



Review

Worldwide Illegal Gold Mining Fuelling Environmental Mercury Contamination: Recent Developments, Challenges and Remedies

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ABSTRACT

This review highlights the multifaceted issue of mercury pollution mainly by worldwide illegal gold mining or artisanal and small-scale gold mining (ASGM), apart from several other significant mercury-emitting sources such as coal-powered thermal power stations, mercury mining, volcanic eruptions, forest wildfires, open biomass burning, and several other industrial activities. Important related aspects such as the process of gold extraction during illegal mining activities and the release of mercury into different environmental compartments, especially into water bodies where mercury gets transformed into more toxic form called methyl mercury (MeHg) which enters the food web through a processes called biomagnification, where it becomes more concentrated ultimately increases the risk of human mercury exposure, particularly through the consumption of mercury contaminated fish. Global mercury cycle, pollution of different environmental compartments including aquatic environment, mercury toxicity, accumulation of mercury in different aquatic organisms like fish, biomagnification, and the impact of mercury on human health and ecosystems, are discussed in detail with recent updates. Other aspects, such as air and soil pollution, deforestation, and habitat loss, the land destruction effect on indigenous communities are discussed in detail. Global perspectives on mercury pollution and control, including the Minamata Convention's efforts to combat mercury emissions, as well as techniques for identifying illegal mining areas, are discussed in detail. A brief review of important analytical techniques for determining elemental mercury, mercury isotopes, and mercury species in various media, including air, water, soil, and fish, is also presented.

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Research Highlights

- Mercury is released into the environment by worldwide illegal mining activity.
- South America and Africa are the two major hotspots in the world.
- Coal-fired power plants are among which release significant amounts of mercury.
- The Minamata Convention on mercury aims to protect human health.

1. Introduction

Rising gold prices and the demand for this yellow metal are fuelling a rush of illegal mining or artisanal and small-scale gold mining (ASGM) operations across the world, especially in countries such as Ghana, Senegal, Cameroon, Zimbabwe, South Africa, Niger, Mali, and Burkina Faso in Africa, Mexico in North America, Brazil, Columbia, Peru, Bolivia, Surinam, and French Guiana in South America, Indonesia, Malaysia, China, and India in Asia. Though large-scale illegal gold mining, often linked to organized crime, is a significant issue in Mexico, there is no clear evidence of similar large-scale illegal gold mining operations in Canada or the United States. Illegal gold mining has been officially prohibited in China and India since 1957 and 1996, respectively, but some illicit operations continue to persist in remote areas in both countries, causing an ongoing legacy of mercury pollution [1]. The private individuals were completely banned from gold mining in Russia for much of the 20th and early 21st centuries. There are no reports of illegal gold mining either in Europe or in Australia. But the majority of the countries in the world are responsible for atmospheric emission of mercury through other means, such as coal-fired power plants, from open biomass burning, emissions from ferrous, non-ferrous, and cement industry, mercury mining, illegal gold mining, and forest wildfires [2]. Human activities like burning fossil fuels in power plants and small-scale gold mining are the largest contributors, while natural sources like volcanic emissions also play a role. The use of mercury in artisanal and ASGM poses a significant environmental threat and health risks in different countries worldwide and is a target of government crackdowns and international conventions. Soaring gold prices and tax policies have driven a global surge in informal ASGM activity worldwide. While this practice provides a livelihood for millions, it also causes severe environmental degradation, human rights abuses, and other socioeconomic issues. These unregulated small-scale and artisanal mining activities are also responsible for releasing thousands of tons of mercury into the atmospheric air, soils, and waterways annually [3]. Illegal mining or ASGM is often associated with several negative issues like the miners' health and safety, child labour, violence, and organised crime within the sector, and environmental degradation [4]. This illegal gold mining activity contributes to climate change, mainly due to the high energy demands of mining and processing by using primitive techniques, which are often powered

by fossil fuels like diesel [5]. There have been several individual case studies as well as reports and reviews published before [6, 7]. The purpose of this study is to provide a comprehensive understanding of this problem worldwide with updated information, including detailed discussions on various related issues. The discussed issues include updates on various sources of mercury emission, details of the use of mercury in illegal gold mining, global mercury cycle, air and water pollution, soil erosion and degradation, biomagnification of mercury in aquatic environment, effect of mercury on agriculture, deforestation, land destruction and habitat loss, effect on worldwide native communities, mercury toxicity to humans, analytical techniques for the determination of elemental mercury, isotopic concentrations, and mercury species, global perspectives on mercury pollution including the Minamata Convention, how to identify illegal gold mining areas and ways to combat illegal gold mining and other anthropogenic mercury emissions.

2. Worldwide Problem

The problem of mercury emissions from illegal gold mining is a severe environmental and public health emergency driven by global economic forces and complex criminal networks. This issue is recognized as the largest source of global mercury pollution, causing profound damage to ecosystems, human health, and communities, particularly in regions such as the Amazon, Africa, and Asia. The criminal groups in Amazon nations, once focused on drug and arms trafficking, have moved to illegal gold mining in hotbeds of the Amazon rainforest, creating unprecedented damage to the environment. Colombia, Peru, Venezuela, and Brazil are major hotspots for illegal gold mining in South America. Colombia is the world's top per-capita mercury polluter, largely driven by unregulated, small-scale, and artisanal gold mining (ASGM), which accounts for 87% of the country's gold production. This pervasive pollution, frequently used to extract gold, has led to significant human health risks, such as neurotoxicity and kidney damage in areas like the Antioquia region and the Colombian Amazon [8, 9]. In addition, market restrictions on mercury for mining activities have promoted organized crime, with illegal armed groups controlling the illicit trafficking of mercury into the country. In Venezuela, some criminal organizations involved in the mining sector operate independently. On the other hand, hotspots for illegal mining in Africa include Ghana, Mali, Zimbabwe, Burkina

Faso, Mali, Niger, and South Africa. Mexico is one of the largest producers of mercury, a toxic chemical with massive health and environmental impacts. China is by far the world's top mercury producer, followed by countries like Tajikistan, Mexico, and Argentina. While China produces the vast majority of new mercury, other countries like Mexico also reclaim significant amounts from old mining waste [10]. Most mercury produced in Mexico is trafficked to the Amazon, where miners use it to extract gold. The leftover mercury often flows into nearby lakes, rivers, and other water bodies, poisoning the water, fish, and communities that depend on them. For example, 60% of Ghana's water bodies are now polluted, largely due to illegal mining activities. Ghana is one of the world's top 10 gold producers, and about 35% of its gold is extracted by small-scale miners, most of them operating illegally [11, 12]. Illegal gold mining in southeastern Senegal is causing dangerous levels of mercury contamination in the air, soil, and waters. According to Mulenga et al. [13], in Africa, the illegal gold mining is highest in West Africa (50.2%), followed by Central Africa (39.6%), Southern Africa (9.6%), and Eastern Africa (<1%). Both Africa and the Amazon region countries in South America are the two major hotspots of illegal gold mining regions in the World (Figure 1). Artisanal or illegal mining is a small-scale industry, providing income opportunities for rural people, can be operated by a limited number of labourers, with simple machinery, and limited investment. Most of these mines operate illegally without a license and belong to the informal sector, and even encourage hazardous child labour. MacFarlane et al. [7] reported a twenty-year inventory of anthropogenic mercury emissions in Australia spanning from 2000 to 2019 with annual resolution. The gold production sector, coal-fired power plants, and industrial waste dominate the inventory of mercury emissions. Brazil contains the largest portion, with about 60% of the Amazon rainforest, and illegal gold mining in this area releases substantial quantities into waterways annually. For example, the Peruvian Amazon was heavily impacted by artisanal gold mining, and the total

mercury concentrations, including the total mercury, particulate, and gaseous mercury, and methylmercury in the atmosphere, were the highest ever recorded in a forested area [14]. Gold mining in the Amazon rainforest has increased dramatically in recent decades, primarily driven by rising global gold prices and insufficient regulation. While pre-colonial societies practised gold mining for ceremonial purposes, the modern gold rush, fuelled by global demand and easy access to new technologies, has resulted in widespread environmental and social destruction [15]. In India, too, illegal gold mining is prevalent at a lower level in several regions where gold is found, with significant hotspots identified in the state of Karnataka (Figure 2). The other states where illegal gold mining is going on in India include Rajasthan, Madhya Pradesh, Jharkhand, Chhattisgarh, Tamil Nadu, and Andhra Pradesh, resulting in huge losses to the respective state governments. It is also a significant problem with severe environmental and social consequences. Enforcement and Regulation Boards of both state and central governments are taking specific actions to detect and penalize illegal mining. South Africa incurs gold production losses of approximately R14 billion a year due to illegal gold mining, which is one of the highest on the African continent [16]. In South Africa, illegal mining references may be found in the archives over the past 100 years [17]. The Tapajós River basin in Brazil is a global epicentre for illegal ASGM, driving severe environmental destruction and health crises. Over 2000 illegal operations release roughly 2.5 tonnes of mercury annually into the environment, contaminating waterways and poisoning Indigenous communities [5]. The Kuantan River is a major river in Kuantan Singingi regency, Riau, Indonesia. Hatika et al. [18] reported significant mercury pollution from illegal gold mining around the Kuantan River. Gold mining in the Guianas (French Guiana and Guyana) has a history that stretches back more than 150 years [19]. Senegalese artisanal gold mining leads to severe environmental contamination, including high levels of mercury in soil, water, and sediment [14].

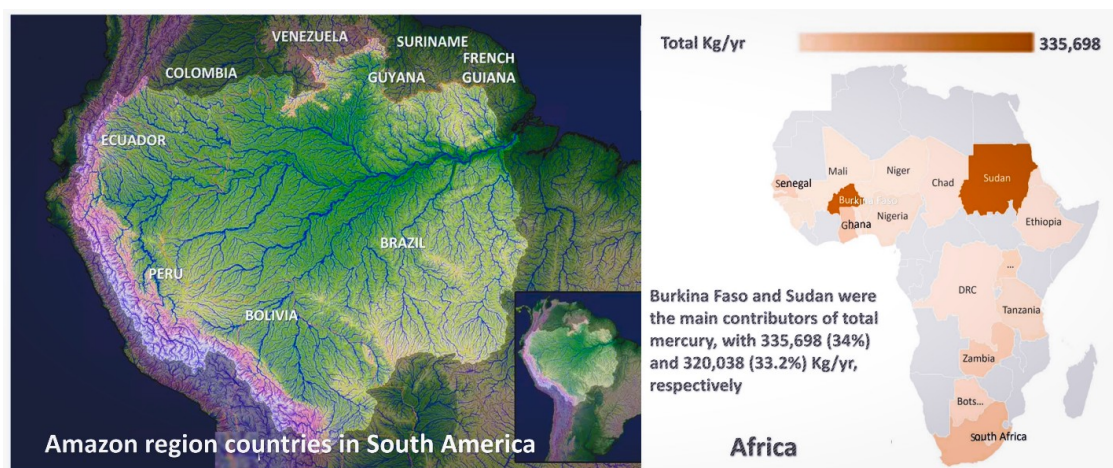


Figure 1. Amazon region countries in South America, and some African countries, as shown in the figure, are the two major hotspots of illegal gold mining regions in the World where illegal gold mining and mercury pollution is very high (modified after Mulenga et al. [13]; mongabay.com).



Figure 2. Different steps involved in the extraction of gold from gold ore using mercury, illegal gold mining practices in Hosur, Karnataka, India.

3. Sources of Atmospheric Mercury Emissions

Atmospheric mercury emissions originate from a variety of natural and anthropogenic sources. The global cycle of mercury is complex because it can be emitted, deposited, and re-emitted [20]. Natural sources of atmospheric mercury include volcanic activity, geothermal vents, and wildfires that release significant amounts of elemental mercury gas from the Earth's crust and mantle. Weathering of mercury-rich rocks and the natural erosion of cinnabar (mercury sulphide) deposits also significantly contribute. Additionally, oceans, lakes, and soils act as major sources through the re-emission of previously deposited mercury (secondary sources) and primary volatilization. Anthropogenic sources of mercury include illegal ASGM, which is the largest single source of mercury emissions [21]. In addition, coal-fired power plants world over, mercury mining, production of metals like zinc, lead, and copper, cement production, recycling of fluorescent lights, and other Industrial processes like production of items like paints, vinyl, and other chemicals also emit significant quantities of mercury. Figure 3 presents different important natural as well as anthropogenic emission sources of mercury in the environment, and their approximate contributions. In addition to the illegal gold mining, other activities like mining and coal combustion significantly contributed to mercury pollution even in a country like Canada, and these actions affect environmental

processes like methylation, which converts mercury into its more toxic form, methylmercury. This makes managing mercury a priority to protect ecosystems and human health, particularly through controlling emissions and improving waste management.

A recent analysis of satellite imagery shows that small-scale gold mining in the Peruvian Amazon is accelerating, causing significant damage to carbon-rich peatlands and unique ecosystems. The mining activity, which includes digging pits and creating ponds, releases stored carbon, exacerbates mercury contamination, and threatens wildlife [22]. According to Streets et al. [23, 24], historical mercury emissions can be broadly divided into three major phases, reflecting technological, industrial, and regulatory developments that have shaped mercury's global environmental footprint (Figure 4). The first period is the pre-industrial period (before ~1850) which include natural background levels of mercury in the environment, with some early anthropogenic contributions, the second one is the industrial period (1850–1970s), which marks a significant and rapid increase in global mercury emissions, driven by colonial expansion, industrialization, and new technologies, and the third phase is the current phase (1980s–Present). This phase is defined by an initial explosive peak driven by post-war industry, followed by a decline in the West due to regulations, and a shift of emissions to Asia, Africa, and South America.

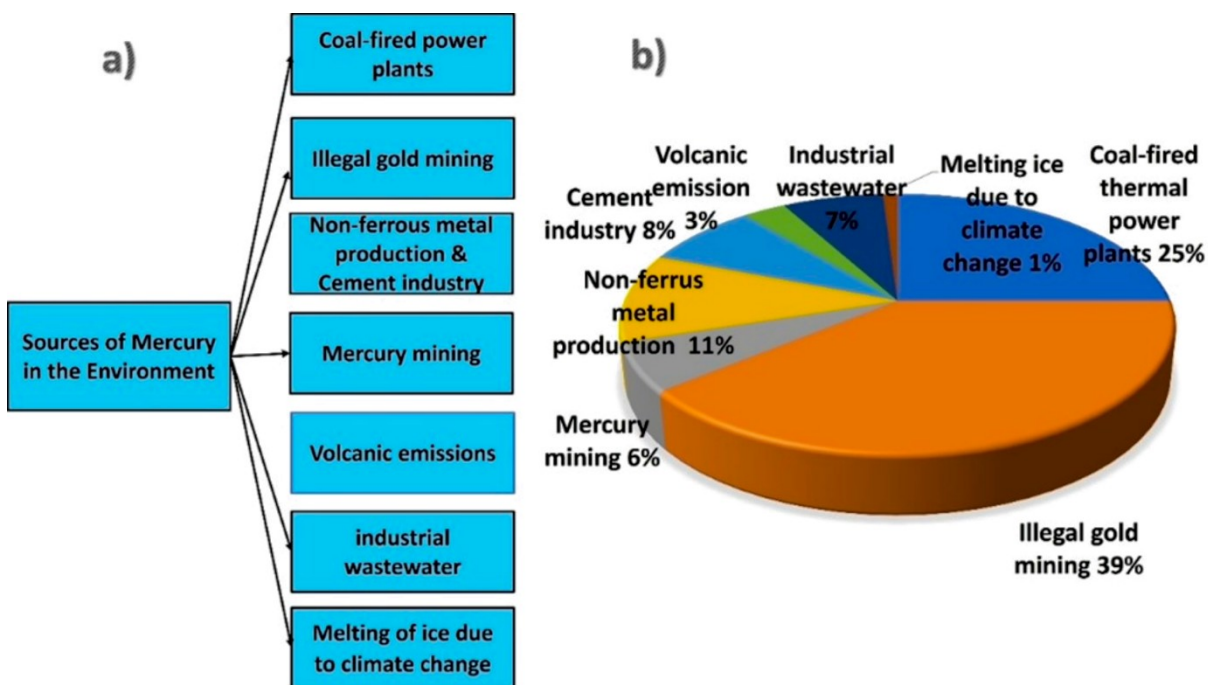


Figure 3. (a) Different important sources of mercury in the environment, and (b) Their approximate contributions.

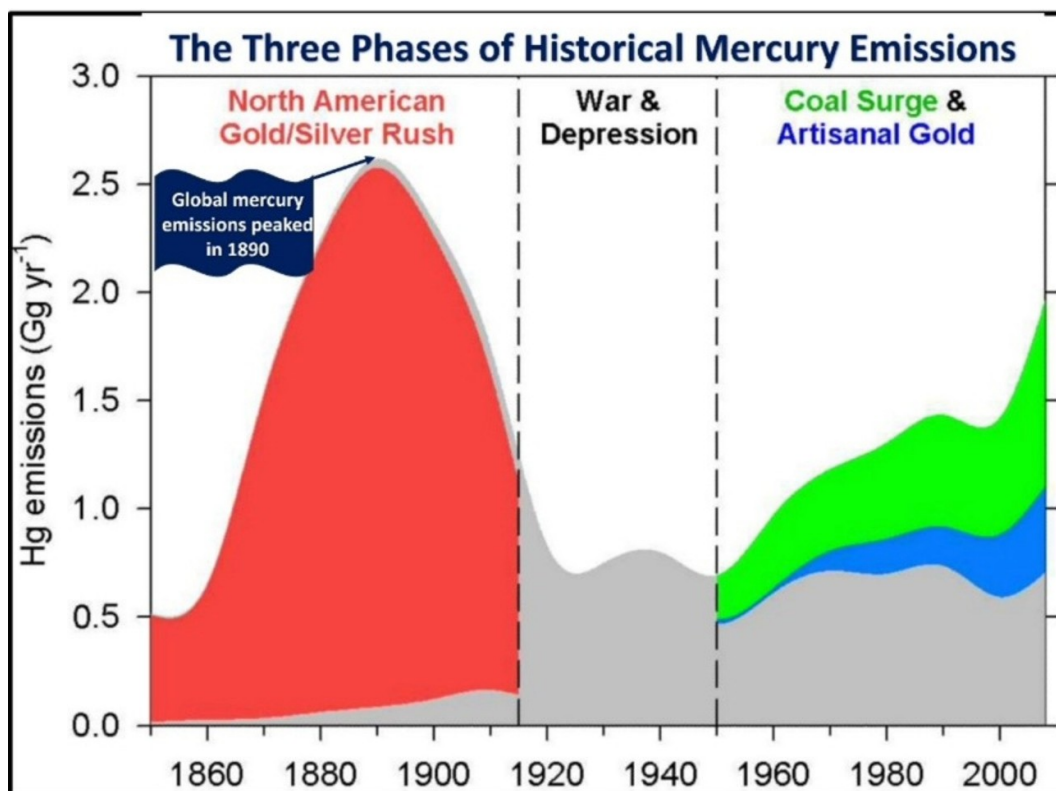


Figure 4. Three major phases of historical mercury emissions reflecting technological, industrial, and regulatory developments that have shaped mercury’s global environmental footprint, modified after [23].

4. The Process of Gold Extraction, Release, and the Fate of Mercury

Spanish colonists introduced the amalgamation technique in the 16th century to separate gold and silver from

gold ore using mercury [25]. The extraction of gold in illegal mining is a primitive and brutally efficient process designed for maximum short-term profit with zero regard for human life or the environment. Miners, often working by hand with

basic tools like picks, shovels, and hammers, dig pits or tunnels to reach gold-bearing ore. Most often, illegal miners create alternative openings to the closed and abandoned shafts to enter underground workings. Then, the ore is often transported to makeshift grinding mills. Very often a big boulder of hard rock, like a huge dyke is used to crush the gold ore. The most dangerous step is the mercury amalgamation process. After panning, concentrated gold-bearing material is mixed with liquid mercury. Typically, it requires 0.5 kg of mercury for every 50 kg of mixed sand or ore. Gold has a property that allows it to dissolve into mercury, forming a silvery paste-like substance called an amalgam (Figure 2). The amalgam is heavier than the rest of the material, so it's easily separated by hand. The amalgam is then heated, often with a blowtorch or over an open flame, in a pan. Mercury vaporizes, and most of it escapes into the atmosphere at a relatively low temperature, leaving behind a crude lump of porous gold. Often, a simple distillation device called a retort is used to separate gold from mercury. The use of a retort device has some kind of control on the release of mercury into the environment. Some amount of mercury will be spilled into nearby soils and waterbodies, and part of it will be absorbed by nearby trees. The rest of the mercury travels long distances in the atmosphere before depositing onto land and water, where it can be converted by microbes into methylmercury, a potent neurotoxin. Once in aquatic environments, the mercury released thus isn't staying in the mining zone, but rather the trees in the surrounding area are scrubbing mercury from the air and transferring it into forest ecosystems, and into forest wildlife and people, where it moves up the food chain with unknown effects. Forests act as a buffer, but this also means they become a sink for mercury pollution. Thus, mercury becomes a broader forest and food web problem. Figure 2 clearly explains the gold extraction process using the mercury amalgamation method. Fritz et al. [5] found that 1.7 kg of mercury is used per kg of gold extracted in the Tapajós River basin, Brazil, with retort use reducing environmental release to approximately 0.19 kg per kg of gold. Despite this, their findings suggest that even with retorts, significant environmental contamination occurs. The final gold sponge is melted in a crucible to form a bar. This technique is commonly used in artisanal (or illegal) and small-scale mining. This illegal gold is then sold to local buyers, who mix it with legally sourced gold to "launder" it into the international market, making it nearly untraceable.

The reliance on mercury amalgamation is its most defining and derogatory characteristic, leaving a legacy of poison that can persist for generations. Understanding this process is key to appreciating the true, horrific cost of illegally sourced gold. Gaseous elemental mercury can be deposited onto the landscape through three main atmospheric pathways: oxidation to ionic mercury (Hg^{2+}) followed by wet or dry deposition, sorption to particles that are then washed off tree leaves via throughfall, or direct

uptake into leaf tissue and deposition via litterfall. Throughfall and litterfall together are considered the total mercury deposition [26, 27]. Most illegal miners use mercury due to a lack of affordable alternatives. However, more sophisticated and larger illegal operations use sodium cyanide, which is the same chemical used by legal, industrial mines, but in a completely uncontrolled manner. Cyanide is even more dangerous to human health [28].

5. Global Mercury Cycle

Mercury is an integral part of Earth's biogeochemical cycles. Growing scientific and regulatory focus on mercury's global atmospheric cycle, which includes its emission from both natural and human sources, its long-distance transport, its transformation into different chemical forms, and its deposition back to land and water, is increasingly studied due to its importance for understanding mercury's fate in the environment and its potential impacts on ecosystems and human health [29]. Mercury enters the environment from several natural processes, including volcanic eruptions, the weathering of rocks, forest fires, and emissions from the ocean [30]. While natural phenomena are an important part of the global mercury cycle, human activities such as illegal gold mining and coal-fired power have significantly enhanced the amount of mercury circulating throughout the planet (Figure 5). Major volcanic eruptions significantly disrupt the natural mercury cycle by injecting large quantities of the element into the atmosphere, causing elevated deposition rates that can persist for years. This process is clearly demonstrated by historical and scientific records [29]. Industries such as non-ferrous metal production and the cement industry together will have substantial input. Another important contribution of mercury comes from climate change. As global temperatures rise due to climate change, the mercury that has been trapped in places like frozen Arctic permafrost is being released back into the environment, potentially posing a significant environmental and health concern as this thawed mercury can become more mobile and toxic, impacting waterways, ecosystems, and food chains [31]. There are also minor contributions from cremation, ferrous metal industry, oil refining, and refined petroleum products [7]. Mercury can also come through the industrial wastewater from chemical factories, which is a known cause of poisoning, as tragically demonstrated by the 1956 Minamata disease outbreak in Japan, where chemical factory effluent contaminated Minamata Bay with methylmercury [32]. The mercury in the atmosphere will be deposited in the oceans or on land, but this deposited Hg can be reemitted to the atmosphere. The mercury thus deposited from the atmosphere into soils can be released back into the environment through various processes, like volatilization, where it returns to the atmosphere, and by transport in water, which moves it to surface waters like streams and lakes. Other factors, such as changing weather (temperature, solar irradiance) and soil moisture, also play a

significant role in governing mercury release [33]. This remobilized mercury can then be converted into its more toxic form, methylmercury, which enters the food web through processes like biomagnification, where it becomes more concentrated, ultimately through the consumption of contaminated food, increasing the risk of mercury exposure to humans [34].

Atmospheric elemental mercury absorption by tree leaves contributes abundantly to the global atmospheric Hg sink in forests. Atmospheric relative humidity, the rate at which gases, like carbon dioxide and water vapor, move through a plant's stomata, and leaf photosynthesis are key drivers of spatial-temporal variations in foliar Hg accumulation. Subtropical evergreen forests (broad-leaved forests) will have a greater Hg accumulation rate than tropical rainforests and tropical savannas [35]. Thus, mercury moves between the atmosphere, land, and oceans in a continuous loop, often taking years or even centuries to set-

tle into deep ocean sediments and again re-emitted into the atmosphere through volcanic eruptions. This cycling is driven by processes like atmospheric deposition, re-emission from soil and water, and its uptake by organisms like fish and trees, which release it again upon death and decay. Mercury concentration in tree tissues varies by part, with higher levels often found in bark and leaves, and lower levels in wood and roots, although this can change based on the species and environmental factors (Table 1). Human activity has increased the amount of mercury in the environment, leading to more re-emissions and a higher overall burden in ecosystems. Mercury is a persistent, non-biodegradable pollutant that cycles indefinitely between air, water, soil, and living organisms. It bioaccumulates in food webs, particularly as toxic methylmercury in fish. Eventually, much of this mercury settles and is buried in deep ocean sediments, effectively removing it from the active cycle.

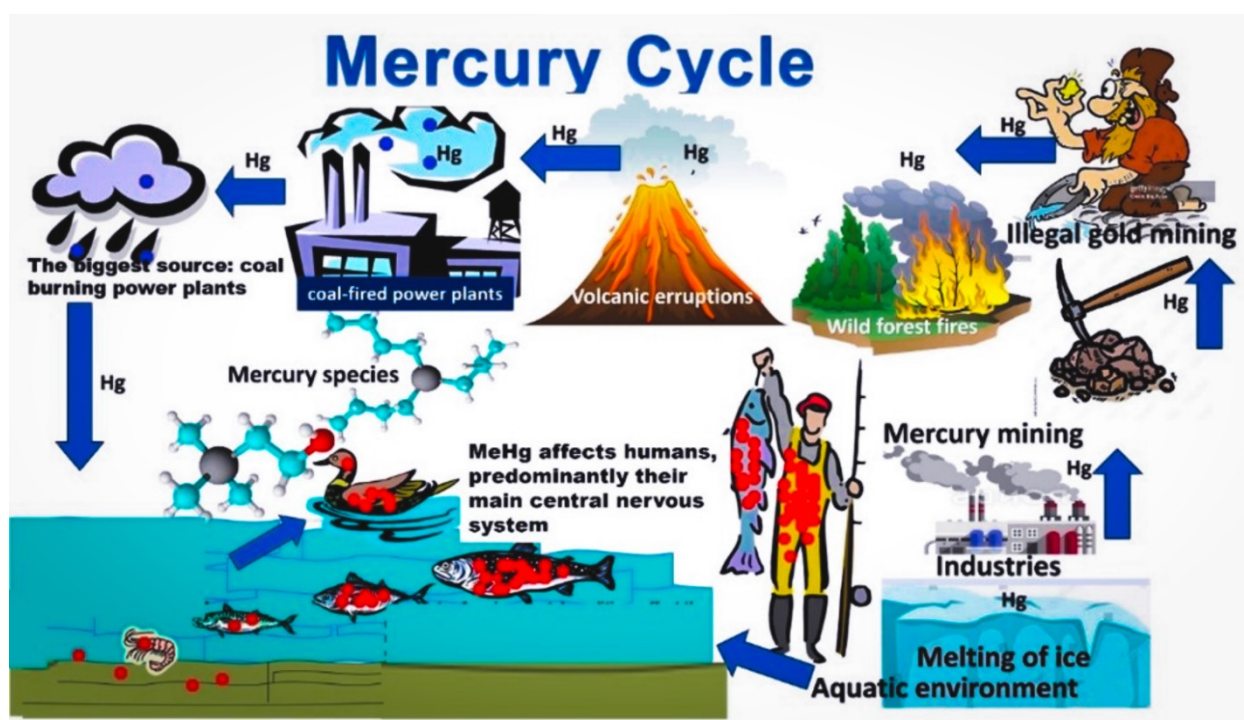


Figure 5. The mercury cycle describes the continuous movement and transformation of mercury through the atmosphere, ocean, land, and living organisms, beginning with its release from natural sources like volcanic eruptions or human activities like illegal mining and coal burning.

Table 1. Indicative mercury concentration in some trees and parts of trees.

Region/Country	Type of Samples	Mercury Concentration	Reference
Columbia	<i>F. luschnathiana</i> trees	18.3 ± 2.3 ng/g	[36]
USA	Hardwood specie	28.6 ng/g	[37]
USA	Leaves, hardwood species	6.3 ng/g	[37]
USA	Yellow birch, wood	2.1–2.8 ng/g	[37]
Romania	White poplar leaves	72 ng/g	[38]

While mercury is a heavy metal, its unique chemistry allows it to cycle through the environment in a way that mimics persistent organic pollutants. Methylmercury deposited in one place can change back to its elemental form, re-emit into the atmosphere, and continue traveling ever further from the source in a series of similar hops, a phenomenon called the grasshopper effect [29]. The “grasshopper effect” of mercury refers to the cycle of evaporation, long-range atmospheric transport, and re-deposition of mercury, which allows it to travel from warmer to colder regions and back again. After being emitted into the atmosphere, mercury travels on air currents, condenses, and is deposited on land and water, where microorganisms convert it into methylmercury. This process is then repeated as the mercury evaporates again, allowing it to circulate globally for decades and accumulate in colder regions, such as the Arctic. In the Arctic, the process is accelerated by atmospheric oxidation and deposition during spring, followed by the re-emission of mercury into the atmosphere as temperatures rise in summer, a cycle that is amplified by factors such as sea ice melt and permafrost thaw [39, 40].

6. Air Pollution and its Tracking

The process of grinding the gold ore generates large amounts of dust containing silica and heavy metals, leading to the incurable lung disease silicosis among workers, who rarely have any protective equipment when amalgam is heated, often over open flames, to evaporate the mercury and isolate the gold. This process releases mercury vapor into the atmosphere, which settles on surrounding soils, plants, and waterways. During the extraction of gold, the mercury vapor is released directly into the air. Mercury from illegal gold mining in the Amazon enters the terrestrial food web through atmospheric deposition, where it gets scrubbed from the air by forests, settles into the soil, and is then absorbed by plants and invertebrates. Songbirds ingest this mercury by eating contaminated plants and insects, and this process allows the toxin to move up the food chain, potentially harming wildlife that preys on birds [41]. The satellite data identified a significant rise in mercury in the air around Brazilian border towns during the Amazon Gold Rush, due to the use of mercury in illegal gold mining. This airborne mercury can then travel

long distances and contaminate soil and water through dry and wet deposition, impacting human health and ecosystems [15].

South Africa has been ranked as a significant global mercury emitter. The country has historically been ranked among the top ten anthropogenic mercury emitters globally, with coal-fired power plants operated by the state utility, Eskom, identified as the most significant contributor. These power stations, which accounted for approximately 93% of the country’s electricity production in 2015, release significant amounts of mercury during coal combustion, and at one point were estimated to be the second highest, after China. In addition, current emission abatement technologies in many South African power stations are less efficient at removing mercury compared to technologies used in many industrialized Northern Hemisphere countries, contributing to higher emissions. However, South Africa does have an extensive atmospheric mercury monitoring network that provides essential insights into regional pollution and atmospheric processes across diverse environments [42].

Mercury in soil and water can harm the human body, and mining workers are particularly at risk for health problems due to mercury exposure through inhalation of vapours or contact with contaminated materials. Effects can range from acute symptoms like respiratory distress and tremors to long-term issues such as nerve damage, memory loss, and developmental problems in children [43]. Atmospheric mercury deposition is the main way mercury enters the water bodies, such as the Great Lakes, but this deposition is decreasing in North America. The Great Lakes are particularly good at accumulating methylmercury and bioaccumulating it in fish. This makes fish, especially top predators, excellent indicators to track the effectiveness of efforts to reduce atmospheric mercury pollution [44]. While mercury isotope analysis is a valuable tool for tracking mercury sources and atmospheric concentrations, Lepak et al. [44] utilized fish-Hg isotope values to determine the sources of bioaccumulated mercury and atmospheric Hg concentrations, as these isotope values are indeed unaffected by ecological disturbances. However, the isotope values in fish can be influenced by various ecological factors and processes within the environment and the food [45]. Table 2 presents Mercury concentration in the air in the gold mining-affected areas.

Table 2. Mercury concentration in air in the gold mining affected areas.

Region/Country	Type of Samples	Mercury Concentration	Reference
Indonesia	Air	2096–3299 ng/m ³	[46]
Madre de Dios region of Peru	Air	~10 to >5000 ng m ⁻³	[47]
Gavea, Rio de Janeiro, Brazil	Air PM _{2.5}	19 ± 8 mg m ⁻³	[48]
Parnaso, Rio de Janeiro, Brazil	Air PM _{2.5}	24 ± 11 mg m ⁻³	[48]
Campos, Rio de Janeiro, Brazil	Air PM _{2.5}	10 ± 6 mg m ⁻³	[48]

7. Soil Erosion and Degradation and Their Effect on Agriculture

Mining activities disrupt soil profiles and clear land, triggering severe soil erosion, decreasing soil fertility, and altering the landscape. For example, in French Guiana, formerly gold-mined soils had reported very broad variability from 0.09–9.22 µg/g of mercury, which is very high levels of contamination [49]. Gerson et al. [14] found high levels of mercury in Peruvian Amazonian soils, plants, and songbirds, even in protected areas. Table 3 presents mercury concentration in soils, sediments, and mine tailings in the gold mining-affected areas. This accumulation was found to be from the nearby gold mining areas, highlighting how mercury pollution poses a significant threat to conser-

vation efforts and ecosystems. These studies also raise questions on how to manage and mitigate this pollution to protect biodiversity in the area in the long term.

A recent study by Huang et al. [50] on methylmercury (MeHg) and carbon emissions has shown a complex, often antagonistic relationship between elevated CO₂ levels and MeHg dynamics in rice paddy ecosystems. Mercury contamination in soil affects microbial activity and alters greenhouse gas emissions. The accumulation of MeHg in rice grains during agricultural activities is found to contribute significantly to emissions of greenhouse gases, CH₄, and CO₂ into the atmosphere. More deposition of mercury into the soil will lead to enhanced cumulative emissions of CO₂ and CH₄ from a paddy ecosystem.

Table 3. Methyl mercury (MeHg) concentrations in soils, water, and fish.

Region/Country	Type of Samples	MeHg Concentration*	Reference
Eastern Uganda	Lake Victoria (water)	0.2 to 1.0 pg/ml	[13]
South Africa, Berg River	Sediment	50 ng/g	[51]
South Africa, Ga-Selati River	Water	0.036 ng/ml	[52]
Edfu, Egypt	Gold tailings	13.7 ng/g	[53]
Edfu, Egypt	Surface water (ng/L)	0.064 pg/ml	[53]
Edfu, Egypt	Groundwater	0.16 pg/ml	[53]
Seychelles	Fish	<0.5 µg/g	[54]

*WHO has set a Provisional Tolerable Weekly Intake (PTWI) of 1.6 µg/kg body weight for methylmercury (<https://www.who.int/news-room/fact-sheets/detail/mercury-and-health> accessed on 01 January 2020).

Illegal gold mining is also affecting the agricultural sector of a country because these activities can result in the formation of sinkholes, contamination of soil, ground, and surface water. An increase in MeHg levels in rice through both microbial and geochemical mechanisms creates a more favourable environment for methylation and its subsequent uptake by plants. Pu et al. [55], through controlled pot and incubation experiments, demonstrated that Cd exposure leads to increased MeHg levels in both rice soil and grains, even when total mercury levels are not considered. Cd resistance to Hg-methylating bacteria, Cd exposure alters the soil's redox potential (Eh) and increases the amount of dissolved organic carbon (DOC), thereby creating conditions favourable for Hg methylation.

8. Contamination of Water Bodies, Aqueous Chemistry, and Biomagnification of Mercury

Gold mining, particularly ASGM, is a major source of mercury pollution, releasing substantial quantities into waterways annually. When a miner heats the gold-mercury amalgam, the elemental mercury (Hg^0) vapor enters the atmosphere. From there, it can travel globally before being deposited by rain or dust into aquatic systems. Several water bodies, such as lakes and rivers around the world are polluted with mercury and other toxic chemicals like arsenic and cyanide. For example, the Pra River basin in Ghana is highly polluted due to illegal gold mining [12]. In Senegal, illegal gold mining is contaminating rivers like the Gambia and Falémé. Table 4 provides mercury concentration in water samples near illegal gold mining areas.

Table 4. Mercury concentration in water samples nearby illegal gold mining areas.

Region/Country	Type of Samples	Mercury Concentration	Reference
US-EPA limit	Drinking water	2 ng/ml	[56]
North Musi Rawas District, South Sumatra Province, Indonesia	Well water	0.55 ng/ml	[57]
Santiago River, Coast of Ecuador	River water	4.2 ng/ml	[58]
Cayapas River, Coast of Ecuador	River water	2.3 ng/ml	[58]
Esmeraldas River, Coast of Ecuador	River water	4.5 ng/ml	[58]
Tanzania	Surface water	0.01 to 0.07 ng/ml	[59]
Eastern Uganda	Okame River	19 ng/ml	[13]
Eastern Uganda	Nankuke River	16.3 ng/ml	[13]
Eastern Uganda	Nabweo River	15.8 ng/ml	[13]
Eastern Uganda	Rwizi River	0.01 to 0.3 ng/ml	[60]
Eastern Uganda	Lake Victoria	0.7 to 5.8 ng/ml	[61]
Kenya	Lake Victoria Basin	0.36 ng/ml to 0.66 $\mu\text{g}/\text{ml}$	[62]
Sudan,	River Nile State Albenda region streams	0.001 to 0.005 $\mu\text{g}/\text{ml}$	[63]
Zimbabwe, Farvic Gold mine area streams, Bulawayo. Chimanimani, East Zimbabwe Mazowe and Chivaro Reservoirs	Water	0.06–0.4 $\mu\text{g}/\text{ml}$	[64]
Cameroon	Lom River water	0.01–1.83 $\mu\text{g}/\text{ml}$	[65]
Democratic Republic of Congo	Fizi Basin River systems, south Kivu, Water	7.8–41.3 pg/ml	[66]
West Ghana	Bonsa River	0.18 ng/ml–0.061 $\mu\text{g}/\text{ml}$	[67]
Senegal	Gambia River water	22 pg/ml	[6]
Nigeria	Manyera River water	0.014–0.025 $\mu\text{g}/\text{ml}$	[68]
Indonesia	Water	0.7–9.9 ng/ml	[69]
Indonesia	Kuantan River water	0.0117–0.0407 $\mu\text{g} / \text{ml}$	[18]
Philippines	Water	0.009–80 ng/ml	[70]
Venezuela	Surface water	4.60 ng/ml	[71]

Environmental impacts of mercury used in gold mining in Colombia. World Health Organization (WHO) permissible limits (1991): Water: 0.001 mg/l, Fish 0.5 µg/g, Blood 10 µg/l, Urine 20 µg/l, hair 5 µg/g and air 200 ng/m³.

When mercury enters terrestrial and aquatic ecosystems, it can be converted to MeHg, the most toxic form of mercury that bioaccumulates in aquatic food webs. The Amazon is the world's largest tropical rainforest, containing about 10% of Earth's known biodiversity and accounting for approximately 15% of the world's total river discharge into the oceans [72]. Illegal gold mining's intensive use of water leads to severe contamination and disruption of waterways, causing long-lasting harm to ecosystems and human health in surrounding communities. Mining activities also generate enormous amounts of sediment that increase turbidity, suffocating aquatic life and altering river dynamics [3, 73]. For example, the maximum levels of mercury in water allowed by the Colombian legislation are 1 ng/ml for drinking water and 20 ng/ml for surface water [74].

The aqueous chemistry of mercury is fundamental to understanding how mercury pollution from sources like illegal gold mining spreads through the environment and becomes toxic. Mercury's behaviour, toxicity, and ability to accumulate in living things all depend on its chemical form (speciation) in water. Elemental mercury is volatile and relatively insoluble. Inorganic mercury (ions Hg²⁺) is the most common reactive form in water, highly soluble, binds strongly to organic matter and particles, which is highly toxic to microorganisms. Methylmercury (CH₃Hg⁺) is the most toxic form, formed from Hg²⁺ by microbial activity (methylation). Easily absorbed by organisms and bioaccumulate, s in the food web. Dimethylmercury [(CH₃)₂Hg] is volatile and also toxic, formed in low-oxygen waters [75, 76]. This transformation occurs in water systems, air, and sediment environments. It is primarily facilitated by microbial activity: certain microorganisms (such as anaerobic bacteria) utilize specific enzymes to methylate inorganic

mercury. Another important process that can also contribute to methylation is by non-living chemical processes [43]. The methyl mercury (MeHg) is then absorbed by fish and other marine organisms [75, 77, 78]. Thus, while fish provide essential omega-3 fatty acids for foetal brain development, certain species contain high levels of methylmercury (MeHg) that can cross the placenta and potentially harm a developing baby's nervous system [79, 80]. Hence, the U.S. Food and Drug Administration (FDA) and the U.S. Environmental Protection Agency (U.S.EPA) issued a joint advisory in March 2004 recommending that pregnant women, those planning to become pregnant, breastfeeding mothers, and young children avoid fish high in mercury (shark, swordfish, king mackerel, and tilefish).

Mercury biomagnification is a process where mercury becomes increasingly concentrated in the tissues of organisms at each successive step up a food chain. The free-floating tiny plants, phytoplankton, and algae absorb MeHg directly from the water faster than they can get rid of it, and the concentration of MeHg in their bodies becomes higher than the concentration in the surrounding water. This is called bioaccumulation. Small aquatic animals like zooplankton, insect larvae, and small fish consume large quantities of phytoplankton, which is filled with MeHg. Since MeHg is soluble in fat and binds tightly to proteins, it is not easily excreted [81]. The toxin accumulates over the organism's lifetime. A small fish eats many zooplankton and insects, leading to an accumulation of methylmercury, and the concentration of mercury is now significantly higher in the small fish than it was in the zooplankton. Large predatory fish like tilefish, swordfish, shark, king mackerel, tuna in marine environments, and fish-eating birds like eagles or kingfishers, and mammals like otters or humans will accumulate mercury in the body. A large fish eats many smaller fish throughout its life and accumulates the mercury from every single one of those small fish because it is at the top of the food chain and lives a long time (Figure 6).

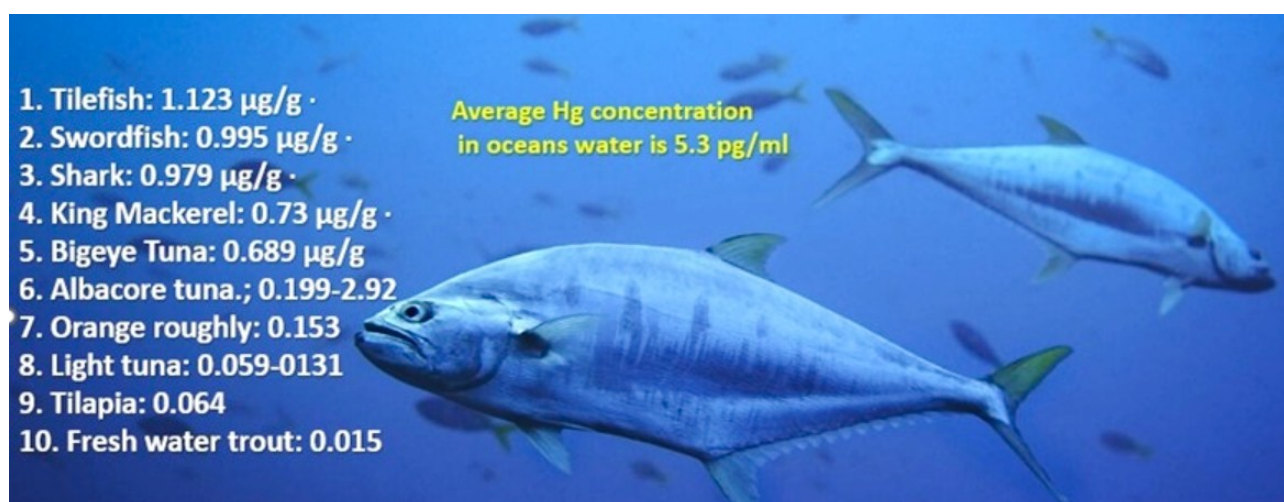


Figure 6. Example of biomagnification where bigger fish in oceans containing more mercury (Mercury data from [82]); U.S. Food and Drug Administration (FDA) ([32, 75] and the references in Table 1).

Their tissues can become tens of thousands to millions of times higher than the concentration in the surrounding water with respect to mercury [75, 83]. The average Hg concentration in ocean water is 5.3 pg/ml [32]. The

concentration of mercury in big fish can go up to $>1 \mu\text{g/g}$ (Table 5). Maximum allowable concentrations of mercury in different food items are presented in Table 6.

Table 5. Concentration ($\mu\text{g/g}$) of mercury in some varieties of big fish in oceans with an average Hg concentration in oceans water is 5.3 pg/ml [32].

Type of Fish	Name of the Ocean	Concentration of Mercury	Reference
Tile fish	Off the coast of South Carolina, USA	1.123	[82]
Shark		0.979	[84]
Atlantic sharp nose shark	Atlantic coast of Florida	1.06	[85]
King mackerel		0.73	[86]
Bigeye Tuna		0.689	[87]
Albacore tuna		0.199–2.92	[88]
Atlantic bluefin tuna		0.52	[89]
Atlantic cod	Baltic Sea, Poland	0.019–0.646	[89]
Billfish	UK	0.153–2.706	[90]
White tuna	USA	0.407	[91]
Fish	Lake Victoria, Tanzania	0.007	[59]
Fish: <i>Rastrineobola argentea</i>	Kenya, Migori Goldbelt, Lake Victoria Basin	0.26–355	[62]
Fish: <i>Lates niloticus</i>	River Nile State Albenda region streams, Sudan	0.085–0.172	[63]
Fish	Gambia River, Senegal	0.03–0.5	[6]
Shell fish	Gambia River, Senegal	0.5–1.05	[6]
Fish: <i>Heterotis niloticus</i>	Nigeria, Manyera River	0.008	[68]
Brazil	Madeira river	0.1–1.242	[92]
Peru	Palometa fish	1.22	[93]
Columbia	<i>Macropomum</i> <i>Prochilodus sp.</i>	0.02 0.53	[36]
Amazon	<i>Riverine fish</i>	0.02	[54]
Arctic	<i>Marine fish</i>	0.01–0.02	[54]

The United Nations and the World Health Organization (WHO) consider 0.5 µg/g to be the maximum safe limit of mercury concentration in fish for human consumption [9, 94, 95].

According to the United Nations Environment Programme's (UNEP) Global Mercury Assessment for 2018, about 3100 tons of mercury were released into the environment annually as a result of human activities. This estimate includes both atmospheric emissions and direct releases into aquatic environments. Illegal gold mining accounted for 38% of the global total in 2015, which was the single largest source, with the primary driver of mercury pollution in South America and Sub-Saharan Africa.

It is stated that 82% of the US population is exposed to MeHg is from the consumption of marine seafood [96, 97]. Mestanza-Ramón et al. [58] found elevated mercury concentrations in surface waters in two Ecuadorian provinces within the coastal region of Ecuador, El Oro and Esmeraldas, with at least 88% and 75% of samples, respectively, exceeding the limit for aquatic life. The study, which assessed human health risks in the coastal region, identified children as the most vulnerable group and highlighted the urgent need for regulations to protect river users in these contaminated areas. Table 7 presents methyl mercury concentrations in soils, water, and fish.

Table 6. Maximum allowable concentrations of mercury in different food items.

Food Item	Maximum Allowable Concentration of Mercury	Reference
Natural mineral waters	0.001 µg/g	[94, 95]
Salt food grade	0.1 µg/g	[94]
Fish for human consumption	0.5 µg/g	[94]
Predatory fish such as shark, swordfish, tuna, pike and others	1 µg/g	[94]

Table 7. Mercury concentration in soils and sediments in the gold mining affected areas.

Region/Country	Type of Samples	Mercury Concentration	Reference
Tanzania	Sediment	0.10–0.66 µg/g	[59]
Ghana	Waste soils	0.56–5.27 µg/g	[98]
Ghana	Soil, active mining area	9.1–409.3 µg/g	[98]
Kenya, Lake Victoria Basin	Sediment	430 ng/g–149.9 µg/g	[99]
Zimbabwe, Farvic Gold mine area streams, Bulawayo. Chimanimani, East Zimbabwe Mazowe and Chivaro Reservoirs	Sediment	6–154 µg/g	[64]
Democratic Republic of Congo, Fizi Basin River systems, south Kivu	Sediment	17.1–89.8 µg/g	[66]
West Ghana, Bonsa River	Sediment	1.13–1.21 µg/g	[67]
Senegal, Gambia River	Sediment	22 pg/g	[6]
Nigeria, Manyera River,	Sediment	0.021 µg/g	[68]
Ecuador	Sediment	2.7–20 µg/g	[100]
Ecuador	Tailings	89–1535 µg/g	[101]
Brazil	Sediment	0.1–1.21 µg/g	[102]
Peru	River sediment	20–53 ng/g	[93]
	Lake sediment	64–86 ng/g	
Columbia	The Rattlesnake River sediments	1.05 µg/g	[36]

9. Deforestation, Land Destruction, and Habitat Loss

Illegal mining is a destructive, unregulated process that severely harms the environment through deforestation, water contamination, land destruction, and biodiversity loss. These activities are particularly rampant in resource-rich but economically vulnerable areas like the Amazon and certain parts of Africa, often driven by high commodity prices and organized criminal groups. A lot of forest area is unofficially cleared for these illegal mining activities. This, together with water contamination with toxic chemicals and loss of biodiversity, added to the problem [97]. A high-resolution remote sensing study revealed that gold mining caused an accelerated loss of protected forests in the Peruvian Amazon between 1999 and 2016, with an annual forest loss of 4437 hectares during the period, and the rate of deforestation from mining nearly doubled in 2013–2014 [103]. During the last two decades, illegal mining in Suriname increased by 522%, and 85% of Suriname's Amazon forest loss was caused [104].

Deforestation in the Amazon, particularly in Brazil and Venezuela, significantly affects indigenous territories, where illegal mining and land grabbing drive forest loss. While indigenous lands are traditionally effective barriers to deforestation, they are increasingly targeted, with Yanomami territory in Brazil/Venezuela seeing a 308.8% rise in illegal mining-related deforestation between 2018 and 2022. Endangered pink river dolphins in the Amazon area are facing a growing hazardous mercury threat primarily from illegal gold mining, which releases mercury into the waterways. With mercury levels up to 20–30 times above safe limits, mercury bioaccumulates in the dolphins' bodies as they eat contaminated fish, leading to neurological and organ damage [105]. Illegal gold miners move deeper into forest areas, encroaching on protected areas and indigenous territories. This encroachment has triggered severe humanitarian and environmental emergencies, particularly within protected areas and indigenous territories [106].

Roulet et al. [107] demonstrated that deforestation increased with mercury levels by disturbing soil cycles, leading to the erosion of mercury-rich soil particles and their transport to aquatic ecosystems. Additionally, deforestation releases mercury stored by vegetation, and fires used for clearing can cause further atmospheric emissions, adding to the overall increase of mercury in the environment. Illegal gold mining causes severe and often irreversible land destruction through deforestation, toxic contamination, and soil degradation [108]. This is a global crisis, with particularly devastating impacts in the rainforests of Latin America, and agricultural lands in West Africa, primarily through widespread mercury contamination, massive deforestation/land degradation, and severe human rights abuses [109]. The use of heavy machinery and explosives in illegal mining creates large, unclaimed pits that are hazardous to both humans and wildlife. These activities can lead to deforestation and habitat loss, clearing of vast forest areas, and destruction of floodplains and wetlands. In the Amazon, an estimated 20 trees are lost

for every kilogram of gold mined [110]. The damage goes beyond trees. In the Amazon, illegal placer mining has led to at least 350,000 hectares of forest and wetland habitat loss. In Ghana, protected forest reserves that are biodiversity hotspots for rare species have been destroyed due to human activities, including illegal mining, logging, agricultural expansion, and human settlements. This destruction has led to significant biodiversity loss and ecosystem collapse [111]. The destruction caused by illegal gold mining is a stark reminder of the high cost of this illicit economy, where short-term profit for a few leads to the long-term loss of vital ecosystems and community health for many.

10. Effect on Worldwide Native Communities

The situation faced by native communities from illegal gold mining is a complex crisis involving environmental crime, violation of human rights, and fuelling violence. The most severe documented impacts are currently in the Amazon basin, but the problem is global in nature. Illegal gold mining in the Amazon, characterized by severe environmental crimes, gross human rights violations, and escalating violence. The resulting impacts are devastating to indigenous communities and the rainforest ecosystem across the basin [112]. Illegal gold mining is causing devastating effects on native communities worldwide through environmental destruction, severe health crises, and profound social disruption. For example, a lot of gold mining activity is happening in the British Columbia-Alaska border. This mining is happening without the free, prior, and informed consent of Alaska Native communities [113]. Large-scale gold miners employ centrifuges or cyanide, and see that they do not pollute. But artisanal and small-scale gold mining (ASGM) heavily relies on mercury due to its low cost, simplicity, and availability. In the same way, the native people of several other areas such as Peruvian Amazon (140,000 hectares cleared), Yanomami territory in Venezuela/Brazil, and the Atrato River in Colombia are affected. Brazil took several steps to eradicate illegal mining from indigenous lands and support the formalization of miners under environmental and social safeguards [114].

11. Mercury Toxicity to Humans and Health Effects

Mercury pollution from artisanal and small-scale gold mining (ASGM), much of which is illegal, is the largest human-caused source of mercury in the environment globally, continuing to pose one of the greatest threats to public health and the environment. Human mercury exposure primarily occurs from breathing mercury-contaminated air, consuming mercury-contaminated water, and marine fish, as mercury builds up in the food chain [80]. Fish are an important part of the diet for human populations, but they can accumulate mercury, which poses a health risk, particularly with high consumption. Larger, predatory fish tend to have higher mercury levels, and the exposure is a major concern for those who eat a lot of fish or who are pregnant, planning a pregnancy, or have young children. Table 8 presents mercury concentration in humans in the affected areas.

Table 8. Mercury concentration in humans in some affected areas.

Region/Country	Type of Samples	Mercury Concentration	Reference
South Sumatra Province, Indonesia	Mine workers hair*	0.27 to 19.0 µg/g Average: 2.55 µg/g	[57]
Semarang, Central Java, Indonesia	Pregnant Women	0.146–8.105 µg/g Average: was 0.434 µg/g	[115]
Asia	Blood, people exposed to e-waste recycling	0.60 ng/ml	[54]
Asia	Blood serum, people exposed to e-waste recycling	0.7 ng/ml	[54]
Asia	Urine, people exposed to e-waste recycling	0.104 ng/ml	[54]
Asia	Hair, people exposed to e-waste recycling	0.72 µg/g	[54]

*The threshold set by US-EPA is 1 µg/g.

Mercury is a naturally occurring heavy metal (Hg, atomic number 80) that exists in three primary, toxic forms—elemental (metallic), inorganic, and organic (methylmercury), all of which can be poisonous to the human nervous system, digestive system, immune system, and other organs. Most of the Hg emitted by various natural and anthropogenic processes can end up in the ocean. Once, in the marine environment, bacteria in the bottom sediments convert inorganic mercury (Hg^{2+}) to methylmercury (CH_3Hg^+), the most dangerous form of mercury, through a process called methylation. This neurotoxic compound then builds up in the food chain through a process called biomagnification, leading to the accumulation of high quantities of the toxin in fish, especially large predatory fish at the top of the food chain, such as shark and swordfish, due to biomagnification, where the concentration of mercury increases at each successive trophic level (Figure 6). The specific health effects depend on the form of mercury, duration, and level of exposure, and the age of the individual [116]. High levels of exposure can cause blindness, seizures, and intellectual retardation. Mercury is a neurotoxin that particularly affects the developing brain, leading to problems with vision, hearing, and attention, and can lower IQ. Gestational exposure to mercury pollution is linked to lower birth weights and can increase the risk of infant and foetal mortality [15]. Exposure to MeHg and other forms of mercury is highly toxic and can lead to the following severe health problems: blindness and deafness, cerebral palsy, growth, and mental impairment, lung function impairment and movement and coordination problems. Common symptoms include ataxia (loss of full control of bodily movements), muscle weakness, and tremors [117]. Individuals concerned about mercury exposure should choose smaller, low-mercury fish such as salmon, sardines, and tilapia, which are high in healthy fats and omega-3 fatty acids [118]. da Silva and Lima [119] found that in fish's highest concentration of mercury is in the liver of *Cichla ocellaris* (4549 µg/g) and the lowest in the gills of *Hoplosternum littorale* (2 µg/g). The distribu-

tion of total mercury differed between tidal periods, with the Ebb period showing higher concentrations in muscle, then liver, then gills, and the flood period showing a higher concentration in the liver, followed by muscle, then gills.

International agencies, including the WHO, have identified that mercury exposure can cause severe, long-term neurological damage to children, affecting their cognitive thinking, memory, language, and fine motor skills. Foetuses, infants, and young children are particularly vulnerable, and exposure can lead to developmental delays and a wide range of learning difficulties. This is because mercury can cross the placenta and negatively impact foetal development, leading to potential issues such as reduced foetal growth, lower birth weights, and an increased risk of mortality. Vegetated areas along the banks of rivers, streams, and other bodies of water are known biogeochemical hotspots for MeHg production [120]. Countries such as Colombia reported a high incidence of paraesthesia among informal gold miners and non-miners [121].

Inhalation of mercury-contaminated air causes severe, irreversible neurological damage, kidney failure, and other health problems for the miners and their families. In Mexico, from the Sierra Madre mountains to river valleys downstream, mercury contamination is leaving a signature in fish, farmland, and human blood samples [122]. The high levels found in resident hair samples (Table 3) are evidence of widespread exposure to the human body [54]. Jayanti et al. [57], in a study conducted in Suka Menang Village, Indonesia, it was found that a significant portion (66.1%) of artisanal and small-scale gold miners had mercury levels of about 2.55 µg/g in their hair samples exceeding the 1 µg/g threshold limit established by the United States Environmental Protection Agency (US-EPA), indicating substantial exposure to mercury contamination through their mining activities food and air. Mercury in blood, urine, and hair can indicate exposure levels, with each sample providing different information about recent vs. long-term exposure and the type of mercury. Urine is the best indicator for assessing

the recent exposure to metallic and inorganic mercury, while blood and hair are better for monitoring exposure to methylmercury from sources like fish. Symptoms of mercury toxicity include tremors, numbness, and memory loss, especially with high-level, prolonged exposure.

12. Global Perspectives on Mercury Pollution

Mercury pollution is a complex global issue with significant health and environmental impacts. When emitted into the air, it can travel thousands of miles and cross continents before being deposited, making it an international issue. Artisanal and small-scale gold mining (ASGM) is the largest source of global anthropogenic mercury emissions, responsible for roughly 38% of emissions. Other major sources include stationary coal combustion (21%), non-ferrous metal production (15%), and cement production (11%). Increasing climate-driven wildfires in high latitudes are also mobilizing significant mercury stored in permafrost and soils. Increasing wildfire activity in high northern latitudes has the potential to mobilize large amounts of terrestrial mercury from soils and permafrost peatlands, such as those in the Arctic, releasing it into the atmosphere and local ecosystems. Wildfire mercury emissions from northern peatlands (~25.4 Mg/y) are an important component of the northern mercury budget [123]. The primary route of human exposure to methylmercury is the consumption of contaminated fish and shellfish, with predatory species (e.g., shark, swordfish, tuna) posing the highest risk due to bioaccumulation. This dietary pathway accounts for 87–95% of total mercury exposure for the general population. While emissions have declined in North America, Europe, and more recently in China, they are rising rapidly in other parts of the Global South, leading to an overall stagnation in global totals since the 2013-Minamata Convention. Understanding mercury pollution requires a deeper look into its pathways, health effects, and the challenges in controlling it. Mercury's journey begins when it is emitted from industrial activities or re-emitted from soil and water. Once deposited in water, bacteria convert it into MeHg, which then bioaccumulates in fish and shellfish. This is why dietary consumption of seafood is the major exposure route for humans, even far from the original pollution source. The tragic incident in Minamata, Japan, where industrial mercury waste caused severe poisoning, disabilities, and deaths, stands as a clear historical example of its devastating effects. Recent research highlights a critical shift. Efforts in developed nations and in China have successfully reduced their emissions. However, this progress is being offset by rapid growth in emissions from other Global South countries, such as Indonesia, Ghana, and Brazil. This means that while the geography of emissions has changed, the global problem persists, highlighting the urgent need for targeted support and action in these rapidly developing regions. The global community is actively working to address this challenge through policy and cooperation. Progress is being made, but many feel the response has not matched the scale of the crisis.

13. The Minamata Convention

The Minamata Convention on Mercury (effective August 2017) is a binding global treaty aimed at protecting human health and the environment from mercury pollution. It mandates reducing, phasing out, or controlling mercury use in products (e.g., batteries, lights), industrial processes (e.g., chlor-alkali), artisanal gold mining, and emissions from power plants. The Minamata Convention on mercury was initiated in response to the devastating and widespread health and environmental effects of mercury pollution, driven by the tragic lessons from historical mercury poisoning incidents, most notably in Minamata Bay, Japan, in the 1930s and discovered in the 1950s. A chemical factory in Minamata discharged wastewater contaminated with MeHg into the bay, where industrial wastewater containing methylmercury was discharged into Minamata Bay, contaminating the seafood that was a staple food for the local community. This led to an outbreak of what became known as Minamata disease. Victims suffered severe neurological damage, including tremors, loss of motor control, and hallucinations; many died, and children were born with severe birth defects. The Minamata disaster provided irrefutable proof of mercury's extreme toxicity and its ability to cause widespread human health crises through environmental contamination. In 2001, the United Nations Environment Programme (UNEP) began a global assessment of mercury, which was concluded in 2003, that found that there was sufficient evidence of significant global adverse impacts to warrant international action. The understanding that mercury pollution is a global problem that requires a coordinated international solution. The convention was finally adopted and opened for signature on October 10, 2013, in Kumamoto, Japan. The convention became legally binding in August 2017, after being ratified by the required 50 countries [124, 125]. As of early 2026, there are 153 parties to the Minamata Convention on Mercury. Figure 7 presents an overview of parties by May 2020. A few more countries: the Bahamas, Albania, Cyprus (in 2020); Bahrain, Burundi, Cambodia, Cameroon, Central African Republic, Poland, Zimbabwe, Iraq (in 2021); Algeria, Türkiye (2022); Bangladesh, Belize, Georgia, Kenya, Malawi, Saint Vincent and the Grenadines, Ukraine (2023); Mozambique, Liberia, Maldives, Ethiopia (in 2024); Serbia (in 2025) joined the Convention. It now reflects a truly global commitment and reach (UNEP: <https://www.unep.org/news-and-stories/speech/making-mercury-histor> accessed on 15 January 2025).

This treaty is the cornerstone of the international response. It requires participating countries to take concrete actions, such as controlling air emissions from coal-fired power plants and industrial facilities by using mercury scrubbers [126], phasing out mercury in products like batteries, a few electronic items, and cosmetics, and reducing the use of mercury in artisanal gold mining. Sharma et al. [127] described challenges in the implementation of the Minamata Convention in India. The Basel Convention is the 1989 treaty that regulates the international movement of hazardous and other wastes.

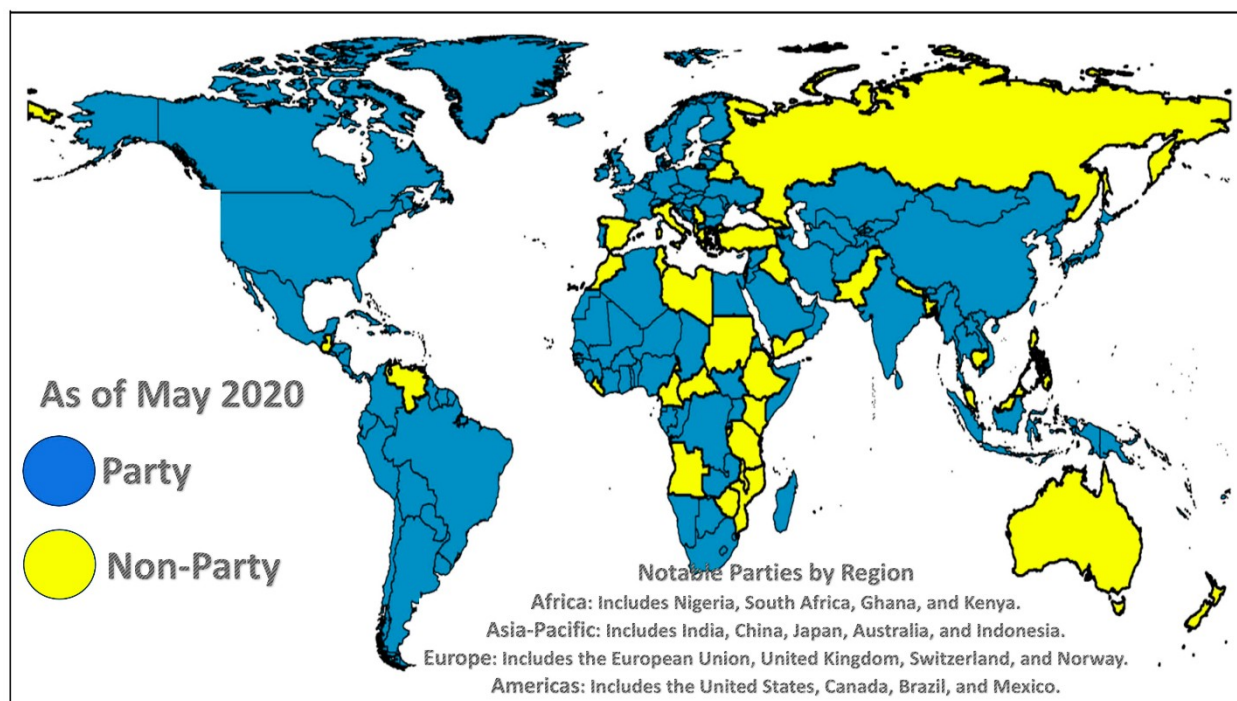


Figure 7. Party and non-party nations of the Minamata Convention on mercury as of May 2020, modified after [128].

It provides technical guidelines for the environmentally sound management of various wastes, including those containing or contaminated with mercury. The objective is to protect human health and the environment from the dangers of hazardous waste by controlling its transboundary movements and ensuring proper management. The two conventions are deeply interconnected in their mission to combat mercury pollution. The Minamata Convention defines the comprehensive global effort to reduce mercury use and releases, while the Basel Convention provides the specific tools and international rules for handling the waste that is generated. The Minamata Convention addresses the entire life cycle of mercury, from its supply and use in products to its emissions and safe disposal. The global community is taking strong early steps to address mercury use across to reduce the use, emissions, and releases of the chemical and to create new financial opportunities for those engaged in mining will accelerate the move away from mercury, leaving both people and the planet healthier [124]. The major objectives include setting controls on mercury emissions from major industrial sources, and ensuring sound management of waste by promoting the environmentally sound storage and disposal of mercury waste, in close cooperation with the Basel Convention. Recent data suggests that regulatory efforts are having a positive effect. One study noted that atmospheric mercury levels have decreased by almost 70% over the past 20 years, largely due to reduced human-caused emissions. However, projections indicate that future success depends on implementing targeted mercury control policies in addition to broader climate and clean air measures. However, the largest uncertainty and reduction potential lies in artisanal and small-scale gold mining.

In 2013, Indonesia also signed the Minamata Convention on Mercury, an international treaty aimed at protecting human health and the environment from mercury pollution. The Minamata Convention obliges signatory countries to take measures to eliminate the use of mercury and decrease mercury emissions. Indonesia subsequently passed a national law in 2017 following its ratification of the convention. Since the approval of Law 1658 of 2013, which established a phase-out plan for mercury use, the Colombian government has implemented several key regulations and policies [74]. MacFarlane et al. [7] showed a 3–4% reduction in the anthropogenic emission of mercury in the year 2019 compared to the emissions from the year 2000, suggesting a significant benefit to Australia. In 2017, Canada ratified the Convention [129]. As of early 2026, the Minamata Convention on Mercury has garnered broad international support, with 153 parties (countries that have ratified or acceded) (<https://www.epa.gov/international-cooperation/minamata-convention-mercury> accessed on 25 June 2026). Mercury entering waste increased from 14.6 to 1662.1 tons, and aquatic releases grew from 0.30 to 31.3 tons, likely due to industrial activity and changes in waste management. Simultaneously, atmospheric emissions rose from 91.3 tons in 1978 to a peak of 468.9 tons in 2011 before decreasing to 288.8 tons by 2021, a trend explained by economic development and subsequent emission control policies [130]. According to Qiu et al. [131], the following trends were observed for global anthropogenic mercury emissions between 1960 and 2021: there is an overall increase in global mercury emissions by 330% during this period. Global northern countries have seen declines in emissions since the 1990s, and China has experienced declines since the 2010s. These reductions have

been completely offset by rapid emissions growth in Global South countries (excluding China). Consequently, global mercury emissions have continued to rise slightly since 2013. These findings highlight a critical juncture in global control of mercury emissions.

14. How to Identify Illegal Gold Mining Areas?

In general, identification of illegal gold mining areas relies on a combination of advanced technologies, environmental monitoring, and supply chain tracking.

14.1. Using Satellites

Illegal gold mining is brutally destructive to forests. The process typically involves: (i) deforestation involving clearing large areas of forest to access the soil beneath, (ii) digging large, open pits, (iii) sediment mobilization using high-pressure water hoses to break down soil, creating a slurry, and (iv) mercury contamination of soil and water. Each of these stages creates a unique and detectable signature in the landscape, which is reflected in the health and presence of the trees. Satellite imagery and specialized analysis can help to detect these disturbances. Satellites capture data across the electromagnetic spectrum, including near-infrared (NIR) and short-wave infrared (SWIR). Healthy vegetation strongly reflects NIR light. Generally, before and after satellite images showing deforestation from illegal gold mining in any area will be clearly visible in the form of light-coloured bare patches. While satellites can't directly "see" Mercury, they can detect the environmental stress it causes. Contaminated water and soil can lead to vegetation stress in the surrounding area, which shows up in spectral analysis as abnormal patterns. Peru uses a satellite-based radar system called RAMI (Radar Mining Monitoring), developed with partners like the National Aeronautics and Space Administration (NASA) and the U.S. Agency for International Development (USAID), to send real-time alerts on illegal gold mining in the Peruvian Amazon. This system uses Synthetic Aperture Radar (SAR) to "see" through cloud cover and detect deforestation from mining, identifying the location and timing of forest loss in near real-time within sensitive areas like indigenous territories and protected zones. The alerts empower authorities to focus resources on stopping illegal activity [132].

14.2. Drone Surveillance

Drone surveillance provides high-resolution, real-time imagery for spotting fresh excavations, equipment, and makeshift camps on the ground.

14.3. Using Tree Rings

Measurement of mercury concentrations in tree rings helps to create a timeline of atmospheric mercury pollution. It works with the historical reconstruction of mercury emissions to identify past and ongoing mining areas. Trees absorb mercury primarily through their roots from the soil

and, to a lesser extent, through stomata (pores) in their leaves from the atmosphere. Tree physiology also controls the amount of mercury absorption. The chemical composition of tree rings reflects the environmental conditions and bioavailable mercury during that specific year. Therefore, by analysing the mercury concentration in a sequence of rings from the bark to the pith, it is possible to reconstruct a historical timeline of mercury pollution. Thus, tree rings provide a valuable, high-resolution historical record of mercury pollution. While not a perfect recorder due to complexities in plant physiology, they offer a unique and powerful way to peer into the past, complementing other archives like ice cores and lake sediments, and helping us validate the known phases of historical mercury emissions [25, 133].

Tree rings were used to determine the release of mercury into the air due to mining activities in South and Central America. This study was crucial in determining illegal mining activity and reducing mercury pollution, according to the UN Minamata Convention. Trees provide a cost-effective, widespread biomonitoring network by storing historical atmospheric Hg emissions in their annual wood rings, particularly effective near artisanal gold mining sites. Studies found that *Ficus insipida* trees in the Amazon record high, traceable mercury concentrations in their wood, allowing for temporal and spatial tracking of pollution. When gaseous elemental mercury is released into the atmosphere, trees such as *Ficus insipida* (wild figs), Brazil nuts (*Bertholletia excelsa*), and tornillos (*Cedrelinga cateniformis*) absorb and accumulate it in their bolewood, making them potential bio-monitors for atmospheric mercury pollution by analysing the mercury concentration within trees' annual growth rings. By determining the concentration of mercury in trees annual rings, it is possible to reconstruct historical atmospheric mercury levels over decades or even centuries. The tree ring Hg concentrations will be higher near illegal mining activity, about 6.0 ng/g compared to remote sites with about 0.9 ng/g [27]. Such studies contribute to global Hg regulation efforts, particularly under the UNEP Minamata Convention, an international treaty that aims to protect human health by reducing mercury pollution.

14.4. Other Methods

Direct testing of water and soil for mercury concentrations and other contaminants (e.g., cyanide) in the local environment is one important and reliable method. Gold "fingerprinting" can create a unique geochemical profile for gold samples to trace its origin to a specific mining region [134, 135].

15. Analytical Techniques for the Determination of Mercury

The determination of mercury is critically important in environmental studies for several interconnected reasons, all stemming from its unique and highly hazardous properties. Understanding the complex environmental cycling of

a global pollutant, for example, protecting human health, especially vulnerable populations, preserving ecosystem integrity by monitoring its most sensitive components, and informing and enforcing local and international policies aimed at reducing mercury pollution at its source. For mercury determination in different types of samples, including air, soils, water, and biological tissues, several well-established analytical techniques ranging from traditional laboratory methods to advanced online monitoring systems are available. The choice often depends on the required detection limits, the sample matrix (solid, liquid, gas), and whether measurement of total mercury or specific species, like highly toxic forms like methylmercury, is needed. Methods such as cold vapour atomic absorption spectrometry (CV-AAS) with light absorption at 253.7 nm by mercury vapor with ~ 2 pg/ml detection limit (for liquids) are one of the most popular techniques [136]. Direct mercury analysis, which uses thermal decomposition to liberate mercury from the sample, amalgamates it onto a gold trap, and then quantifies it using AAS with a detection limit of ~ 0.005 ng, is important [137]. Savoie et al. [138] have developed an analytical procedure for mercury quantification in Atlantic salmon muscle using cold vapor–MP-AES (CV-MP-AES). The detection limit for mercury by CV-MP-AES can go as low as 0.22 ng/ml [139]. Liang and Liu [140] reported a detection limit of 0.002 $\mu\text{g/g}$ by ICP-MS with microwave digestion of the sample. Vapour generation inductively coupled plasma mass spectrometry (VG-ICP-MS) with a detection limit 0.2 ng/ml, is another important analytical technique for the determination of mercury because it combines the specificity of ICP-MS with the sensitivity boost from vapor generation, which effectively separates mercury from complex sample matrices, reducing interferences and improving detection limits for mercury at trace levels [141–144]. For mercury speciation analysis, for example, to determine MeHg or ethyl mercury, a chromatographic technique like high-pressure liquid chromatography (HPLC) has to be coupled with ICP-MS [32]. Selecting the appropriate method depends heavily on the specific analytical needs. If samples are liquids like water and wastewater for standard compliance monitoring, CV-AAS is a robust and widely accepted choice. Cold vapour atomic fluorescence spectrometry (CV-AFS) is another important analytical technique for the determination of elemental mercury [145]. If speciation information is needed, HPLC-ICP-MS is the best choice. Capodiferno et al. [146] determined the concentrations of mercury species in wild fish and seafood from the western Mediterranean Sea by thermal decomposition-gold amalgamator-AAS. Gerson et al. [27] determined mercury in tree rings using a direct mercury analyzer, which works on thermal decomposition, reduction, amalgam preconcentration, and

the atomic absorption principle. Tandem ICP-MS coupled with cold vapour (CV) technology is one of the best techniques for an interference-free determination of mercury [147]. Yan et al. [148] used ICP-MS/MS with oxygen as reaction gas to determine ultra-trace Hg in geothermal water with a detection limit of 0.5 pg/ml.

15.1. Identification of the Source of Illegal Gold

Major gold-buying nations, such as China, the United Arab Emirates, the United Kingdom and Switzerland, are indeed tightening regulations to ensure traceability and prevent the laundering of illegal gold into the legitimate market. Legally mined gold comes from licensed operations and generally has a consistent composition, while illegally mined gold, often from unregulated sources can be identified by the presence of specific trace elements like Pb, As, and Sb, which are not found in legally produced refined gold. Roberts et al. [135] developed an analytical method to distinguish between legal and illegal gold, based on the presence of trace elements like Pb, As, Sb, Sn, Se, and Te, using inductively coupled plasma optical emission spectrometry (ICP-OES). These elements are not present in legally produced gold.

15.2. Mercury Isotope Ratios

For mercury isotope analysis, MC-ICP-MS is the best technique [149, 150]. Atmospheric gaseous elemental mercury (GEM) concentrations and stable Hg isotopes at fine spatial resolution in the Madre de Dios region of Peru revealed significantly elevated atmospheric GEM concentrations due to artisanal and ASGM, and confirmed that these activities are the dominant source of local and regional atmospheric Hg [47]. Coal-fired power and cement plants are important anthropogenic mercury emission sources. Mercury isotopic concentrations from the emissions of these sources act as a useful tool for monitoring environmental Hg emissions and identifying sources [151]. Figure 8 presents some important analytical methods for the determination of elemental mercury, mercury isotopes, and mercury species such as, methyl mercury and ethyl mercury, in different types of materials such as air, soil, sediment, water, and fish. According to Wang et al. [152], mercury content in human hair serves as a reliable indicator for potential Hg exposure to the human body. He utilized data on Hg speciation in hair and its corresponding sources, including consumption of Hg-polluted food and occupational exposure, from 88 regions across 44 countries worldwide. Mercury isotope signatures, as well as X-ray absorption spectroscopy, were utilized for the identification of Hg speciation in hair, which could have been influenced by exposure sources.

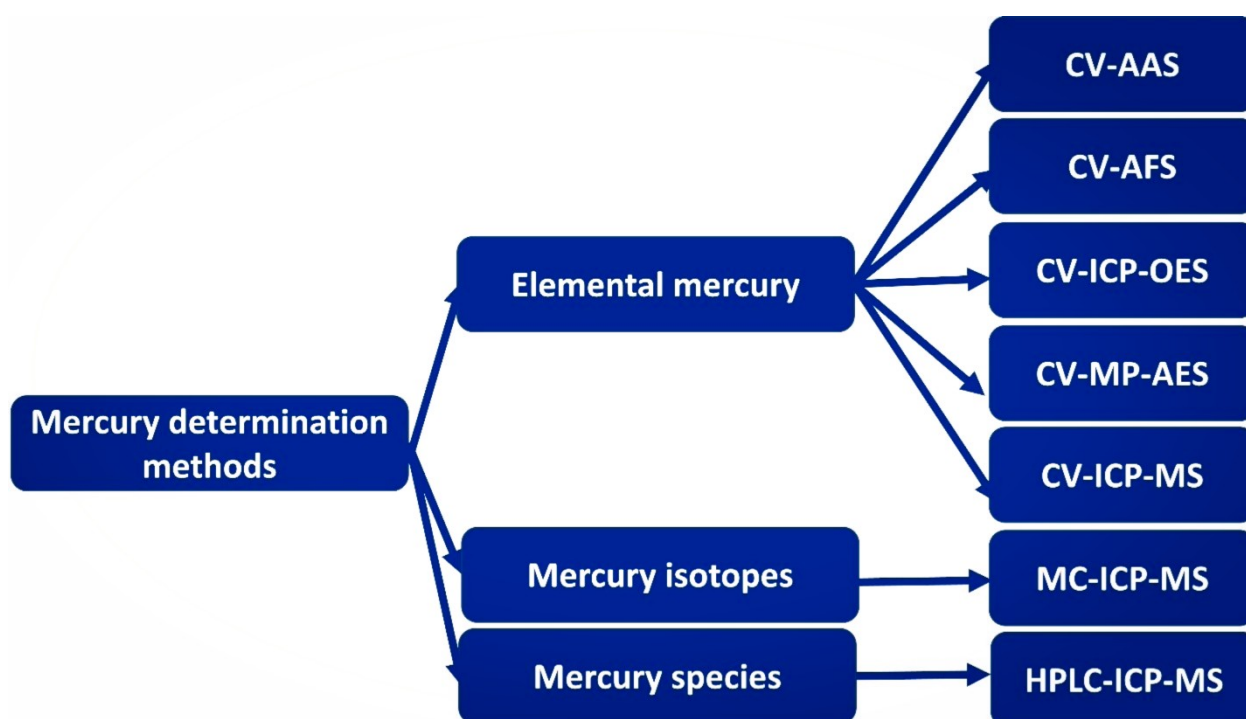


Figure 8. Some of the most important analytical methods for the determination of elemental mercury, mercury isotopes, and mercury species such as methyl mercury and ethyl mercury, in different types of materials such as air, soil, sediment, water, and fish.

16. Combating Illegal Gold Mining and Other Anthropogenic Mercury Emissions

Controlling mercury emissions is a global challenge, addressed by international agreements and national regulations, which set requirements for major industrial sources like mining and power generation, and other industries. Mercury emissions from artisanal and ASGM, coal-fired power plants, industrial boilers, cement industry, non-ferrous metal industry, and fluorescent lamp recycling facilities are very important in this context [153]. Bans are already in effect for items like batteries, certain lamps, switches, relays, and some cosmetics. More stringent regulations are needed to control illegal gold mining, requiring increased international cooperation, stronger domestic laws, and better enforcement against the criminal networks involved. Key strategies include strengthening anti-money laundering laws to target illicit gold profits, implementing traceability measures for supply chains, and providing technical and financial support to formalize artisanal and ASGM where possible.

The study conducted by Díaz-Somoano et al. [154] focused on the role of wet flue gas desulphurization (WFGD) systems (scrubbers) in coal-fired power plants. This study showed that these scrubbers, under certain operating conditions (specifically addressing oxidized mercury in the slurry solution), can achieve mercury removal efficiencies of up to 75% or higher, depending on the specific parameters considered. The significant financial investment in air scrubbers and related technologies is primarily designed to remove hazardous pollutants, specifically sul-

phur dioxide and nitrogen oxides, from industrial exhaust before it enters the atmosphere. These technologies are critical for reducing environmental and health issues, including the formation of acid rain, smog, and respiratory illnesses. The lower mercury emissions were an additional benefit. Illegal gold mining poses a severe, multi-faceted threat to several regions in the world, fuelling environmental degradation, causing severe human health problems, particularly to the health of the indigenous people, creating problems for good governance, and driving corruption. Most informal sites lack the funding and training needed to transition towards mercury-free mining. Most governments are taking strict measures to crack down on illegal gold mining, but communities are frustrated with the limited change, as the environmental damage continues, particularly with mercury and cyanide contamination. To reduce mercury pollution, the Colombian government has restricted the use of mercury in mining and is considering implementing a legal ban on illegal mining and encouraging informal miners to enter the formal market [9]. In 2019, the Peruvian government used armed force intervention against illegal mining, which yielded positive results, and mining activity was shifted to permitted areas [155]. Even in South Africa, the policing the illegal mining is very ineffective so far [4]. Recent police actions against illegal mining in La Pampa, Peru, in 2019, where authorities evicted miners and destroyed equipment. This ongoing struggle highlights the persistence of illegal mining in the region, driven by high gold prices and the involvement of organized crime, which often results in continued activity

even after police operations, as miners move to new locations [155]. Canada mitigates mercury from gold mining through strict, multi-level regulation and monitoring, setting a global precedent for balancing economic growth with environmental protection. By enforcing stringent rules on industrial, small, and medium-sized enterprises, such as in the Yukon, Canada has largely adopted mercury-free, formalized operations, providing a model for international cooperation [156]. Recent mercury pollution control measures in China, driven by stricter emission standards and industrial upgrades, have significantly reduced anthropogenic mercury releases into the air and water, leading to a 38%–50% decrease in air emissions from 2013 to 2022. Even riverine Hg export has dropped by roughly 46% since 2016, with water pollution controls accounting for ~95% of this reduction [157]. Effective mitigation processes include creating alternative livelihoods and using technology not just for enforcement, but also to help legitimate small-scale miners prove their gold is sourced responsibly.

17. Conclusions and Future

This study provides a comprehensive understanding of how illegal gold mining and other industrial activities, such as coal-fired power plants, nonferrous metal industries, the cement industry, and fluorescent lamp recycling, contribute to increased mercury pollution in the environment. Especially, the negative effects of illegal gold mining, particularly in the African and South American continents, result in widespread mercury contamination of different environmental compartments (atmosphere, hydrosphere, and pedosphere). Mercury pollution is a complex global issue with significant human health and environmental impacts. When emitted into the air, it can travel thousands of miles and cross continents before being deposited, making it an international issue. In particular, the process of gold extraction during illegal mining releases significant concentrations of mercury into the environment. The mercury component released into water bodies is converted into the more toxic MeHg form. This neurotoxic compound then builds up in the food chain through a process called biomagnification, leading to the accumulation of huge quantities of this toxin in fish, especially large predatory fish at the top of the food chain, which ultimately increases the risk of human mercury exposure, particularly through the consumption of contaminated food. The consumption of contaminated fish poses severe health risks to local communities, especially pregnant women and children. The Minamata Convention on mercury is the most recent global agreement on environment and health which advocates reduction or total elimination of the use of mercury and have control on the mercury air emissions from coal-fired power plants, coal-fired industrial boilers, certain non-ferrous metals production operations, waste incineration, and cement production, and phase-out mercury use in certain products such as batteries, lights, switches, pesticides, and cosmetics. There is also a need for understanding contamination mechanisms and reducing their impacts. It is the responsibility of individual governments

across the globe, including regulatory reinforcement, a tax on pollution, and nudging through education. There is a need for stringent regulations to mitigate the health risks associated with illegal gold mining, which is resulting in large-scale mercury contamination in soils, air, and waterbodies. Preventing and mitigating mercury contamination in water and protecting public health requires a multifaceted approach by adopting improved water treatment technologies. This requires a coordinated effort from industry, government, and the public. It is important for individuals concerned that they avoid eating predatory fish with high amounts of mercury in them and should choose smaller, low-mercury fish. It is also important to educate people and support sustainable practices that prioritise the health and well-being.

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Data Availability Statement

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Conflicts of Interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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