

Environmental and health risks posed to children by artisanal gold mining: A systematic review

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Abstract

There are an estimated 5 million children working in artisanal and small-scale gold mines worldwide; however, the hazards are poorly characterized and often underreported. We systematically reviewed the literature on reports of hazards among children as a consequence of such activities through PubMed database using pre-defined search terms. We identified 113 articles published between 1984 and 2021 from 31 countries. Toxicological hazards were reported in 91 articles, including mercury, lead, and arsenic. Infectious hazards, noted in 18 articles, included malaria, cholera, and hepatitis. Six articles reported occupational hazards, including malnutrition, heat stroke, and reactive airway disease. Three articles reported traumatic hazards, including cave-ins, burns, animal attacks, falls, and weapon-inflicted wounds. Those findings likely indicate a profound underreporting of the prevalence and consequences of such hazards among children. More work is needed both to characterize the burdens of those hazards and to address the underlying drivers of child labor in those settings.

Keywords

Artisanal and small-scale gold mining, global health, hazards, pediatric

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Introduction

The global mining of gold among artisanal and small-scale mines is associated with numerous hazards. Traumatic and occupational hazards include mine collapse and cave-ins, crush injuries, burns, falls, barotrauma, drowning, asphyxiation, lacerations injuries from mining equipment, temperature-related maladies, and noise exposure.^{1–3} Chronic inhalational exposure to mine dust and particulate matter leads to silicosis and possible lung cancer.⁴ Miners are also exposed to numerous toxic hazards, most notably mercury, lead, and arsenic.^{5,6} These heavy metals have consequential toxic effects on neurocognitive development,^{7–11} increased carcinogenicity,¹² and teratogenic effects.^{13,14} Effects on the surrounding environment^{15–17} are profound, including contamination of soil, air, water, and wildlife (particularly fish) from propagation and bioaccumulation of toxic contaminants.¹⁸ In addition, artisanal and small-scale gold mining communities also suffer a disproportionate burden of infectious diseases, such as tuberculosis, malaria, typhoid, Zika, Ebola, and SARS-CoV-2.^{4,19–21} Other chronic maladies include malnutrition and psychiatric disorders.

Younger miners are also vulnerable to the acts of labor exploitation and sex trafficking.²²

While prior work has highlighted the problems faced globally among small-scale miners,^{23,24} inadequate attention has been paid to the hazardous consequences among children, who are often encouraged or forced to work in the mines to support for their families. Of the estimated

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10–18 million gold miners worldwide, one-third to one-half are thought to be women and children, with children specifically constituting up to 5 million workers.^{23,25,26} Children are often used for work in mines given their small size and ability to fit into tight spaces. Therefore, children may be at significant risk for many of the hazards posed by mining activities. Furthermore, the indirect consequences of lost educational years are far reaching, due to long work hours in the mines or because of injuries and illnesses preventing them from attending school.

Recently, as a result of the social and economic consequences arising from the SARS-CoV-2 pandemic, mining communities likely face heightened tensions. Furthermore, evidence suggests that some mining communities, albeit not artisanal and small-scale mining communities, are at a disproportionate risk for SARS-CoV-2 infection,²⁰ although the direct infectious risk posed to children in artisanal and small-scale mining communities specifically is as of yet unclear. Exacerbated economic insecurities in the wake of the pandemic, however, likely continue to have a notable impact on children while simultaneously propagating the need for gold mining activities, which increases the demand for child labor; additionally, those economic challenges consequent to the SARS-CoV-2 pandemic may further limit government expenditures on local agencies to enforce mining regulations, including child labor laws.²⁷ In this systematic review, we aimed to review the existing literature to characterize the hazardous consequences of artisanal and small-scale gold mining specifically on children and highlight the efforts made to resolve those issues.

The process of gold mining

The process by which gold is mined and extracted involves four steps. First, gold ore is excavated from the soil, rock, and surrounding water tributaries either through direct excavation from the earth or through repurposing of old abandoned industrial gold mines and digging around mine shafts.²⁸ The gold ore is then processed and concentrated by gravity methods (sluice, shaker table, etc.) and subsequently combined with elemental mercury, which forms a gold–mercury amalgamation. That amalgam is subsequently burned, removing the mercury as vapor and leaving a relatively pure gold alloy, which can be further refined.²³

Mercury exists in predominantly three forms: elemental, organic, and inorganic.²⁹ Elemental mercury, when vaporized by heat, is readily inhaled and absorbed in lungs resulting in systemic toxicity.³⁰ In addition, vaporized mercury can be spread through the air³¹ to nearby areas and deposit in the soil or surrounding rivers and streams. Organic methylmercury is formed through biomethylation by aquatic microorganisms, which is then taken up by various animals, such as fish, mammals, birds, and various sea plants.^{15–17} Inorganic mercury does not play a significant role in the gold mining process, thus will not be further discussed this review.

Methods

Search strategy and selection criteria

A systematic literature search was carried out in accordance with the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) guidelines, and articles were considered if found through PubMed database. We used the following pre-defined search terms: (“Artisanal Small-Scale Mining” or “Gold Mining”) and (“Pediatric” or “Child” or “Children”). Our search was performed on 13 October 2021. The resulting articles were then assessed for relevance by two independent reviewers (L-T.A.B. and T.B.E.). Three reviewers (L-T.A.B., C.G., and T.B.E.) then assessed the identified articles for inclusion. There was no pre-published protocol for this study.

We included articles that reported on the activities of gold mining among children (defined as age less than 18 years). Our intention was to describe the effects of mining on child miners; however, acknowledging the likely underreporting of child labor, we included articles that reported the impact of mining activities on children in mining communities so long as the ages of the children included were older than 5 years, to allow for the possibility of direct exposure to mining-related activities. We excluded review studies and studies that did not include children. Articles that included both adults and children were included if outcomes were reported specifically among children independently of adults. We did not apply a restriction on year or language of publication, but only included articles that had previously been translated into English. Furthermore, we excluded articles that pertained to the impact of mining activities on newborns, as our focus was specifically on the consequences to child miners. See supplementary table for complete list of articles included.

Statistical analysis

From the articles that met our inclusion criteria, we extracted the following variables: date of publication, country or countries studied, report of traumatic hazards, report of toxic hazards, infectious disease exposures, report of occupational hazards, report of treatment or interventions provided, resultant chronic disease, impact on life expectancy or disability-adjusted life years, educational impact, and any proposed solutions. We then assessed the quality of each article using a standardized rating scale of A for randomized control trials or meta-analyses, B for non-randomized control trials, systematic reviews, or epidemiologic studies, and C for consensus or expert opinions; further numeric qualifiers were defined from 1 to 7, ranging from randomized and non-randomized clinical control trials to historical uncontrolled trials and epidemiologic studies.³² Given the nature of most studies identified, which were predominantly case series and selected cohorts, we did not assess the risks of bias in any individual study.

Table 1. Traumatic hazards affecting children in artisanal and small-scale gold mining sites around the world.

First author's last name	Year	Country	Traumatic hazard reported
Gyamfi et al.	2021	Ghana	Cave-ins
Egmann et al.	2018	French Guiana	Burns, wild animal attacks, falls, weapon wounds
Caraballo	1996	Venezuela	Wild animal attacks

Table 2. Occupational hazards affecting children in artisanal and small-scale gold mining sites around the world.

Article	Year	Country	Occupational hazard reported
De Salazar et al.	2021	Guyana	Heat stroke
Wyatt et al.	2019	Peru	Malnutrition
Egmann et al.	2018	French Guiana	Heat stroke, musculoskeletal injuries
Herrera et al.	2017	Chile	Reactive airway disease
Saunders et al.	2013	Nicaragua	Hearing loss
Amon et al.	2012	Mali	Musculoskeletal injuries

lack of studies on some of the traumatic and occupational hazards among children may be due in part to the latency period for specific hazards; silicosis exposure in childhood, for example, may not manifest until adulthood³⁵ and thus would not have been captured by our review. However, the notable lack of identifying numerous hazards reported among adult miners more likely reflects both a paucity of health outcome tracking capabilities in resource-limited settings and an underreporting of hazards among children. Interviews among 33 children who worked in artisanal mines (the youngest being 6 years of age), reported constant, unprotected contact with mercury amalgam and various other activities, such as suffering prolonged periods of time in dark mines and digging in mine shafts.³³

It is particularly meaningful to characterize such hazards among children, as the consequent reduction in quality of life years is by definition more substantial than among adults, as are the lost educational opportunities. Several studies have commented on the lower-than-average rates of education among artisanal gold mining communities.^{36,37} One study calculated 32,300 disability-adjusted life years among 9- to 14-year-old children as a consequence of chronic mercury intoxication among underaged gold miners in Zimbabwe.³⁸ Other research has reported similar results among numerous other countries, though not specifically among children.³⁹ None of the articles calculated the impact on the quality of life or life expectancy secondary to trauma, occupational hazard, or infectious exposure.

Infectious hazards

Infectious hazards and consequences among children were noted in 18 articles with malaria being the most common hazard reported (Table 3). Other reports included tuberculosis, ebola, zika, typhoid, and cholera.^{21,40–42} Such communities are at particular risk for endemic infections and zoonotic

infections given the lack of basic sanitation equipment in mining environments,² lack of preventive healthcare services, such as routine vaccination, lack of disease surveillance, the proximity to wildlife, and, importantly, the encroachment on and disruption of the natural habitat of wild animals as a consequence of the mining operations.⁴³ The origin of an outbreak of marburg virus, for example, in 1998 in the People's Republic of the Congo began among a community of artisanal gold miners and was thought to be result of exposure to the animal reservoir.⁴⁴

Furthermore, children in artisanal gold mining communities may be especially vulnerable to infections; one study concluded that the combination of malnutrition and mercury exposure attenuated the children's immune response to routine vaccinations.⁴⁵ Thus, even among those communities that received appropriate vaccination, the immune protection conferred may be suboptimal.

Toxicologic hazards

Of the toxic hazards mentioned in 91 articles (Figure 2), mercury was the most frequently cited toxicity ($n=72$ articles), followed by lead ($n=28$ articles). Exposure to toxins constituted the largest proportion of studies of hazard among children associated with artisanal and small-scale gold mining, with mercury being the most frequently studied toxin. Workers in artisanal and small-scale gold mines are exposed to mercury vapor, while neighboring communities are exposed through consumption of fish heavily contaminated with methylmercury.⁴⁶ The neurotoxicity of mercury is one salient feature, but other toxic effects among children who's mothers were exposed during pregnancy include precocious puberty⁴⁷ and developmental delays and various adverse birth outcomes, such as spontaneous abortion, preterm birth, low birth weight, and congenital anomalies.^{13,14,48}

Table 3. Infectious hazards affecting children in artisanal and small-scale gold mining sites around the world.

Article	Year	Country	Infectious hazard reported
Grillet et al.	2021	Venezuela	Malaria
Arisco et al.	2021	Venezuela	Malaria
Souza Hacon et al.	2020	Brazil	Malaria, hantavirus, yellow fever
Ducharme et al.	2020	French Guiana	Leishmaniasis
Sulaiman et al.	2020	Sudan	Measles
Tercas-Trettel et al.	2019	Brazil	Malaria, hantavirus
Cruz-Franco et al.	2019	Brazil, French Guiana	Malaria
Egmann et al.	2018	French Guiana	Unspecified infections
Opore et al.	2012	Ghana	Cholera
Bausch et al.	2006	Democratic Republic of the Congo	Marburg
Silbergeld et al.	2002	Brazil	Malaria
Crompton et al.	2002	Brazil	Malaria
de Oliveira Santos et al.	2002	Brazil	Malaria
Souto et al.	2002	Brazil	Malaria, hepatitis B
Souto et al.	2001	Brazil	Malaria, hepatitis B, hepatitis C
Bertherat et al.	1999	Gabon	Ebola, leptospirosis
Carvalho et al.	1999	Brazil	Malaria
Bertherat et al.	1998	Gabon	Rickettsia

Despite its known hazards, mercury continues to be used by artisanal and small-scale gold miners, accounting for nearly 15% of the world's gold supply, yet nearly 40% of worldwide mercury emissions.^{46,49} The Minamata Convention of 2013 aimed to phase out the production, import, and export of products that contain mercury and has made major strides in increasing awareness of the consequence of continued use of mercury, improving monitoring systems, and in curbing the world's mercury emission;^{46,50} however, with specific regard to artisanal and small-scale gold mining, the convention merely stipulated a reduction in mercury usage and directed countries to develop their own approach to the problem. Consequent regulations and bans from governmental and nongovernment organizations^{50–53} have attempted to reduce mercury use and limit mercury exposure.

Second to mercury, lead was the most commonly identified exposure among children. The consequences of lead toxicity among children are similarly far reaching: lead toxicity results in renal dysfunction, learning disabilities, reduced intelligence quotient (IQ), anemia, worse birth outcomes, and future reproductive deficits among both boys and girls.⁵⁴ Furthermore, artisanal and small-scale gold mining have proven to be an important source of lead exposure for children.⁵⁵ Importantly, children are at higher risk than adults for both lead exposure given hand-mouth behaviors among children⁵⁶ and for the consequences of lead toxicity for a host of reasons, including more efficient absorption from the gastrointestinal tract and immature protective barriers (such as the blood–brain barrier and the hepatic detoxification system).⁵⁶ In addition, less commonly identified toxic exposures among children related to artisanal and small-scale gold mining also have notable consequences. Arsenic can cause acute and chronic intoxication and is a known carcinogen.⁵⁷

Cadmium results in severe renal toxicity and can interfere with bone mineralization.⁵⁷ Notably, absent from the identified articles were analyses of methane and carbon monoxide toxicities secondary to artisanal and small-scale gold mining, which are important subjects for future research.

Overall risk assessments from cancer and non-cancer hazards

In addition, nine articles performed risk assessments for cancer and non-cancer hazard indices as consequences of mining activities among children. *Gymafi* et al.⁵⁸ calculated the non-cancer hazard index as a consequence of mercury exposure among children at mining sites to be 76 (notably higher than the hazard index of 10 noted among adults). Other studies from the Amazon, Bolivia, Ecuador, Ghana, Nigeria, and Tanzania reported increased risk of cancer among children from mining communities based on concentrations of trace metals detected; arsenic, in particular, has been associated with an increased risk of cancer in children, although estimates range substantially between 1 in 1,000 and 4 in 1,000,000.^{6,59–62}

Future directions and solutions

Based on the findings above, the need for further action is clear in two primary domains: child labor and harm prevention. Fundamentally, child labor is a human rights issue. While numerous countries around the world have signed or ratified the Prohibition and Immediate Action for the Elimination of the Worst Forms of Child Labor, which was adopted by the International Labor Organization in 1994,³³ the persistence of child labor reflects the ongoing poverty

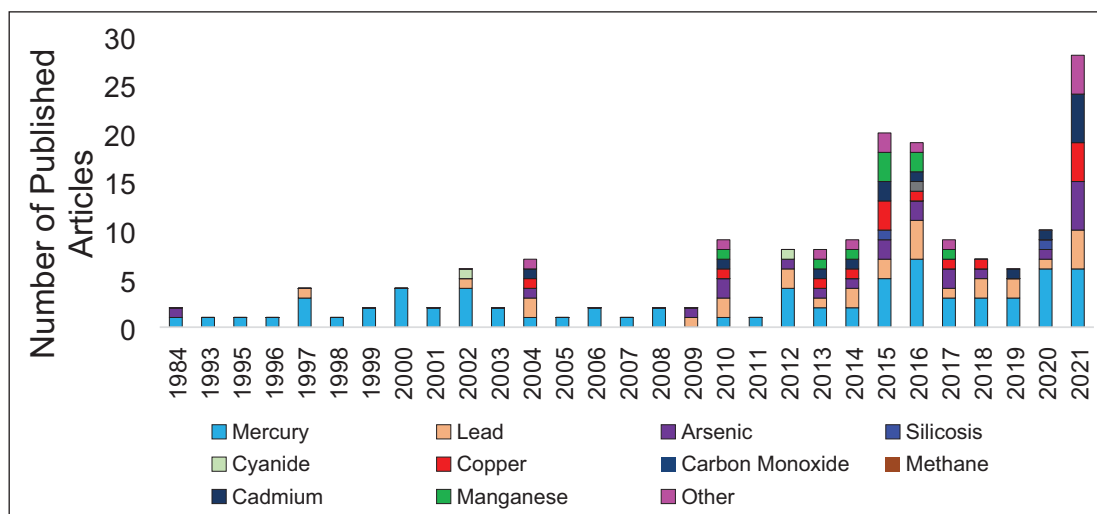


Figure 2. Number of studies reporting toxic exposures among children as a consequence of artisanal and small-scale gold mining globally, 1984–2021.

and exploitative conditions around the world.³⁴ No meaningful progress can be made, much less sustained, toward improving the health of children in mining communities, without viewing the problem through the lens of human rights. Thus, further work from the international community must also address the multiple facets of global poverty.

Government interventions will also likely be instrumental. Governments can and should enforce selected mining bans, such as the 2015 ban on mercury use in underwater mining in the Philippines⁶³ and ratify the 2013 Minamata Convention treaty. Governments should also focus on child labor monitoring and child protection systems, and preemptively engage children who have dropped out of school to prevent entry into the mines. Governments can also ensure that programs targeted against the ill-effects of poverty, such as free school meals and social support programs, are reaching families in mining areas, who frequently depend on the labor of children for survival. With regard to mining, governments should support the creation of a legal, regulated, child labor-free, small-scale gold mining sector that helps rural families thrive. In addition, the central bank and international gold trading and refining companies should put in place robust safeguards to trace the gold back to the mines of origin, oblige their suppliers to source only child labor-free gold, and monitor child labor.⁶³

Further governments can support infrastructure development to ensure adequate access to health systems, which can function to both provided preventive services, such as immunizations, and in tracking health outcomes among children in mining communities. Simultaneously, governments should invest in harm-reduction strategies, such as those to reduce the toxic impact of mercury, including low-cost mercury monitoring systems; however, further development is still needed before they are sufficiently optimized for field implementation.⁶⁴ Simultaneously, reduction of

environmental accumulation of mercury will be important to reduce ongoing exposures. There are promising strategies for improved remediation of mercury from soil,^{65–69} inclusive of the use of phytoremediation,⁷⁰ which uses plants to extract the mercury. In addition, methods for water remediation,⁷¹ particularly using sulfur-based sorbents,^{72,73} are encouraging given that supplies are relatively inexpensive and often produced as by-products of the petroleum industry. Mercury recycling has also been proposed, using homemade, cost-effective retorts, which reportedly recover up to 90% of mercury used;⁷⁴ however, uptake may be limited by the initial costs of equipment, required training prior to use, and the maintenance and repair of equipment.⁷⁵ Furthermore, retorts are not used in the place of heating and burning mercury.

Additional innovative solutions have been suggested that require less mercury used, such as concentrating ores with basic separators or centrifuges, which may reduce the amount of mercury needed for amalgamation by 90%.⁷⁶ Alternatives to mercury have also been studied. Potassium cyanide is reportedly more effective and faster than mercury,⁷⁷ however, has its own significant toxicities and thus requires training for safe use. Polythionates may be more favorable than cyanide for several reasons: (1) they are less discriminatory and therefore result in higher yields, (2) they are less reactive with copper containing ores, and (3) they may have broad applicable use because some ores cannot be treated with cyanide.⁷⁸ Finally, the gravity-borax method is a particularly appealing approach given its lack of toxicity. Such an approach uses gravity to separate the gold initially and subsequently by borax, which lowers the melting point of the mineral concentrate. However, the gravity-borax approach is limited by the time required for processing. Notably, an iteration of the gravity-borax approach has been implemented and studied, though the authors concluded that the feasibility

and success of the endeavor was predicated on the involvement and acceptance by local governments and mining organizations.⁷⁹

Importantly, direct exposure to mercury and other toxins, such as lead and silica, through mining activities is only one of a host of toxicologic exposures those communities are at risk for. While beyond the scope of this review, such activities include artisanal cookware production, metal scraping, and electronic waste recycling.⁸⁰ Similar health equity and human rights work must be concurrently directed toward those arenas as well.

Furthermore, occupational hazards may be reduced through improved awareness and educational interventions.⁶ In addition, improved sanitation, provision of basic health resources including a clean water supply, food, personal protective equipment, and access to health services will likely improve the well-being of the mining communities. Those interventions will also likely reduce the burden of infectious diseases, though there may be specific interventions to reduce the disturbance of, and thus number of encounters with, wildlife that may further afford protections. Notably, our review identified studies predominantly focused on open cast pit mining, whereas underground mining also occurs, is perhaps more dangerous, and also affects children. Further research should specifically aim to elucidate the hazards and consequences of underground mining on children, and any of the above interventions should be made with consideration for such other forms of mining.

Limitations

Our study was primarily limited in that the data included in the identified articles were predominantly of middle quality (evidence-base Category B), most often limited to retrospective analysis, epidemiological studies, and case series. Little data exist on the health impacts of artisanal and small-scale mining on children. Furthermore, there was a paucity of data describing health hazards associated with specific roles (e.g. mining vs ore processing). However, these findings are in themselves, essential. Underreporting and lack of awareness contribute to perpetuation of the underlying problem, which in turn likely impacts children in far greater ways. The strengths of our study include the diversity of studies included, from 29 countries, spanning more than 60 years.

Conclusion

Artisanal and small-scale gold mining activities are associated with numerous health hazards among children, including exposure to dangerous toxins, infectious diseases, occupational-related maladies, and acute traumatic injuries. The consequences therein are particularly devastating among the children who work the mines, who suffer the immediate cost of the hazard as well as the opportunity costs of lost education, high disability-adjusted life years, and increased risk for

cancer in later life. However, most notably from our review was a profound underreporting of the prevalence of such hazards among children. More work and interventions are needed to characterize the burdens of those hazards and to address the underlying drivers of child labor in these settings.

Declaration of conflicting interests

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Supplemental material

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