) called Gold Kacha, which consists of a crusher, miller, concentrator, and smelting system (Minerals Commission Ghana, 2021). This device is mercury-free recovery equipment that is reported to be very efficient. Also, Sika Bukyia is another smelting kit developed by the University of Mines and Technology (UMaT). According to NAP (2020), gold concentrate is mixed with chemical fluxes and placed in a furnace at high temperatures, and it is reported to give high recoveries relative to amalgamation (NAP, 2020).

Three initiatives that have been introduced to formalize the ASGM operations include the Ghana Artisanal and Small-Scale Mining Formalization Project (GASMFP), the Inter-Ministerial Committee on Illegal Mining (IMCIM), and the Community Mining Program (CMP) (NAP, 2020). The GASMFP is a 5-year joint scheme between the World Bank and the Ministry of Lands and Natural Resources with the intent to solve environmental issues, strengthen regulatory laws, provide other ventures besides illegal mining, and build technical capacity. In 2019, the CMP sought to improve livelihoods and create jobs for the locals in mining communities by encouraging them to carry out responsible and sustainable small-scale mining within the legal framework. The goal of this initiative was to improve miners' working conditions and minimize the degradation of the environment (GHEITI, 2020). According to Drace et al. (2016), to improve the health of locals in the mining communities and their environment, a united effort that involves the participation of miners, the host community, and support from the government is crucial to sustaining the ASGM sector. Thus, the CMP ensures that proceeds are distributed fairly among direct shareholders, which encompass miners, landowners, and traditional authorities (host community participation). In 2017, IMCIM was assigned to vet and verify the licenses of mining firms, set up tracking devices on registered excavators, and train about 4500 miners on best practices (NAP, 2020).

The AKOBEN program, which was initiated in 2010 to operate as a monitoring and verification tool to achieve sustainability and environmental compliance in the LGM sector, is to undergo some modification in the near future so it can be adapted in the ASGM sector (Bedu-Addo et al., 2019). This included visual information and data (qualitative and quantitative) that rated the mines with colors based on their daily processes. This initiative supported the Environmental Protection Agency (EPA) to ensure that mines meet the requirements stipulated in the environmental and social impact assessment reports (Bedu-Addo et al., 2019).

Another initiative by the Alliance for Responsible Mining and Fairtrade established standards and a certification scheme with a focus on curbing the challenges of the ASGM sector. These were referred to as the Fairmined and Fairtrade Gold standards, respectively. The drive was to support miners work under standard procedures, support the development of mining communities, increase gold production, and establish a record-keeping system to regulate the operations of ASGM (Bedu-Addo et al., 2019).

Another initiative called the Multilateral Mining Integrated Project (MMIP) was instituted by the Ministry of Lands and Natural Resources to streamline artisanal and small-scale mining in the country. It used satellite imagery to locate, monitor, and quantify the sectors' activities (IGF, 2021). The goal of this initiative was to minimize the negative impact on the sector and enhance the implementation of environmental safety measures for the management of mine waste and the protection of water bodies.

Additionally, the government has put in place a number of incentives to help the ASGM sector. Kazapoe et al. (2023) identified the provision of technique assistance and training on best management practices and safety protocols, financial aid to small-scale miners, reduced tax on machinery to boost miners' earnings, fair access to land, a fair market price, and a simplified and efficient procedure for getting a permit and license to mine.

Mercury remediation strategies

The imperative need for remediation is because water and soil have been severely affected by anthropogenic activities, especially ASGM (Anekwe & Isa, 2022). Restoration of mined lands has the potential to promote alternative livelihoods, conserve biodiversity, and sequester carbon (Timsina et al., 2022). In developing countries, remediation is often limited to phytoremediation (where plants are used to metabolize, immobilize, and remove contaminants from soil and water), excavation to remove sediment or soil for treatment off-shore, and physical barriers to prevent the movement of contaminants in soil or air (Schwartz et al., 2021). Achina-Obeng and Aram (2022) identified that the reclamation of mined lands should be a corporate social responsibility, including the government and all entities involved in the ASGM operations. According to Timsina et al. (2022), before the start of a mining operation, restoration plans are to be outlined to include the preservation of topsoil containing roots and stumps of trees for reuse after the end of operations, backfilling of excavated pits and leveling of slope areas, and reapplication of preserved topsoil, ideally within a year to prevent erosion and loss of nutrients. This is because, under favorable natural conditions, plant propagules, which are found in the buried seed bank, and microbes and fauna in the soil aid in the spontaneous growth of native plants. Plowing compacted soil helps with the development of plant roots and the addition of binding agents. Finally, initial application of fertilizers, transplanting of hardened nursed seedlings in containers (instead of bare roots), irrigation, and liming all help in the restoration of degraded lands using plants (Timsina et al., 2022).

The reclamation procedure carried out by the ASGM operator in the eastern region of Ghana involved the backfilling of the excavated pit with stockpiled overburden materials and leveling by dozers and excavators to fit the surrounding topography. Revegetation with native plant species was done after the addition of an organic material to the surface soil (Bansah et al., 2016).

In Indonesia, government regulation that controls the management of tailings waste from the ASGM sector requires that waste comprising less than 260 mg/kg of Hg undergo stabilization or encapsulation remediation methods before disposal in a waste landfill. Mercury-laden waste greater than 260 mg/kg is to be shipped to other countries with advanced remediation techniques (Yuliyanti & Aminuddin, 2023).

According to Blagodatsky et al. (2020), there must be a legislative enactment to support the restoration of mined lands to reduce soil Hg concentration using the phytoremediation method by developing arbuscular mycorrhizal fungi plant systems. Also, leguminous trees, which produce enormous amounts of biomass (a dense linkage of fine roots and leaves), have a good potential to restore soil contaminated by Hg and have been used in Ghana and Burkina Faso (Blagodatsky et al., 2020).

Recommendations for mitigating the effect of ASGM activities on the environment and human health

To transform the ASGM sector, Bedu-Addo et al. (2019) suggest that an obligatory environmental impact assessment should be required to ensure best mining practices, irrespective of the size (concessions below or above 10 acres) and location of the mines during the production of gold, to help mitigate problems such as pollution of soil and water. Preservation of the rule of law, accountability, protection of the rights of people (especially the indigenous communities where the mining occurs), and adaptation of internationally standard practices would help the sustainability and maximization of the benefits accrued from the ASGM operations in Ghana. Also, periodic monitoring and sanctions are used to ensure that ASGM activities are done properly.

A large body of literature that supports the need for decentralization demonstrates the potential for improvements in resource governance by showing that local users participate in rule-making, monitoring, and enforcement; decision-makers are held horizontally and downwardly accountable; local institutions are given discretionary powers; and their capacity is invested in Hirons (2014). This implies that the registration of informal operators must be simplified (easy to go through paperwork) without exploitation of miners and unnecessary delays to establish formalized mining activities that adhere to stipulated guidelines (Hilson & Potter, 2003). According to Kazapoe et al. (2023), to mitigate the potential negative effects of ASGM operations, a combined effort involving the host community, traditional leaders, mining enterprises, and municipal and district assemblies is necessary to address the above concerns and benefit all stakeholders (grassroots participation). Also, the execution of current laws and amendment of the legal framework through reforms could address challenging issues in the future. For instance, the purchase of a reasonable amount of Hg that may be necessary by miners from licensed suppliers must be stated clearly in the law to reduce the use of Hg (Bedu-Addo et al., 2019).

Donkor et al. (2023) recommend that to promote good health among miners in the ASGM sector, the government should provide support services, education on health hazards and best practices, resources, and equip miners with the requisite technical skills. According to data collected in an ASGM area by Achina-Obeng and Aram (2022), to reduce the impact of their operation on the environment, the strict enforcement of regulations and laws, the setup of central processing facilities in the community, the provision of jobs, and the measures to transform ASGM operations into sustainable work should be taken into consideration, as should reclamation plans to be implemented after the closure of mines and education on best practices before the license is granted. Also, to protect water bodies, the construction of containment ponds to be recycled for the washing of ore has been suggested by Achina-Obeng and Aram (2022). Kazapoe et al. (2023) suggested that to restore the environment from any damage, the ASGM sector should post bonds so that after mining operations, the monies can be used if the land is abandoned, and the setup of Environmental Protection Agency offices at the district level would facilitate effective monitoring and assessments. These strategies would transform the ASGM sector into something more productive (cost-effective ways to increase gold yield), socially beneficial, and environmentally friendly (less pollution). According to Kinyondo and Huggins (2020), a study in Tanzania also suggests that to identify the locations of mines and encourage coordination and organization among stakeholders, ASGM sites should be captured in land-use planning development. Finally, a study in Ghana identified three pitfalls that must be addressed to transform the ASGM sector: flaws in the legal framework and bureaucratic system of licensing, failures on the part of traditional and political governance, and dishonest institutional officers (Ampaw et al., 2023; Bansah, 2023).

Conclusion

This review examines the ASGM sector, which has gained popularity over the years globally due to its socio-economic benefits to gold-producing countries like Ghana, and addresses the associated negative impact on miners and communities. In this review, significant ASGM-related issues were identified, including land degradation, water pollution, soil erosion, toxic metal contamination, and health and safety concerns. This review also sheds light on some initiatives, sustainable approaches, and remediation strategies that have been implemented to ensure accountability and restore mined lands following closure. The conclusions draw attention to the need for a coordinated effort from all interested parties to streamline ASGM operations, implement policy reforms, allocate funds for training and monitoring the transition from conventional methods to best practices, and enhance working conditions for miners to ensure safety practices. Thus, the ASGM sector can move toward becoming a sustainable activity when the government works with other stakeholders to effectively implement policies and regulate the sector's activities. The government should promote the adoption of responsible mining procedures, including transitioning to a mercury-free operation in the ASGM sector, while discouraging the mindset of miners who prioritize making ends meet at all costs without considering the broader effects on public health and the environment. Finally, to maximize the benefits of the ASGM sector, all ASGM must be governed by a regulatory framework that effectively enforces adherence to its requirements. This review is an attempt to provide a concise summary of some research in an effort to raise awareness of the inherent issues associated with ASGM activities in Ghana and the interventions put in place to lessen their negative impacts on the environment and public health.

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Data Availability All data generated during this review is included in this article.

Declarations

Ethics approval and consent to participate All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors.

Competing interests The authors declare that they have no competing interests.

References

Achina-Obeng, R., & Aram, S. A. (2022). Informal artisanal and small-scale gold mining (ASGM) in Ghana: Assessing environmental impacts, reasons for engagement, and mitigation strategies. *Resources Policy, 78*, 102907.

Adranyi, E., Stringer, L. C., & Altink, H. (2023). The impacts of artisanal and small-scale gold mining on rural livelihood trajectories: Insights from Ghana. *The Extractive Industries and Society, 14*, 101273.

Adu-Baffour, F., Daum, T., & Birner, R. (2021). Governance challenges of small-scale gold mining in Ghana: Insights from a process net-map study. *Land Use Policy, 102*, 105271.

Akorlie, C. (2023). Ghana returns to gold top spot as output jumps 32%. https://www.mining.com/web/ghana-returns-to-gold-top-spot-as-output-jumps-32/ (accessed on 11 August, 2023).

Amara, M., Mends, E. A. & Ofori-Sarpong, G. (2022). Recovery of gold from barren black sands in Artisanal and Small-Scale Gold Mining (ASGM). *Proceedings of the 7th UMaT Biennial International Conference on Mining & Mineral Processing. Expanding the Frontiers of Mining Technology*, (pp. 1–5). Tarkwa, Ghana.

Ampaw, E. M., Chai, J., Jiang, Y., Dumor, K., & Edem, A. K. (2023). Why is Ghana losing the war against illegal gold mining (Galamsey)? An artificial neural network-based investigations. *Environmental Science and Pollution Research, 30*, 73730–73752.

Anekwe, I. M. S., & Isa, Y. M. (2022). Bioremediation of acid mine drainage–Review. *Alexandria Engineering Journal, 65*, 1047–1075.

Armah, F. A., Quansah, R., & Luginaah, I. (2014). A systematic review of heavy metals of anthropogenic origin in environmental media and biota in the context of gold mining in Ghana. *International Scholarly Research Notices*, 1–37.

Arthur, F., Agyemang-Duah, W., Gyasi, R. M., Yeboah, J. Y., & Otieku, E. (2016). Nexus between artisanal and small-scale gold mining and livelihood in Prestea mining region, Ghana. *Geography Journal, 2016*, 1–18.

Artiola, J. F., Pepper, I. L., & Brusseau, M. L. (2004). *Monitoring and characterization of the environment. Environmental monitoring and characterization* (pp. 1–9). Elsevier Inc..

Aryee, B. N. (2001). Ghana's mining sector: Its contribution to the national economy. *Resources Policy, 27*(2), 61–75.

Bansah, K. J. (2023). Artisanal and small-scale mining formalization in Ghana: The government's approach and its implications for cleaner and safer production. *Journal of Cleaner Production, 399*, 136648.

Bansah, K. J., Sakyi-Addo, G. B., & Dumakor-Dupey, N. (2016). Post-mining reclamation in artisanal and small-scale mining. *International Conference & Exhibition on Advanced and Nanomaterials*, 172–179.

Barbosa, F., Tanus-Santos, J. E., Gerlach, R. F., & Parsons, P. J. (2005). A critical review of biomarkers used for monitoring human exposure to lead: Advantages, limitations, and future needs. *Environmental Health Perspectives, 113*, 1669–1674.

Barenblitt, A., Payton, A., Lagomasino, D., Fatoyinbo, L., Asare, K., Aidoo, K., Pigott, H., Som, C. K., Smeets, L., Seidu, O., & Wood, D. (2021). The large footprint of small-scale artisanal gold mining in Ghana. *Science of the Total Environment, 781*, 146644.

Bartrem, C., von Lindern, I., von Braun, M., & Tirima, S. (2022). Climate change, conflict, and resource extraction: analyses of Nigerian Artisanal Mining Communities and Ominous Global Trends. *Annals of Global Health, 88*(1), 17, 1–17.

Basu, N., Clarke, E., Green, A., Calys-Tagoe, B., Chan, L., Dzodzomenyo, M., Fobil, J., Long, R., Neitzel, R., Obiri, S., & Odei, E. (2015). Integrated assessment of artisanal and small-scale gold mining in Ghana—Part 1: Human health review. *International Journal of Environmental Research and Public Health, 12*(5), 5143–5176.

Bedu-Addo, K., Palekhov, D., Smyth, D. J., & Schmidt, M. (2019). Responsible gold mining at the artisanal and small-scale level: A case study of Ghana. *Sustainable Global Value Chains*, 545–563.

Blagodatsky, S., Ehret, M., Rasche, F., Hutter, I., Birner, R., Dzomeku, B., Neya, O., Cadisch, G. and Wünsche, J., (2020). Myco-phytoremediation of mercury polluted soils in Ghana and Burkina Faso. In EGU General Assembly Conference Abstracts (p. 19583) https://presentations.copernicus.org/EGU2020/EGU2020-19583_presentation.pdf

Bortey-Sam, N., Nakayama, S. M. M., Akoto, O., Ikenaka, Y., Baidoo, E., Mizukawa, H., & Ishizuka, M. (2015). Ecological risk of heavy metals and a metalloid in agricultural soils in Tarkwa, Ghana. *International Journal of Environmental Research and Public Health, 12*(9), 11448–11465.

Briggs, D. (2003). Environmental pollution and the global burden of disease _ British Medical Bulletin _ Oxford Academic. *British Medical Bulletin, 68*(1), 1–24.

Brown, E. K. A., and Kimani, E. (2021). Artisanal and small-scale mining: the paradox of extraction. The African Center for Economic Transformation, Discussion paper, 1-5.

Brugger, F., Clarke, E., Kwakye, A. T. and Ow, A. von. (2020). Institutional capacity assessment report, Ghana. Piloting a New WHO Framework to Support the Development of Public Health Strategies on Artisanal and Small-scale Gold Mining in the Context of the Minamata Convention on Mercury. https://www.afro.who.int/sites/default/files/2020-06/ASGM_Ghana_ICA_21052020_web.pdf (accessed on 11 July, 2022).

Butscher, F. M., Rakete, S., Tobollik, M., Mambrey, V., Moyo, D., Shoko, D., Muteti-Fana, S., Steckling-Muschack, N., & Bose-O'Reilly, S. (2020). Health-related quality of life (EQ-5D+ C) among people living in artisanal and small-scale gold mining areas in Zimbabwe: a cross-sectional study. *Health and Quality of Life Outcomes, 18*(1), 1–13.

Cecil, K., Brubaker, C., Adler, C., Dietrich, K. N., Altaye, M., Egelhoff, J. C., Wessel, S., Elangovan, I., Hornung, R., Jarvis, K., & Lanphear, B. P. (2008). Decreased brain volume in adults with childhood lead exposure. *PLoS Medicine, 5*(5), e112.

Cheng, Y., Watari, T., Seccatore, J., Nakajima, K., Nansai, K., & Takaoka, M. (2023). A review of gold production, mercury consumption, and emission in artisanal and small-scale gold mining (ASGM). *Resources Policy, 81*, 103370.

Cobbinah, I. J., Gbedemah, G. M. K., Nurudeen, Z. K., Saim, A. K., & Amankwah, R. K. (2021). Characterisation of small-scale gold mining tailings in the Western Region of Ghana. *Ghana Mining Journal, 21*(2), 27–32.

Cossa, H., Scheidegger, R., Leuenberger, A., Ammann, P., Munguambe, K., Utzinger, J., Macete, E., & Winkler, M. S. (2021). Health studies in the context of artisanal and small-scale mining: A scoping review. *International Journal of Environmental Research and Public Health, 18*(4), 1555.

Darko, G., Adjei, S., Nkansah, M. A., Borquaye, L. S., Boakye, K. O., & Dodd, M. (2020). Accumulation and bioaccessibility of toxic metals in root tubers and soils from gold mining and farming communities in the Ashanti region of Ghana. *International Journal of Environmental Health Research*, 1–11.

De Lacerda, L. D., & Salomons, W. (1998). Mercury from gold and silver mining: A chemical time bomb? *Environmental Science Series*, 97–109.

Dietler, D., Clarke, E., Kwakye, A., Osei, C., Gyansa-Lutterod, M. & Winkler, M. (2020). Ghana: Piloting a new WHO framework to support the development of public health strategies on artisanal and small-scale gold mining in the context of the Minamata convention on mercury (pp. 1–101). Rapid Health Situation Assessment Report, Ghana.

Donkor, P., Siabi, E. K., Frimpong, K., Mensah, S. K., Siabi, E. S., & Vuu, C. (2023). Sociodemographic effects on role assignment and associated occupational health and safety issues in artisanal and small-scale gold mining in Amansie Central District, Ghana. *Heliyon, 9*(3), e13741.

Dooyema, C. A., Neri, A., Lo, Y. C., Durant, J., Dargan, P. I., Swarthout, T., Biya, O., Gidado, S. O., Haadu, S., Sani-Gwarzo, N., & Nguku, P. M. (2012). Outbreak of fatal childhood lead poisoning related to artisanal gold mining in northwestern Nigeria, 2010. *Environmental Health Perspectives, 120*(4), 601–607.

Drace, K., Kiefer, A. M., & Veiga, M. M. (2016). Cyanidation of mercury-contaminated tailings: Potential health effects and environmental justice. *Current Environmental Health Reports, 3*, 443–449.

Duker, A. A., Carranza, E. J., & Hale, M. (2004). Spatial dependency of Buruli ulcer prevalence on arsenic-enriched domains in Amansie West District, Ghana: Implications for arsenic mediation in Mycobacterium ulcerans infection. *International Journal of Health Geographics, 3*, 19.

Duncan, A. E. (2020). The dangerous couple: Illegal mining and water pollution—A case study in Fena River in the Ashanti Region of Ghana. *Journal of Chemistry, 2020*, 1–9.

Emmanuel, A. Y., Jerry, C. S., & Dzigbodi, D. A. (2018). Review of environmental and health impacts of mining in Ghana. *Journal of Health, 8*(17), 43–52.

Eshun, P. A. (2005). Sustainable small-scale gold mining in Ghana: Setting and strategies for sustainability. *Geological Society, London, Special Publications, 250*(1), 61–72.

Fashola, M. O., Ngole-Jeme, V. M., & Babalola, O. O. (2016). Heavy metal pollution from gold mines: Environmental effects and bacterial strategies for resistance. *International Journal of Environmental Research and Public Health, 13*(11), 1047.

Friends of the Nation. (2017). Baseline Information for the National Action Plan on Artisanal and Small - Scale Gold Mining: Ghana. https://www.unep.org/globalmercurypartnership/resources/report/baseline-information- (accessed on 3 July, 2023).

Fu, S. & Lu, J. M., (2018). Column leaching test on oxidized and non-oxidized tailings in northern Norway. In *IOP Conference Series: Earth and Environmental Science* (Vol. 191, No. 1, p. 012010). IOP Publishing.

Gatune, J. & Besada, H. (2020). Artisanal and Small-Scale Mining (ASM) in Ghana – Creating value or destroying value: The search for a way forward. United Nations University-Institute for Natural Resources in Africa. https://collections.unu.edu/eserv/unu:8538/Ghana_Working_Paper_1.pdf. Accessed 3 Aug 2023

GEF (2020). Evaluation of Global Environment Facility (GEF) interventions in the artisanal and small-scale gold mining sector. https://www.thegef.org/sites/default/files/council-meeting-documents/EN_GEF_.E_C59_02_ASGM_Evaluation_Nov_2020.pdf (accessed 16 August, 2023).

Genchi, G., Sinicropi, M. S., Lauria, G., Carocci, A., & Catalano, A. (2020). The effects of cadmium toxicity. *International Journal of Environmental Research and Public Health, 17*(11), 3782.

Ghana Chamber of Mines (2021). Annual report. https://ghanachamberofmines.org/wp-content/uploads/2023/05/Annual-Report-2021-REPORT-Final.pdf, (accessed on 3 June, 2023).

GHEITI. (2020). Mining Report. Ghana Extractive Industry transparency initiative. https://www.gheiti.gov.gh/site/index.php?option=com_phocadownload&view=categ

ory&download=461:2020-gheiti-mining-report&id=35:mining-oil-a-gas-reportsandItemid=54, (accessed on 23 July, 2023).

Gyamfi, O., Sørensen, P. B., Darko, G., Ansah, E., Vorkamp, K., & Bak, J. L. (2021). Chemosphere contamination, exposure and risk assessment of mercury in the soils of an artisanal gold mining community in Ghana. *Chemosphere, 267*, 128910.

Gyamfi, O., Sorenson, P. B., Darko, G., Ansah, E., & Bak, J. L. (2020). Human health risk assessment of exposure to indoor mercury vapor in a Ghanaian artisanal small-scale gold mining community. *Chemosphere, 241*, 125014.

Harada, M. (1995). Minamata disease: Methylmercury poisoning in Japan caused by environmental pollution. *Critical reviews in toxicology, 25*(1), 1–24.

Harianja, A. H., Saragih, G. S., Fauzi, R., Hidayat, M. Y., Syofyan, Y., Tapriziah, E. R., & Kartiningsih, S. E. (2020). Mercury exposure in artisanal and small-scale gold mining communities in Sukabumi, Indonesia. *Journal of Health Pollution, 10*(28), 201209.

Hilson, G., & Potter, C. (2003). Why is illegal gold mining activity so ubiquitous in rural Ghana? *African Development Review, 15*(2-3), 237–270.

Hinton, J. (2012). Analysis of formalization approaches in the artisanal and small-scale gold mining sector based on experiences in Ecuador, Mongolia, Peru, Tanzania and Uganda, Uganda case study. https://www.responsiblemines.org/wp-content/uploads/2018/05/Case_Study_Uganda_June_2012.pdf, (accessed on 24 July, 2023).

Hirons, M. (2014). Decentralising natural resource governance in Ghana: Critical reflections on the artisanal and small-scale mining sector. *Futures, 62*, 21–31.

Hunter, M. (2020), "Illicit financial flows: Artisanal and small-scale gold mining in Ghana and Liberia", OECD Development Co-operation Working Papers, No. 72, OECD Publishing, Paris, https://delvedatabase.org/uploads/resources/Illicit-financial-flows-Artisanal-and-Small-scale-Gold-mining-in-Ghana-and-Liberia.pdf

Hunter, M. (2022). Beyond blood: Gold, conflict and criminality in West Africa. Global Initiative Against Transnational Organized Crime (GI-TOC), Research report. pp 1-53

IGF, (2021). Mine waste management: Case studies from Ghana and Canada. The Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development (IGF) Case Study. https://www.iisd.org/system/files/2021-12/igf-case-study-mine-waste-management-canada-ghana.pdf, (accessed on 16 August, 2023).

Kazapoe, R. W., Amuah, E. E. Y., Abdiwali, S. A., Dankwa, P., Nang, D. B., Kazapoe, J. P., & Kpiebaya, P. (2023). Relationship between small-scale gold mining activities and water use in Ghana: A review of policy documents aimed at protecting water bodies in mining communities. *Environmental Challenges*, 100727.

Keane, S., Bernaudat, L., Davis, K. J., Stylo, M., Mutemeri, N., Singo, P., Twala, P., Mutemeri, I., Nakafeero, A., & Etui, I. D. (2023). Mercury and artisanal and small-scale golding mining: Review of global use estimates and considerations for promoting mercury-free alternatives. *Ambio*, 1–20.

Kerin, E. J., & Lin, H. K. (2010). Fugitive dust and human exposure to heavy metals around the red dog mine. Rockville Pike, USA. *Reviews of Environmental Contamination and Toxicology, 206*, 49–63.

Kinyondo, A., & Huggins, C. (2020). Centres of excellence for artisanal and small-scale gold mining in Tanzania: Assumptions around artisanal entrepreneurship and formalization. *The Extractive Industries and Society, 7*(2), 758–766.

Kosai, S., Nakajima, K., & Yamasue, E. (2023). Mercury mitigation and unintended consequences in artisanal and small-scale gold mining. *Resources, Conservation and Recycling, 188*, 106708.

Kwaansa-Ansah, E. E., & Armah, E. K. (2019). Assessment of total mercury in hair, urine and fingernails of small – Scale gold miners in the Amansie West District, Ghana. *Journal of Health and Pollution, 9*(21), 9.

Macdonald, K. F., Lund, M. A., Blanchette, M. L., & Mccullough, C. D. (2014). Regulation of Artisanal Small Scale Gold Mining (ASGM) in Ghana and Indonesia as currently implemented fails to adequately protect aquatic ecosystems. In Sui, Sun, & Wang (Eds.), *An Interdisciplinary Response to Mine Water Challenges*. China University of Mining and Technology Press.

Malehase, T., Daso, A. P., & Okonkwo, J. O. (2016). Initiatives to combat mercury use in artisanal small-scale gold mining: A review on issues and challenges. *Environmental Reviews, 25*(2), 218–224.

Malone, A., Figueroa, L., Wang, W., Smith, N. M., Ranville, J. F., Vuono, D. C., Zapata, F. D. A., Paredes, L. M., Sharp, J. O., & Bellona, C. (2023). Transitional dynamics from mercury to cyanide-based processing in artisanal and small-scale gold mining: Social, economic, geochemical, and environmental considerations. *Science of the Total Environment*, 165492.

Markham, K. E., & Sangermano, F. (2018). Evaluating wildlife vulnerability to mercury pollution from artisanal and small-scale gold mining in Madre de Dios, Peru. *Tropical Conservation Science, 11*, 1940082918794320.

Marshall, G., Ferreccio, C., Yuan, Y., Bates, M. N., Steinmaus, C., Selvin, S., Liaw, J., & Smith, A. H. (2007). Fifty-year study of lung and bladder cancer mortality in Chile related to arsenic in drinking water. *Journal of the National Cancer Institute, 99*(12), 920–928.

McQuilken, J., & Hilson, G. (2016). Artisanal and small-scale gold mining in Ghana. Background Research to inform an Action Dialogue. IIED, London. https://www.iied.org/sites/default/files/pdfs/migrate/16618IIED.pdf. Accessed 26 June 2023

Milési, J. P., Ledru, P., Ankrah, P., Johan, V., Marcoux, E., & Vinchon, C. (1991). The metallogenic relationship between Birimian and Tarkwaian gold deposits in Ghana. *Mineralium Deposita, 26*, 228–238.

Minerals and mining policy of Ghana (2021). https://www.mincom.gov.gh/wp-content/uploads/2021/06/Mineral-and-Mining-Policy-Ghana.pdf, (accessed on 6 June, 2023).

Minerals Commission Ghana. (2021). President Commissions 100 Mercury-Free Gold Processing Machines. https://www.mincom.gov.gh/mincom-news/president-commissions-100-mercury-free-gold-processing-machines/ (accessed on 6 June, 2023).

Nakua, E. K., Owusu-Dabo, E., Newton, S., Koranteng, A., Otupiri, E., Donkor, P., & Mock, C. (2019). Injury rate and risk factors among small-scale gold miners in Ghana. *BMC Public Health, 19*(1), 1–8.

NAP. (2020). National action plan to reduce and where feasible eliminate mercury use in artisanal and small-scale gold mining in Ghana (in accordance with the Minamata Convention on Mercury). https://mercuryconvention.org/sites/default/files/documents/national_action_plan/Ghana_ASGM_NAP_Final_March_2022.pdf, (accessed on 26 June, 2023).

Nunoo, S., Manu, J., Owusu-Akyaw, F. K. B., & Nyame, F. K. (2022). Impact of artisanal small-scale (gold and diamond) mining activities on the Offin, Oda and Pra rivers in Southern Ghana, West Africa: A scientific response to public concern. *Heliyon, 8*(12), e12323.

Nyanza, E. C., Bernier, F. P., Manyama, M., Hatfield, J., Martin, J. W., & Dewey, D. (2019). Maternal exposure to arsenic and mercury in small-scale gold mining areas of Northern Tanzania. *Environmental Research, 173*, 432–442.

Obeng, E. A., Oduro, K. A., Obiri, B. D., Abukari, H., Guuroh, R. T., Djagbletey, G. D., Appiah-Korang, J., & Appiah, M. (2019). Impact of illegal mining activities on forest ecosystem services: Local communities' attitudes and willingness to participate in restoration activities in Ghana. *Heliyon, 5*(10), e02617.

Ovadje, L., Calys-Tagoe, B. N., Clarke, E., & Basu, N. (2021). Registration status, mercury exposure biomarkers, and neuropsychological assessment of artisanal and small-scale gold miners (ASGM) from the Western Region of Ghana. *Environmental Research, 201*, 111639.

Quarm, J. A., Anning, A. K., Fei-Baffoe, B., Siaw, V. F., & Amuah, E. E. Y. (2022). Perception of the environmental, socio-economic and health impacts of artisanal gold mining in the Amansie West District, Ghana. *Environmental Challenges, 9*, 100653.

Rajaee, M., Obiri, S., Green, A., Long, R., Cobbina, S. J., Nartey, V., Buck, D., Antwi, E., & Basu, N. (2015). Integrated assessment of artisanal and small-scale gold mining in Ghana—Part 2: Natural sciences review. *International Journal of Environmental Research and Public Health, 12*(8), 8971–9011.

Rakete, S., Moonga, G., Wahl, A. M., Mambrey, V., Shoko, D., Moyo, D., Muteti-Fana, S., Tobollik, M., Steckling-Muschack, N., & Bose-O'Reilly, S. (2022). Biomonitoring of arsenic, cadmium and lead in two artisanal and small-scale gold mining areas in Zimbabwe. *Environmental Science and Pollution Research, 29*(3), 4762–4768.

Richard M., Moher P., Rossin R., & Telmer K. (2014). Using retorts to reduce mercury use, emissions and exposures in artisanal and small scale gold mining: A practical guide, (version 1.0), Artisanal Gold Council. Victoria, BC.

Saalidong, B. M., & Aram, S. A. (2022). Mercury exposure in artisanal mining: Assessing the effect of occupational activities on blood mercury levels among artisanal and small-scale goldminers in Ghana. *Biological Trace Element Research, 200*(10), 4256–4266.

Saim, A. K. (2021). Mercury (Hg) use and pollution assessment of ASGM in Ghana: Challenges and strategies towards Hg reduction. *Environmental Science and Pollution Research International, 28*(44), 61919–61928.

Sarpong, L., Boadi, N. O., & Akoto, O. (2023). Metal fractionation and leaching in soils from a gold mining area in the equatorial rainforest zone. *Journal of Chemistry, 2023*, 3542165.

Schwartz, M., Smits, K., Smith, N., & Phelan, T. (2021). How lessons from an evolving comprehensive approach for water and sanitation can improve artisanal and small-scale mining environmental initiatives. *Journal of Cleaner Production, 282*, 124457.

Selin, N. E. (2014). Global change and mercury cycling: Challenges for implementing a global mercury treaty. *Environmental Toxicology and Chemistry, 33*(6), 1202–1210.

Shantakumari, R., Nurul, M. F., Mahenderan, A., & Kalavathy, R. (2012). Effects of climate changes on dissolved heavy metal concentrations among recreational park tributaries in Pahang, Malaysia. *Biomedical Research, 23*(1), 23–30.

Siabi, E. K., Donkor, P., Mensah, S. K., Dzane, R. K., Kurantin, N., Frimpong, K., Siabi, S. E., Vuu, C., & van Etten, E. (2022). Assessing the knowledge and practices of occupational safety and health in the artisanal and small-scale gold mining sector of Ghana: A case of Obuasi. *Heliyon, 8*(11), e11464.

Smith, A. H., Lingas, E. O., & Rahman, M. (2000). Contamination of drinking-water by arsenic in Bangladesh: A public health emergency. *Bulletin of the World Health Organization, 78*, 1093–1103.

Soe, P. S., Kyaw, W. T., Arizono, K., Ishibashi, Y., & Agusa, T. (2022). Mercury pollution from artisanal and small-scale gold mining in Myanmar and other Southeast Asian countries. *International Journal of Environmental Research and Public Health, 19*(10), 6290.

Sunkari, E. (2018). Orogenic gold deposits in Ghana. (Doctoral Seminar). Turkey: Niğde Ömer Halisdemir University. https://www.researchgate.net/publication/326560479_orogenic_gold_deposits_in_ghana (accessed on 16 August, 2023).

The World Bank, (2020). Addressing youth unemployment in Ghana needs urgent action, calls new world bank report. https://www.worldbank.org/en/news/press-release/2020/09/29/addressing-youth-unemployment-in-ghana-needs-urgent-action, (accessed on 7 May, 2022).

Timsina, S., Hardy, N. G., Woodbury, D. J., Ashton, M. S., Cook-Patton, S. C., Pasternack, R., & Martin, M. P. (2022). Tropical surface gold mining: A review of ecological impacts and restoration strategies. *Land Degradation and Development, 33*(18), 3661–3674.

Toroskainen, K., Fleming, A., & Williams, J. (2018). Governance and trade patterns of gold producers in the 2017 Resource Governance Index. The Natural Resource Governance Institute, https://resourcegovernance.org/sites/default/files/documents/governance-of-gold-production.pdf. Accessed 5 June 2023

Tulasi, D., Fajon, V., Kotnik, J., Shlyapnikov, Y., Adotey, D. K., Serfor-Armah, Y., & Horvat, M. (2021). Mercury methylation in cyanide influenced river sediments: A comparative study in Southwestern Ghana. *Environmental Monitoring and Assessment, 193*, 1–18.

Tychsen, J., Boamah, D., Ahadjie, J., Sandow, A. M., Alidu, S., Awuah, P., Quaicoe, I., Amankwah, R., Fobil, J., Nyame, F., & Davis, E. (2017). *ASM Handbook for Ghana* (p. 160). Geological Survey of Denmark and Greenland (GEUS).

U.S. Borax (2018). https://www.borax.com/products/applications/metals-gold (accessed on 7 August, 2019).

UNEP. (2001). *Abandoned mines: Problems, issues and policy challenges for decision markers* (pp. 1–25). United Nations Environment Programme, Division of Technology, Industry and Economic (DTIE).

USAID, (2022). Economic growth and trade https://www.usaid.gov/ghana/economic-growth-and-trade, (accessed on 10 June, 2023).

Veiga, M. M., Baker, R. F., Fried, M. B., & Withers, D. (2004). *Protocols for environmental and health assessment of mercury released by artisanal and small-scale gold miners. United Nations Publications* (p. 294). GEF/UNDP/UNIDO.

Verbrugge, B., Lanzano, C., & Libassi, M. (2021). The cyanide revolution: Efficiency gains and exclusion in artisanal- and small-scale gold mining. *Geoforum, 126*, 267–276.

Wanyana, M. W., Agaba, F. E., Sekimpi, D. K., Mukasa, V. N., Kamese, G. N., Douglas, N., & Ssempebwa, J. C. (2020). Mercury exposure among artisanal and small-scale gold miners in four regions in Uganda. *Journal of Health and Pollution, 10*(26), 200613.

WHO. (2007). Health risks of heavy metals from long-range transboundary air pollution. Joint WHO/Convention Task Force on the Health Aspects of Air Pollution, (No. EUR/06/5067592). Copenhagen: WHO Regional Office for Europe, https://apps.who.int/iris/handle/10665/107872, (accessed on 13 August, 2023).

WHO (2016). Artisanal and small-scale gold mining and health. Technical paper #1: environmental and occupational health hazards associated with artisanal and small-scale gold mining. https://apps.who.int/iris/bitstream/handle/10665/247195/9789241510271-eng.pdf (accessed on 12 June, 2023).

Wiafe, S., Awuah Yeboah, E., Boakye, E., & Ofosu, S. (2022). Environmental risk assessment of heavy metals contamination in the catchment of small-scale mining enclave in Prestea Huni-Valley District, Ghana. *Sustainable Environment, 8*(1), 2062825.

Wireko-Gyebi, R. S., Asibey, M. O., Amponsah, O., King, R. S., Braimah, I., Darko, G., & Lykke, A. M. (2020). Perception of small-scale miners on interventions to eradicate illegal small-scale mining in Ghana. *Sage Open, 10*(4), 2158244020963668.

World Bank. (2020). 2020 State of the Artisanal and Small-Scale Mining Sector. Washington, D.C.: World Bank. https://delvedatabase.org/uploads/resources/Delve-2020-State-of-the-Sector-Report.pdf, (accessed on 26 June, 2023).

World Gold Council, (2021). The social and economic contribution of gold mining. https://www.gold.org/download/file/16605/The-social-and-economic-contribution-of-gold-mining.pdf, (accessed on 6 June, 2023).

World Gold Council. (2022). ASGM Report 2022, Press Report by World Gold Council. https://www.gold.org/news-and-events/press-releases/asgm-report-2022-press-release (accessed on 16 June, 2023)

Wuana, R. A., & Okieimen, F. E. (2011). Heavy metals in contaminated soils: A review of sources, chemistry, risks and best available strategies for remediation. *Ecology*, 1–20.

Yalala, B. N. (2015). *Characterization, bioavailability and health risk assessment of mercury in dust impacted by gold mining* (pp. 1–275). PhD Thesis, University of the Witwatersrand.

Yeboah, S., & James Nyarkoh, B. (2022). The impact of mining on the Ghanaian economy: A comprehensive review (1992–2020). https://mpra.ub.uni-muenchen.de/117502/. Accessed 6 June 2023

Yevugah, L. L., Darko, G., & Bak, J. (2021). Does mercury emission from small-scale gold mining cause widespread soil pollution in Ghana? *Environmental Pollution, 284*, 116945.

Yoshimura, A., Suemasu, K., & Veiga, M. M. (2021). Estimation of mercury losses and gold production by artisanal and small-scale gold mining (ASGM). *Journal of Sustainable Metallurgy, 7*, 1045–1059.

Yuliyanti, A., & Aminuddin, A. (2023). Mercury contamination in artisanal gold mining sites in Indonesia and the remediation. In *Proceedings of the 3rd Sriwijaya international conference on environmental issues, SRICOENV 2022, October 5th, 2022, Palembang, South Sumatera, Indonesia*.

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