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JOURNAL OF HEAVY METAL RESEARCH

E-ISSN: 3116-0522

Journal of Heavy Metal Research, 2026, vol. 1, Issue 3, 18-33



Review Article

A Review of the Ecological Effects of Mercury Pollution in Aquatic and Terrestrial Ecosystems

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Abstract

Mercury (Hg) is a toxic and persistent environmental pollutant released into ecosystems through both natural processes and human activities. Its environmental persistence, potential transformation into methylmercury (MeHg), and capacity for bioaccumulation and biomagnification pose substantial risks to aquatic and terrestrial ecosystems. Although the Minamata Convention on Mercury provides an international framework for reducing mercury emissions and releases, climate change, permafrost thaw, and land-use changes may alter mercury mobilization, transport, and transformation, potentially complicating ecosystem recovery. Vegetation also plays an important role in the global mercury cycle by facilitating the transfer of atmospheric mercury to terrestrial surfaces, although the magnitude of this contribution varies among ecosystems and environmental conditions. This review examines the major sources and biogeochemical cycling of mercury, its toxicity mechanisms, its effects on aquatic and terrestrial organisms, the consequences of bioaccumulation and biomagnification, and approaches to monitoring and managing mercury pollution. Important knowledge gaps remain regarding mercury uptake and cycling in plants, the interactive effects of climate change on mercury methylation and methylmercury accumulation, and the incorporation of socioeconomic scenarios into environmental risk assessment models. Addressing these gaps through international cooperation, capacity building, improved monitoring, and the development of cost-effective remediation technologies could strengthen mercury risk management and support long-term ecosystem recovery.

Keywords: Ecological effects, Climate change, Mercury, Methylmercury

Receive Date: 27 July 2026

Revise Date: 08 August 2026

Accept Date: 31 August 2026

Publish Date: 22 August 2026

Publisher: Hakim Sabzevari University

Citation: Gholinezhad, E & Salavati S. (2026). *A Review of the Ecological Effects of Mercury Pollution in Aquatic and Terrestrial Ecosystems*. *Journal of Heavy Metal Research*, 1(3), 18–33.

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1. Introduction

Environmental pollution is a major obstacle to sustainable agriculture. Soil and water can become contaminated with heavy metals, pesticides, and excess fertilizers, damaging soil health, reducing biodiversity essential for pest control and pollination, and creating food safety risks. Pollution also exacerbates

climate change, as extreme weather events devastate agricultural yields and water resources (Okereafor et al., 2020). Heavy metals, which have densities greater than water, significantly impact sustainable agriculture. They enter the environment through corrosion, atmospheric deposition, erosion, groundwater leaching, sediment resuspension, and water evap-

oration (MathuMitha et al., 2021). Heavy metal pollution has become a growing environmental and agricultural concern due to the persistence, toxicity, and bioaccumulative nature of metals such as cadmium (Cd), lead (Pb), mercury (Hg), and arsenic (As). These contaminants primarily enter through industrial effluents, mining, and agricultural chemicals, negatively affecting soil health, crop productivity, and food safety, ultimately posing serious risks to ecosystems and human health (Mohamed et al., 2025).

Mercury is among the top ten chemicals of major global environmental concern. This heavy metal has become a global pollutant due to its non-degradable nature, high persistence, and ability to travel long distances through the atmosphere (Ran et al., 2026). Mercury emission sources include natural sources (volcanoes, soil erosion, and ocean evaporation) and anthropogenic sources (fossil fuel combustion, gold mining, cement production, and industrial waste) (Uddin et al., 2024). It is estimated that annually over 6,000 to 8,000 megagrams of mercury enter the atmosphere through anthropogenic activities, biomass burning, and geological degassing (Zhou et al., 2021). The primary concern regarding mercury is its conversion to methylmercury (MeHg) by microorganisms in aquatic sediments (Fan et al., 2026). Due to its lipophilicity and ability to cross the blood-brain barrier, methylmercury is one of the most potent known neurotoxins, affecting not only human health but also the structure and function of entire ecosystems (Kumar et al., 2026). Mercury causes ecological risks, neurological disorders, genetic hazards and gene regulation, damage to pregnancy and reproductive systems, increased cancer risk, cardiovascular risks, pulmonary diseases, and kidney disease (Wu et al., 2024).

2. Review Methodology and Transparency

Given the broad scope and interdisciplinary nature of mercury pollution research, this review was conducted using a systematic and transparent literature search strategy to ensure comprehensive coverage and minimize selection bias.

2.1. Search Strategy and Databases

We performed systematic literature searches in three major scientific databases: Web of Science Core Collection, Scopus, and PubMed. These databases

were selected for their comprehensive coverage of environmental science, ecology, toxicology, and public health literature. Additional relevant publications were identified through manual screening of reference lists of included articles and key review papers.

2.2. Search Terms and Time Frame

The following search string was employed across all databases: ("mercury" OR "Hg" OR "methylmercury" OR "MeHg") AND ("ecological effect*" OR "ecotoxicolog*" OR "biomagnification"

OR "bioaccumulation" OR "food web" OR "trophic transfer") AND ("aquatic ecosystem*" OR "terrestrial ecosystem*" OR "marine" OR "freshwater" OR "soil" OR "sediment" OR "plant*" OR "forest").

The search was limited to peer-reviewed articles, reviews, and book chapters published between January 2000 and July 2026, with particular emphasis on literature from the last decade (2015–2026) to capture recent advances. However, seminal older publications (pre-2000) were included when they provided foundational knowledge essential for understanding key concepts.

2.3. Inclusion and Exclusion Criteria

Studies were included if they met the following criteria:

- Inclusion Criteria:

- Original research articles, systematic reviews, meta-analyses, or authoritative book chapters addressing mercury dynamics in aquatic or terrestrial ecosystems

- Studies reporting empirical data on mercury concentrations, methylation rates, or ecological effects

- Investigations of biomagnification, toxicity mechanisms, or remediation strategies

- Articles with clearly described methodologies and quantitative data

- Publications in English or with English translations available

- Exclusion Criteria:

- Studies focused exclusively on occupational or clinical human health exposure (without ecosystem context)

- Laboratory studies using unrealistic exposure concentrations (exceeding environmentally relevant levels by >100×)

- Conference abstracts, opinion pieces, or non-peer-reviewed reports
- Studies addressing other heavy metals without specific focus on mercury
- Articles where full text was unavailable after reasonable effort

2.4. Evidence Synthesis Approach

Following the identification of relevant studies ($n = 186$ initially screened; $n = 142$ included after full-text review), we employed a thematic synthesis approach to organize findings. This involved:

1. Coding of studies according to ecosystem type (aquatic vs. terrestrial), mercury species investigated, and ecological endpoints measured
2. Critical appraisal of study quality based on methodological rigor, sample size, and analytical techniques
3. Comparison and contrast of findings across studies to identify consistencies, contradictions, and knowledge gaps
4. Integration of quantitative estimates through narrative synthesis, noting ranges and sources of uncertainty

This methodology ensures that our review represents a balanced, critical synthesis of the available evidence rather than a merely descriptive compilation of findings.

3. Sources and Biogeochemical Cycle of Mercury

3.1. Sources of Mercury Emissions

It should be noted that the environmental behavior, toxicity, and cycling pathways of mercury are highly dependent on its chemical species; elemental mercury (Hg^0) is primarily transported over long distances through the atmosphere, inorganic mercury (Hg^{2+}) is soluble in water and soil, and methylmercury (MeHg), as the most toxic form, has the capacity for bioaccumulation and biomagnification in food webs. Accordingly, each of these species will be identified by its respective chemical symbol throughout the remainder of this article. Mercury ex-

ists in the environment in three main forms: elemental mercury (Hg^0), inorganic mercury (Hg^{2+}), and organic mercury (mainly methylmercury) (Li et al., 2024). The dominant form of mercury in the atmosphere is elemental, and due to its long half-life (approximately one year), it can be transported across continents (Guney et al., 2021).

Anthropogenic activities contribute substantially to mercury emissions (Kumar et al., 2026); artisanal and small-scale gold mining (ASGM) alone accounts for more than half of the global mercury flux to watercourses (Yoshimura et al., 2021).

3.2. Biogeochemical Cycle

The mercury cycle has three main gateways for entry into terrestrial ecosystems: atmospheric deposition, food chain uptake, and export via surface runoff (Bishop et al., 2020). Research over the past decade has demonstrated that the bidirectional exchange of mercury between the atmosphere and terrestrial surfaces is far more complex than previously thought, and the interpretation of mercury isotopes has greatly contributed to understanding this process (Sommar et al., 2025). One of the most significant recent findings is that freshly deposited mercury has a greater potential for methylation and rice uptake compared to legacy mercury accumulated in soil (Li et al., 2026).

In aquatic ecosystems, microorganisms (particularly sulfate-reducing bacteria) play a key role in converting inorganic mercury to methylmercury (Li et al., 2024). The sulfur cycle in estuarine sediments substantially influences this process, and various sulfur and mercury species have been identified in sediments from 70 estuaries worldwide (Wang et al., 2022). Furthermore, recent studies have shown that mercury methylation is not limited to bottom sediments but also occurs in the water column of marine and freshwater ecosystems (Gallorini & Loizeau, 2021). Figure 1 presents a schematic overview of the sources, transport pathways, and biogeochemical cycling of inorganic mercury and methylmercury in the environment.

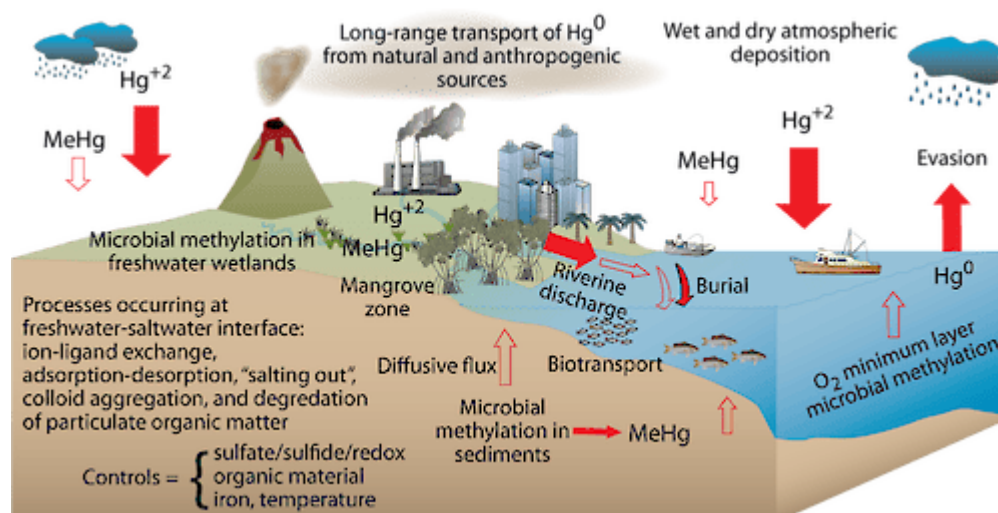


Fig. 1. Sources, Transport, and Cycling of Inorganic Mercury and Methylmercury in the Environment

4. Ecological Effects of Mercury in Aquatic Ecosystems

4.1. Marine Ecosystems

Marine ecosystems are severely affected by mercury pollution due to their extensive surface area and connection to the atmosphere through gas exchange (Osterwalder et al., 2021). Elevated atmospheric total mercury levels impact ocean surface waters, and this contamination is in turn influenced by surrounding emission sources such as industrial and oil-related activities (Al-Sulaiti et al., 2022). Methylmercury (MeHg) accumulates in fish and shellfish and reaches high concentrations in predatory species at the top of the aquatic food chain. This constitutes the primary route of human exposure to mercury, with over 90% of methylmercury exposure in the United States attributed to fish consumption (Ray et al., 2025). Apex predatory fish, such as sharks and tuna, exhibit the highest methylmercury (MeHg) concentrations (Al-Sulaiti et al., 2022; Le Croizier et al., 2022).

In polar regions, shorter but more lipid-dependent food chains result in very high methylmercury concentrations (up to several micrograms per gram wet

weight) in key species such as polar bears (*Ursus maritimus*) and ringed seals (*Pusa hispida*). This not only threatens the health of these species themselves but also exposes indigenous Arctic communities who rely on these animals for food to serious neurological and developmental risks. Given the rapid melting of polar ice and the release of trapped mercury, biomonitoring in these regions must be prioritized globally. Mercury biomagnification in marine food webs is so pronounced that fish consumption by humans remains a serious health concern (Wu & Zhang, 2023), and research has shown that despite measures to reduce mercury emissions, the biomagnification potential of mercury in food webs is far greater than that of elements such as arsenic and selenium (Pelletier et al., 2025).

4.2. Critical Synthesis: Comparing Aquatic Ecosystems

A critical comparison of mercury dynamics across different aquatic systems reveals important differences in contamination sources and ecological responses:

Table 1. Comparison of mercury dynamics across aquatic ecosystem types

Ecosystem Type	Primary Hg Inputs	Methylation Hotspots	Key Biomonitoring	Observed Concentration Range
Marine Open Ocean	Atmospheric deposition, ocean currents	Water column, surface sediments	Tuna, sharks, seabirds	MeHg: 0.1-3.0 µg/g ww in apex predators
Coastal/Estuarine	Riverine inputs, industrial effluents	Wetland sediments, mangrove zones	Shellfish, benthic fish	Total Hg in sediments: 50-500 ng/g dw

Ecosystem Type	Primary Hg Inputs	Methylation Hotspots	Key Biomonitoring	Observed Concentration Range
Freshwater Lakes	Atmospheric deposition, watershed runoff	Anoxic sediments, hypolimnion	Zooplankton, small fish, piscivores	MeHg: Up to 5 µg/g ww in top predators
Polar Ecosystems	Long-range transport, ice melt	Periglacial environments, thaw lakes	Polar bears, ringed seals, seabirds	MeHg: 1-8 µg/g ww in high trophic levels

4.3. Regulatory Thresholds and Ecological Significance

The World Health Organization (WHO) has set the tolerable weekly intake of methylmercury at 1.6 micrograms per kilogram of body weight. Additionally, the United States Environmental Protection Agency (US EPA) has established maximum allowable methylmercury concentrations in edible fish at 0.3 mg/kg wet weight (and 1.0 mg/kg for larger predatory fish such as shark and tuna). In aquatic ecosystems, total mercury concentrations in sediments above 100 ng/g dry weight typically indicate anthropogenic contamination, under which conditions the risk of methylation and subsequent food chain entry increases dramatically. Inclusion of these thresholds in monitoring studies enables comparison of data with global standards.

4.4. Wetland and Estuarine Ecosystems

Coastal wetlands, due to their intermediate position between land and sea, are considered hotspots for mercury methylation (Chen et al., 2025). A systematic review of global studies has shown that publications on heavy metal pollution in coastal wetlands have grown rapidly over the past decade (Li et al., 2022). Research on mercury in wetlands over the past 60 years indicates that research foci in this field have shifted over time, with recent emphasis on the interaction between climate change and mercury methylation (Zhang et al., 2023).

4.5. Freshwater Ecosystems

Lakes, rivers, and reservoirs are among the most sensitive ecosystems to mercury pollution (Liu et al., 2025). Case studies in various regions worldwide, including the Boroo River in Mongolia, have shown that mining activities can increase mercury concentrations in sediments to as high as 2,200 nanograms per gram dry weight (Udodenko et al., 2022). Freshwater invertebrates serve as valuable biomonitoring for methylmercury, and aquatic insects, due to their

position in the food web and high methylmercury accumulation, play a key role in transferring this toxin to higher trophic levels (Malcata Martins et al., 2021).

5. Ecological Effects of Mercury in Terrestrial Ecosystems

5.1. Soil and Plants

Pollution in terrestrial ecosystems is of particular importance due to their role in food production and human habitation. Mercury enters soil through wet and dry atmospheric deposition and can be stored in various soil compartments or re-emitted back to the atmosphere (Gworek et al., 2020). One of the most important findings in recent years is the pivotal role of vegetation in the global mercury cycle. Plants are the primary source of mercury input to terrestrial ecosystems through the uptake of gaseous elemental mercury from the atmosphere and its transfer to soil, accounting for 60 to 90 percent of mercury deposition on land. This process reduces the atmospheric mercury reservoir by approximately 660 megagrams and prevents the deposition of an additional 960 megagrams of mercury into oceans.

Critical Evaluation of the 60-90% Range: It is important to note that the wide range (60-90%) reported for vegetation's contribution to mercury deposition reflects substantial uncertainty arising from several methodological factors:

1. **Measurement Techniques:** Different studies employ varying methodologies, including flux tower measurements, isotopic tracing, and modeling approaches, each with distinct uncertainties ($\pm 15\text{-}30\%$).
2. **Ecosystem Type Variation:** Forests (particularly tropical rainforests) show higher contributions (80-90%) compared to grasslands (60-70%) due to greater leaf area index and longer growing seasons.
3. **Temporal Variability:** Seasonal changes in plant phenology significantly affect uptake rates, with estimates varying by up to 40% between growing and dormant seasons.

4. Analytical Challenges: Partitioning between stomatal uptake and cuticular adsorption remains difficult, introducing additional uncertainty.

Lichens and mosses exhibit higher mercury concentrations than vascular plants, and while mercury in aboveground biomass is primarily absorbed from the atmosphere, root mercury is derived from a combination of soil and atmospheric uptake (Zhou et al., 2021).

5.2. Forest Ecosystems

Forests act as important mercury reservoirs, with most deposited mercury accumulating in forest soils (Yang et al., 2026). The unique characteristics of forest-derived streams, such as high litterfall, organic matter decomposition, and moisture, can enhance microbial mercury methylation (Ma et al., 2025). Extensive studies in Chinese forests have shown that mercury budgets in these ecosystems are influenced by factors such as tree species composition, precipitation, and pollution history (Zhan et al., 2025).

Critical Comparison of Forest Studies: Notably, studies from different regions have produced contrasting findings regarding mercury retention versus export. For example:

- Chinese subtropical forests show net mercury accumulation (Zhan et al., 2025)
- Boreal forests in Scandinavia exhibit significant mercury export via streams, particularly during spring snowmelt (Bishop et al., 2020)
- North American temperate forests demonstrate intermediate behavior dependent on soil organic matter content

These differences likely arise from variations in climate (temperature, precipitation), soil chemistry (pH, organic carbon content), and atmospheric deposition history, rather than reflecting contradictory phenomena.

5.3. Effects on Soil Microorganisms

Mercury exerts significant negative effects on the diversity and structure of soil microbial communities (Yu et al., 2025). Short-term incubation studies have shown that mercury contamination alters bacterial population composition and reduces soil enzyme activities. These changes can have cascading effects on nutrient cycling and soil fertility (Zheng et al., 2019).

5.4. Detoxification Mechanisms in the Soil-Plant System

Heavy metals such as cadmium, lead, mercury, and arsenic disrupt cellular homeostasis, inhibit photosynthesis, induce oxidative stress, and interfere with nutrient uptake, leading to significant reductions in plant productivity (Mohamed et al., 2025). In response to these stressors, plants employ complex molecular mechanisms including activation of antioxidant enzymes, upregulation of metal transporters, production of metal-chelating molecules, and modulation of stress-responsive genes and transcription factors. Conversely, bioremediation, which harnesses the detoxification capabilities of plants, microbes, and their symbiotic interactions, offers a sustainable and environmentally friendly alternative (Mohamed et al., 2025). Recent research has focused on the role of selenium in mitigating mercury toxicity in the soil-plant system (Li et al., 2025). Selenium reduces mercury uptake and toxicity by forming insoluble compounds with mercury and inducing antioxidant defense mechanisms in plants (Yang et al., 2024).

6. Biomagnification and Its Implications in Food Webs

Biomagnification is the most important ecological characteristic of mercury, distinguishing it from many other pollutants (Wang et al., 2025). Methylmercury concentrations increase exponentially as they pass through successive trophic levels. This phenomenon is particularly pronounced in aquatic food webs, which have longer food chains (Eduardo et al., 2026).

Kumar et al. (2023) systematically investigated the relationships between mercury concentration, chemical species, exposure levels, bioavailability, environmental distribution, and ecotoxicological risks. The molecular mechanisms of mercury toxicity include oxidative stress, protein modifications, genomic alterations, and disruption of enzyme activity (Wu et al., 2024).

Figure 2 illustrates the biomagnification of mercury in aquatic food webs and the progressive increase in methylmercury (MeHg) concentrations across successive trophic levels. The diagram illustrates how methylmercury, primarily produced by microbial methylation in sediments, enters the base of the

aquatic food web through phytoplankton and zooplankton uptake. As MeHg moves up the food chain from small forage fish to larger predatory fish (e.g., salmon, tuna, swordfish, and sharks), its concentration increases progressively through dietary accumulation and slow elimination rates. Apex predators and marine mammals at the top of the food web exhibit the highest MeHg concentrations—often millions of times greater than ambient water levels. The

figure emphasizes that biomagnification is the primary driver of elevated mercury exposure in humans who consume predatory fish, highlighting the critical public health implications of mercury pollution in aquatic ecosystems (based on concepts from Al-Sulaiti et al., 2022; Le Croizier et al., 2022; Pelletier et al., 2025; and Wu & Zhang, 2023).

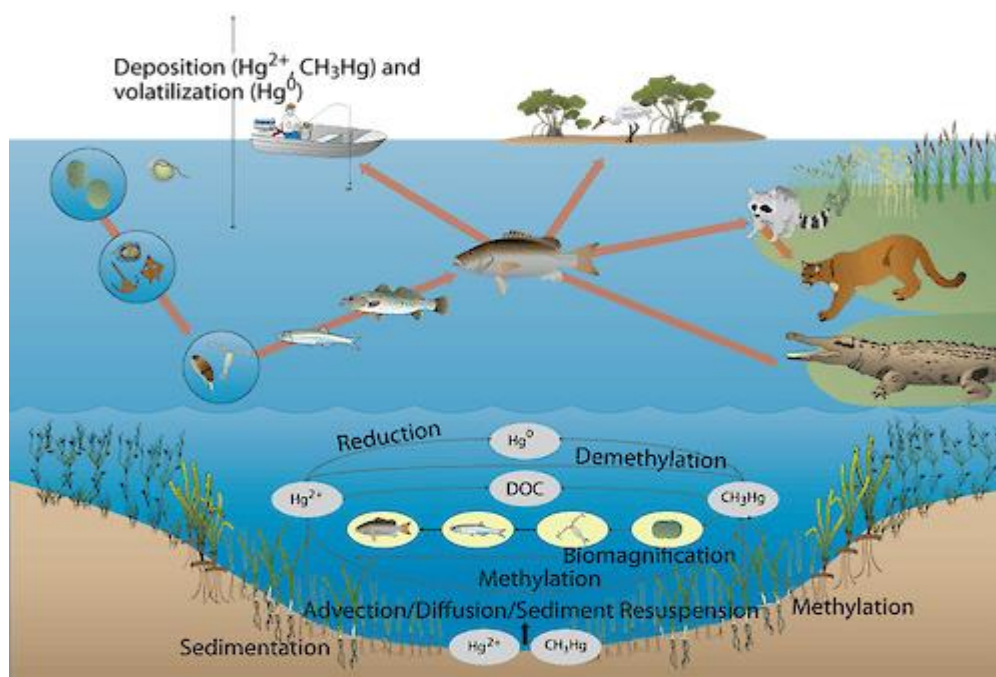


Fig. 2. Biomagnification of mercury (Hg) in aquatic food chains and the exponential increase in methylmercury (MeHg) concentrations across successive trophic levels. The diagram illustrates how methylmercury, primarily produced by microbial methylation in sediments, enters the base of the aquatic food web through phytoplankton and zooplankton uptake. As MeHg moves up the food chain from small forage fish to larger predatory fish (e.g., salmon, tuna, swordfish, and sharks), its concentration increases progressively through dietary accumulation and slow elimination rates. Apex predators and marine mammals at the top of the food web exhibit the highest MeHg concentrations—often millions of times greater than ambient water levels. The figure emphasizes that biomagnification is the primary driver of elevated mercury exposure in humans who consume predatory fish, highlighting the critical public health implications of mercury pollution in aquatic ecosystems. (Based on concepts from Al-Sulaiti et al., 2022; Le Croizier et al., 2022; Pelletier et al., 2025; and Wu & Zhang, 2023)

6.1. Trophic Transfer to Human Populations

The most important route of human exposure to methylmercury (MeHg) is consuming contaminated fish and seafood, the final step in the ecological trophic transfer pathway. Methylmercury readily crosses the blood-brain barrier and, by inducing oxidative stress and disrupting neurotransmitter function, causes neurobehavioral disorders, reduced IQ in children, and increased risk of cardiovascular diseases in adults (Wu et al., 2024). In contrast, elemental mercury (Hg^0) enters the body primarily

through inhalation and has neurotoxic and nephrotoxic effects, but its shorter half-life in the body gives it a different risk profile. Pregnant and lactating women, children under six years of age, and communities residing in coastal and fishing areas are among the most vulnerable population groups.

Epidemiological Evidence: A recent systematic review and meta-analysis of 27 cohort studies across 14 countries reported that fish consumption patterns vary significantly by geographic region, with the highest methylmercury exposure observed in coastal

communities of Japan, the Faroe Islands, and the Seychelles (Grandjean & Herz, 2019). The World Health Organization estimates that approximately 100,000 premature deaths annually are attributable to heart disease associated with methylmercury exposure, with the highest burden in Southeast Asia and Sub-Saharan Africa (WHO, 2022). However, these estimates have substantial uncertainty ($\pm 30\%$) given the challenges in establishing causal relationships and controlling for confounding factors in observational studies. Therefore, developing fish consumption guidelines based on local mercury concentrations and replacing high-risk protein sources with safer alternatives in public nutrition programs is an undeniable necessity.

7. Impact of Climate Change on the Mercury Cycle

Climate change is one of the most important modulators of the mercury cycle in the 21st century (Yuan et al., 2024). Permafrost thaw in Polar Regions releases vast quantities of mercury that have been trapped in ice for millennia (Youssef et al., 2026). The Arctic region has been identified as a hotspot for mercury cycling, and the high mercury flux in watercourses and the massive reserves subject to release due to rapid high-latitude warming have raised serious concerns (Gambardella et al., 2025). Climate change affects the mercury cycle through multiple mechanisms, including altered precipitation and runoff patterns, increased forest fires that release mercury accumulated in biomass, changes in vegetation cover and biogeographic zones, ocean stratification that affects marine mercury cycling, and changes in microbial activity that influence methylation (Chételat et al., 2022).

8. The Minamata Convention and the Outlook for Ecosystem Recovery

The Minamata Convention on Mercury, which entered into force in 2017, is a legally binding international treaty aimed at reducing anthropogenic mercury emissions. Implementation of this convention is projected to reduce mercury emissions in the foreseeable future; however, ecosystem recovery and health benefits will be accompanied by considerable delays (Wu et al., 2022). The study by Wu and colleagues (2022) addressed seven key scientific ques-

tions regarding ecosystem recovery under the influence of the Minamata Convention and climate change, including historical mercury changes in ecosystems, major influencing factors and processes, and future assessments. This study recommended the use of stable mercury isotope tools and process-based integrated global models, combined with future socioeconomic scenarios, for comprehensive assessment. Emerging evidence indicates that reducing mercury inputs to ecosystems may facilitate faster recovery than previously anticipated (Blanchfield et al., 2022). Nevertheless, despite the vast legacy mercury reservoirs from past contamination, freshly deposited mercury has a greater potential for methylation than accumulated soil mercury, further complicating resource management (Liang et al., 2024).

Despite the positive achievements of the Minamata Convention, the treaty faces fundamental challenges: (1) incomplete coverage of natural emission sources and secondary sources such as forest fires, (2) weak monitoring and enforcement mechanisms in developing countries due to insufficient financial and technical resources, (3) neglect of the cumulative effects of mercury with other heavy metals and organic pollutants, and (4) misalignment of the convention's review cycles with the pace of climate change, which itself affects the mercury cycle. For instance, many African and Southeast Asian countries, which have the largest share in artisanal and small-scale gold mining (ASGM), have not yet been able to fully implement their national action plans (UNEP, 2023). Therefore, the success of this convention depends on strengthening international cooperation, transferring clean technologies, and simultaneously considering adaptive strategies to climate change.

9. Monitoring, Mitigation, and Remediation Strategies

9.1. Biomonitoring

The use of living organisms as biomonitors—or more precisely, "biological monitors"—is one of the most effective methods for monitoring mercury pollution (Evers et al., 2024). Seabirds provide valuable information on mercury transfer through food webs and associated risks to humans (Mills et al., 2025). Freshwater invertebrates have also been introduced

as sensitive indicators of methylmercury in freshwater ecosystems (Sinclair et al., 2025). Phytoremediation methods and biochar application have received special attention in recent years as sustainable remediation approaches.

9.2. Remediation Strategies

Phytoremediation methods and the use of microorganisms for remediating mercury-contaminated soils have attracted attention due to their low cost, simple operation, and applicability in-situ (Penalba-Iglesias et al., 2026). Given that engineering-based technological methods are costly, recent research has focused on identifying suitable plant species and associated microorganisms for bioremediation (Lang et al., 2025). Advanced pollution mitigation strategies include algal phytoremediation, biochar application, catalytic oxidation, and mercury stabilization. However, numerous challenges remain, including the identification of appropriate biomarkers and understanding the nature of mercury exposure (Kumar et al., 2023).

To select the appropriate remediation method, it is necessary to compare the advantages and limitations of each approach. Table 2 provides a comprehensive systematic comparison of common mercury remediation methods based on mechanism, target species, application scale, efficiency, cost, and risks of secondary mobilization.

Key considerations for method selection:

- Contamination severity: High concentrations (>100 mg/kg) may require thermal desorption or chemical stabilization; low-moderate levels (<50 mg/kg) are suitable for phytoremediation or biochar.
- Site characteristics: In-situ methods (phytoremediation, bioremediation) are preferred for large areas (>10 ha); ex-situ methods are suitable for point-source contamination.
- Time constraints: Rapid cleanup requires chemical or thermal methods; phytoremediation requires 3-10 years.

- Cost-effectiveness: Biochar and phytoremediation offer the best cost-benefit ratios for agricultural soils.
- Secondary effects: Consideration of Hg^0 re-emission to atmosphere is critical for all methods; bioremediation and thermal desorption pose the highest risks of secondary mobilization.

The selection of an appropriate method should be based on contaminant concentration, site area, soil or sediment type, and available budget. In many cases, combining two or more methods (e.g., bioremediation combined with biochar) has yielded better results (Kumar et al., 2023).

10. Research Priorities and Knowledge Gaps

Despite significant advances in understanding the mercury cycle and its diverse effects, numerous uncertainties remain in this field, including:

1. Understanding uptake mechanisms in plants and mercury cycle modeling: Although the role of plants in the mercury cycle has been clarified, the physiological and environmental controls on mercury uptake and translocation in plants still require further research at the molecular level (Sun et al., 2025).
2. Mercury cycle modeling: Improved model parameterization and harmonization of observational data are essential for more accurate assessment of the impact of plants on the global mercury cycle (Sun et al., 2025).
3. Interactions between climate change and pollution: Better understanding of how permafrost thaw, land-use changes, and aquatic ecosystem changes affect the mercury cycle is a future research priority (Chételat et al., 2022).
4. Integrated risk assessment: Development of integrated models that simultaneously consider socioeconomic scenarios, mercury emission reduction pathways, and climate change is essential for effective evaluation of the Minamata Convention (Dastoor et al., 2025).

Table 2. Comprehensive comparison of common mercury remediation methods

Remediation Method	Mechanism	Target Hg Species	Application Scale	Efficiency Range	Estimated Cost (USD/ha)	Primary Limitations	Secondary Mobilization Risk
Phytoremediation	Plant uptake, translocation, and volatilization	Hg ⁰ , Hg ²⁺ , MeHg (limited)	Field-scale (agricultural soils)	20-60% reduction in soil Hg	5,000-15,000	Time-consuming (3-10 years); disposal of contaminated biomass required; limited efficiency at high concentrations (>50 mg/kg)	Low-moderate (Hg ⁰ release through transpiration; requires monitoring)
Microbial Bioremediation	Microbial reduction of Hg ²⁺ to Hg ⁰ ; enzymatic demethylation of MeHg	MeHg, Hg ²⁺	Field-scale (wetlands, sediments)	40-80% MeHg reduction; 20-50% total Hg reduction	8,000-25,000	Temperature and pH sensitive; risk of secondary air pollution; requires optimal microbial conditions	Moderate-High (Hg ⁰ release to atmosphere; requires containment)
Biochar Application	Adsorption, complexation, and immobilization	Hg ²⁺ primarily and MeHg (limited)	Field and lab scales	50-90% Hg immobilization	3,000-10,000	Depends on feedstock type; requires surface activation; effectiveness decreases with high organic matter	Low (stable binding, minimal remobilization)
Chemical Stabilization	Formation of insoluble Hg complexes (e.g., HgS); precipitation	Hg ²⁺ , Hg ⁰	Field-scale (industrial sites)	70-95% stabilization	20,000-60,000	High cost; alters soil physicochemical properties; may affect soil fertility	Low (if properly applied; binds Hg tightly)
Catalytic Oxidation	Oxidation of Hg ⁰ to Hg ²⁺ ; decomposition of organic Hg	Hg ⁰ , organic Hg	Lab/industrial (wastewater, flue gas)	90-99% removal	50,000-150,000 (capital intensive)	Requires advanced equipment; high energy consumption; primarily ex-situ	Moderate (requires post-treatment of Hg-containing waste)
Thermal Desorption	Heating to volatilize Hg; gas-phase capture	Hg ⁰ , Hg ²⁺ , organic Hg	Ex-situ (industrial scale)	85-99% removal	100,000-300,000	Very high cost; energy intensive; destroys soil structure; ex-situ only	High (requires strict gas capture to prevent air pollution)
Nanoremediation (FeS, Fe ⁰ nanoparticles)	Adsorption and reduction to Hg ⁰	Hg ²⁺ , MeHg	Lab/pilot scale	60-95% removal	30,000-80,000	Emerging technology; limited field validation; nanoparticle transport and fate uncertain	Low-moderate (depends on nanoparticle stability)

11. Conclusion

Mercury pollution is not merely an environmental challenge but a complex socioeconomic problem with consequences spanning from local to global scales. Effective response to this threat cannot be limited to emission reduction alone; simultaneous adaptation to climate change, redesign of food supply chains, and empowerment of local communities in mining regions are essential.

The findings of this review indicate that mercury enters ecosystems through multiple pathways (atmospheric, aquatic, and terrestrial), but the most hazardous stage of its cycle is the conversion of inorganic species (Hg^{2+}) to methylmercury (MeHg) by microorganisms. The toxic effects of mercury are observable across all levels of biological organization---from soil microorganisms to higher vertebrates---and biomagnification of the MeHg species in food webs, particularly in aquatic ecosystems, has irreversible consequences. Climate change, through permafrost thaw, altered hydrological patterns, and increased wildfires, significantly modifies the mercury cycle and delays ecosystem recovery.

Although the Minamata Convention represents a positive step in reducing mercury emissions, the gap between emission reduction and actual ecosystem recovery is substantial and requires complementary policy measures. Development of efficient biomonitoring methods and sustainable remediation approaches, along with further research on molecular mechanisms of toxicity and uptake, is essential for effective mercury pollution management.

Based on the findings of this review, an integrated conceptual model for mercury pollution management can be outlined as follows: (1) identification and prioritization of emission sources at local and national levels, (2) continuous monitoring of different mercury species concentrations in air, water, soil, and biota, (3) prediction of future scenarios considering both climate change and economic growth, (4) design of remediation strategies tailored to local conditions, and (5) periodic evaluation of action effectiveness and policy revision based on emerging evidence. Such a systemic approach is the only way to ensure gradual ecosystem recovery and reduction of mercury health impacts in the coming decades.

Ultimately, a comprehensive understanding of the ecological effects of mercury and the development of effective strategies for mitigation and ecosystem recovery inevitably require an integrated approach that combines knowledge from ecology, environmental chemistry, soil science, and climatology.

Acknowledgements

The authors would like to express their sincere gratitude to the reviewers for their constructive comments, which significantly contributed to improving the scientific quality of this article.

Declarations

Data and code availability

All data generated or analyzed during this study are available from the corresponding author upon reasonable request. No computational code was used in this study.

Conflicts of interest

The authors announced that they have no known conflicts of interest or personal relationships that could have appeared to influence the work reported in this manuscript.

Ethical approval

The authors declare no ethical issues; the research was carried out in full agreement with ethical standards. Also, this paper is neither under Review nor published elsewhere.

References

- Al-Sulaiti, M. M., Soubra, L., & Al-Ghouti, M. A. (2022). The Causes and Effects of Mercury and Methylmercury Contamination in the Marine Environment: A Review. *Current Pollution Reports*, 8(3), 249–272. <https://doi.org/10.1007/s40726-022-00226-7>
- Bishop, K., Shanley, J. B., Riscassi, A., de Wit, H. A., Eklöf, K., Meng, B., Mitchell, C., Osterwalder, S., Schuster, P. F., Webster, J., & Zhu, W. (2020). Recent advances in understanding and measurement of mercury in the environment: Terrestrial Hg cycling. *Science of the Total Environment*, 721, 137647. <https://doi.org/https://doi.org/10.1016/j.scitotenv.2020.137647>

- Blanchfield, P. J., Rudd, J. W. M., Hrenchuk, L. E., Amyot, M., Babiarz, C. L., Beaty, K. G., Bodaly, R. A. D., Branfireun, B. A., Gilmour, C. C., Graydon, J. A., Hall, B. D., Harris, R. C., Heyes, A., Hintelmann, H., Hurley, J. P., Kelly, C. A., Krabbenhoft, D. P., Lindberg, S. E., Mason, R. P., ... Tate, M. T. (2022). Experimental evidence for recovery of mercury-contaminated fish populations. *Nature*, 601(7891), 74–78. <https://doi.org/10.1038/s41586-021-04222-7>
- Chen, X., Zhou, Y., Mai, Z., Cheng, H., & Wang, X. (2025). Mangroves increased the mercury methylation potential in the sediment by producing organic matters and altering microbial methylators community. *Science of the Total Environment*, 962, 178457. <https://doi.org/https://doi.org/10.1016/j.scitotenv.2025.178457>
- Chételat, J., McKinney, M. A., Amyot, M., Dastoor, A., Douglas, T. A., Heimbürger-Boavida, L.-E., Kirk, J., Kahilainen, K. K., Outridge, P. M., Pelletier, N., Skov, H., St. Pierre, K., Vuorenmaa, J., & Wang, F. (2022). Climate change and mercury in the Arctic: Abiotic interactions. *Science of the Total Environment*, 824, 153715. <https://doi.org/https://doi.org/10.1016/j.scitotenv.2022.153715>
- Dastoor, A., Angot, H., Bieser, J., Brocza, F., Edwards, B., Feinberg, A., Feng, X., Geyman, B., Gournia, C., He, Y., Hedgecock, I. M., Ilyin, I., Kirk, J., Lin, C.-J., Lehnher, I., Mason, R., McLagan, D., Muntean, M., Rafaj, P., Zolkos, S. (2025). The Multi-Compartment Hg Modeling and Analysis Project (MCHgMAP): mercury modeling to support international environmental policy. *Geoscientific Model Development*, 18(9), 2747–2860. <https://doi.org/10.5194/gmd-18-2747-2025>
- Eduardo, L. N., Médieu, A., Bertrand, A., Santana, J. L., Lucena-Frédou, F., Point, D., Ferreira, G. V. B., Lorrain, A., Justino, A. K. S., Le Loc'h, F., Munaron, J.-M., Laffont, L., & Mincarone, M. M. (2026). Ocean productivity and trophic structure drive patterns of mercury accumulation in deep-pelagic fauna. *Science of the Total Environment*, 1022, 181583. <https://doi.org/https://doi.org/10.1016/j.scitotenv.2026.181583>
- Evers, D. C., Ackerman, J. T., Åkerblom, S., Bally, D., Basu, N., Bishop, K., Bodin, N., Braaten, H. F. V., Burton, M. E. H., Bustamante, P., Chen, C., Chételat, J., Christian, L., Dietz, R., Drevnick, P., Eagles-Smith, C., Fernandez, L. E., Hammerschlag, N., Harmelin-Vivien, M., ... Wu, P. (2024). Global mercury concentrations in biota: their use as a basis for a global biomonitoring framework. *Ecotoxicology*, 33(4), 325–396. <https://doi.org/10.1007/s10646-024-02747-x>
- Fan, W., Kou, M., Wang, Y., Liu, Y., Zhang, Q., Guo, Y., Yin, Y., Cai, Y., & Jiang, G. (2026). Microbial methylation of particulate-bound mercury in water column and its underlying mechanisms: A critical review. *Water Research*, 289, 124871. <https://doi.org/10.1016/J.WATRES.2025.124871>
- Gallorini, A., & Loizeau, J.-L. (2021). Mercury methylation in oxic aquatic macro-environments: a review. *Journal of Limnology*, 80(2). <https://doi.org/10.4081/jlimnol.2021.2007>
- Gambardella, N., Costa, J., Martins, B. M., Folhas, D., Ribeiro, A. P., Hintelmann, H., Canário, J., & Magalhães, C. (2025). The role of prokaryotic mercury methylators and demethylators in Canadian Arctic thermokarst lakes. *Scientific Reports*, 15(1), 7173. <https://doi.org/10.1038/s41598-025-89438-7>
- Guney, M., Kumisbek, A., Akimzhanova, Z., Kismelyeva, S., Beisova, K., Zhakiyzenova, A., Inglezakis, V., & Karaca, F. (2021). Environmental Partitioning, Spatial Distribution, and Transport of Atmospheric Mercury (Hg) Originating from a Site of Former Chlor-Alkali Plant. *Atmosphere*, 12(2). <https://doi.org/10.3390/atmos12020275>
- Gworek, B., Dmuchowski, W., & Baczewska-Dąbrowska, A. H. (2020). Mercury in the terrestrial environment: a review. *Environmental Sciences Europe*, 32(1), 128. <https://doi.org/10.1186/s12302-020-00401-x>
- Kumar, P., Saravanan, P., Omer, S. N., Rajeshkannan, R., & Venkat kumar, S. (2026). An overview of mercury contamination: Environmental dynamics and mitigation strategies. *Chemosphere*, 405, 144963. <https://doi.org/https://doi.org/10.1016/j.chemosphere.2026.144963>

- Kumar, V., Umesh, M., Shanmugam, M. K., Chakraborty, P., Duhan, L., Gummadi, S. N., Pasrija, R., Jayaraj, I., & Dasarahally Hulgowda, L. K. (2023). A Retrospection on Mercury Contamination, Bioaccumulation, and Toxicity in Diverse Environments: Current Insights and Future Prospects. *Sustainability*, 15(18). <https://doi.org/10.3390/su151813292>
- Lang, T., Hussain, M., Ishfaq, M., Shakoor, N., Tam, N. F.-Y., Li, X., Pan, M., Zhu, Z., Xin, S., & Zhou, H. (2025). Mercury-induced alterations in soil microbiome: A potential for microbiome stewardship to remediate contaminated soils. *Journal of Cleaner Production*, 512, 145717. <https://doi.org/https://doi.org/10.1016/j.jclepro.2025.145717>
- Le Croizier, G., Sonke, J. E., Lorrain, A., Renedo, M., Hoyos-Padilla, M., Santana-Morales, O., Meyer, L., Huveneers, C., Butcher, P., Amezcua-Martinez, F., & Point, D. (2022). Foraging plasticity diversifies mercury exposure sources and bioaccumulation patterns in the world's largest predatory fish. *Journal of Hazardous Materials*, 425, 127956. <https://doi.org/https://doi.org/10.1016/j.jhazmat.2021.127956>
- Li, C., Wang, H., Liao, X., Xiao, R., Liu, K., Bai, J., Li, B., & He, Q. (2022). Heavy metal pollution in coastal wetlands: A systematic review of studies globally over the past three decades. *Journal of Hazardous Materials*, 424, 127312. <https://doi.org/https://doi.org/10.1016/j.jhazmat.2021.127312>
- Li, H., Li, Y., Li, D., Chen, Q., Bai, X., Li, Y.-F., Li, B., Zhao, H., Xu, D., Gao, Y., & Zhao, J. (2026). Mercury Sulfide Nanoparticles Constitute a Long-Term Bioavailable Pool of Mercury in Soil–Rice Systems. *Journal of Agricultural and Food Chemistry*, 74(25), 19607–19616. <https://doi.org/10.1021/acs.jafc.6c07286>
- Li, S., Li, Z., Wu, M., Zhou, Y., Tang, W., & Zhong, H. (2024). Mercury transformations in algae, plants, and animals: The occurrence, mechanisms, and gaps. *Science of the Total Environment*, 911, 168690. <https://doi.org/https://doi.org/10.1016/j.sci-totenv.2023.168690>
- Li, Y., Guan, S., Pei, G., Zhang, X., Zhang, Y., Huang, J., Lv, Y., & Li, H. (2025). Ecological Responses of Mercury to Selenium in Farmland: Insights from Metal Transport in Crops, Soil Properties, Enzyme Activities, and Microbiome. *Agriculture*, 15(16). <https://doi.org/10.3390/agriculture15161753>
- Li, Y., Zhang, H., Guan, Y., Cheng, G., Li, Z., Li, Z., Cao, M., Yin, Y., Hu, L., Shi, J., & Chen, B. (2024). Functional genes and microorganisms controlling in situ methylmercury production and degradation in marine sediments: A case study in the Eastern China Coastal Seas. *Journal of Hazardous Materials*, 476, 134965. <https://doi.org/https://doi.org/10.1016/j.jhazmat.2024.134965>
- Liang, X., Hu, Z.-C., Liu, Y.-R., Gao, C., Zhang, Y., Hao, Y.-Y., Zhang, L., Zhao, J., & Zhu, L. (2024). Precipitation patterns strongly affect vertical migration and methylation of mercury in legacy contaminated sites. *Water Research*, 267, 122511. <https://doi.org/https://doi.org/10.1016/j.watres.2024.122511>
- Liu, S., Liao, L., Liu, J., & Wei, X. (2025). Sediment mercury and methylmercury dynamics during reservoir operation. *Scientific Reports*, 15(1), 18011. <https://doi.org/10.1038/s41598-025-03255-6>
- Ma, W., Huang, J.-H., Lischeid, G., Liu, N., Jia, L., Wu, F., Sun, M., Lei, M., Lin, L., Lu, Z., Yuan, W., Wang, X., & Feng, X. (2025). Climate zone governs mercury fate along forest hydrological pathways. *Journal of Hazardous Materials*, 500, 140542. <https://doi.org/https://doi.org/10.1016/j.jhazmat.2025.140542>
- Mahbub, K. R., Bahar, M. M., Labbate, M., Krishnan, K., Andrews, S., Naidu, R., & Megharaj, M. (2017). Bioremediation of mercury: not properly exploited in contaminated soils! *Applied Microbiology and Biotechnology*, 101(3), 963–976. <https://doi.org/10.1007/s00253-016-8079-2>
- Malcata Martins, B., O'Driscoll, N. J., Mallory, M. L., & Canário, J. (2021). A Review of Freshwater Inver-

- tebrates as Biomonitor of Methylmercury: the Importance of More Complete Physical and Chemical Reporting. *Bulletin of Environmental Contamination and Toxicology*, 107(5), 801–808. <https://doi.org/10.1007/s00128-021-03274-9>
- MathuMitha, C., Mohan Raj, V., Sangeetha, R., Susan, G., & Ragumaran, M. (2021). A Review on the Effect of Heavy Metal Contamination and its Impact on the Environment. *International Journal of Zoological Investigations*, 7(2), 762–771.
- Mills, W. F., Ibañez, A. E., Bustamante, P., Waterman, J., Morales, L. M., Mariano-Jelicich, R., Montalti, D., & Black, S. (2025). Mercury contamination of sympatric seabirds and associated health risks in an Antarctic ecosystem. *Environmental Research*, 281, 121990. <https://doi.org/https://doi.org/10.1016/j.envres.2025.121990>
- Mohamed, H. I., Ullah, I., Toor, M. D., Tanveer, N. A., Din, M. M. U., Basit, A., Sultan, Y., Muhammad, M., & Rehman, M. U. (2025). Heavy metals toxicity in plants: understanding mechanisms and developing coping strategies for remediation: a review. *Biore-sources and Bioprocessing*, 12(1), 95. <https://doi.org/10.1186/s40643-025-00930-4>
- Okerefor, U., Makhatha, M., Mekuto, L., Uche-Okerefor, N., Sebola, T., & Mavumengwana, V. (2020). Toxic Metal Implications on Agricultural Soils, Plants, Animals, Aquatic life and Human Health. *International Journal of Environmental Research and Public Health*, 17(7). <https://doi.org/10.3390/ijerph17072204>
- Osterwalder, S., Nerentorp, M., Zhu, W., Jiskra, M., Nilsson, E., Nilsson, M. B., Rutgersson, A., Soeren-sen, A. L., Sommar, J., Wallin, M. B., Wängberg, I., & Bishop, K. (2021). Critical Observations of Gaseous Elemental Mercury Air-Sea Exchange. *Global Biogeochemical Cycles*, 35(8), e2020GB006742. <https://doi.org/https://doi.org/10.1029/2020GB006742>
- Pelletier, A. R., Villamarin, F., Campos-Silva, J. V., Scabin, A. B., Doig, L. E., & Jardine, T. D. (2025). Trophic magnification rates of eighteen trace elements in freshwater food webs. *Science of the Total Environment*, 958, 178069. <https://doi.org/https://doi.org/10.1016/j.sci-totenv.2024.178069>
- Penalba-Iglesias, D., Robas-Mora, M., González-Reguero, D., Fernández-Pastrana, V. M., Lobo, A. P., & Jiménez-Gómez, P. A. (2026). A novel Bacillaceae bacterium enhances phytoprotection and mercury detoxification in contaminated soils. *Ecotoxicology and Environmental Safety*, 319, 120261. <https://doi.org/https://doi.org/10.1016/j.ecoenv.2026.120261>
- Ran, X., Pang, Q., Wu, Y., & Sun, R. (2026). Environmental geochemical behavior and monitoring techniques of atmospheric mercury: A critical review. *Atmospheric Pollution Research*, 17(7), 102993. <https://doi.org/10.1016/J.APR.2026.102993>
- Ray, S., Vashishth, R., Mukherjee, A. G., Valsala Gopalakrishnan, A., & Sabina, E. P. (2025). Mercury in the environment: Biogeochemical transformation, ecological impacts, human risks, and remediation strategies. *Chemosphere*, 381, 144471. <https://doi.org/https://doi.org/10.1016/j.chemosphere.2025.144471>
- Sommar, J. O., Shi, X., Tang, X., Sun, G., Lin, C.-J., & Feng, X. (2025). Atmospheric mercury: recent advances in theoretical, computational, experimental, observational, and isotopic understanding to decipher its redox transformations in the upper and lower atmosphere and interactions with Earth surface reservoirs. *Atmospheric Chemistry and Physics*, 25(19), 12233–12334. <https://doi.org/10.5194/acp-25-12233-2025>
- Uddin Shihab and Khanom, S. and I. Md. R. (2024). Source and Distribution of Mercury in Environment—A Review. In N. Kumar (Ed.), *Mercury Toxicity Mitigation: Sustainable Nexus Approach* (pp. 3–43). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-48817-7_1
- Udodenko, Y. G., Robinson, C. T., Choihil, J., Badrakh, R., Munkhbat, J., Ivanova, E. S., & Komov, V. T. (2022). Mercury levels in sediment, fish and macroinvertebrates of the Boroo River, northern Mongolia, under the legacy of gold mining. *Ecotoxicology*, 31(2), 312–323. <https://doi.org/10.1007/s10646-021-02502-6>

- UNEP. (2023). Minamata Convention on Mercury: Technical Review of the Effectiveness. <https://www.mercuryconvention.org>
- Wang, D., Lin, X., Wu, G., Xu, Z., Liu, J., Xu, X., Jia, D., Liang, L., Habibullah-Al-Mamun, Md., & Qiu, G. (2025). Synchronous changes in mercury stable isotopes and compound-specific amino acid nitrogen isotopes in organisms through food chains. *Environment International*, 196, 109327. <https://doi.org/https://doi.org/10.1016/j.envint.2025.109327>
- Wang, J., Dai, J., Chen, G., & Jiang, F. (2022). Role of sulfur biogeochemical cycle in mercury methylation in estuarine sediments: A review. *Journal of Hazardous Materials*, 423, 126964. <https://doi.org/https://doi.org/10.1016/j.jhazmat.2021.126964>
- Wu, P., & Zhang, Y. (2023). Toward a Global Model of Methylmercury Biomagnification in Marine Food Webs: Trophic Dynamics and Implications for Human Exposure. *Environmental Science & Technology*, 57(16), 6563–6572. <https://doi.org/10.1021/acs.est.3c01299>
- Wu, Q., Zhang, Y., Li, P., Fu, X., Zhang, Q., Wang, X., Chen, L., Wang, S., Wang, F., & Feng, X. (2022). Ecosystem Mercury Recovery and Health Benefit Under the Minamata Convention in a Changing Climate. *Reviews of Environmental Contamination and Toxicology*, 260(1), 15. <https://doi.org/10.1007/s44169-022-00016-8>
- Wu, Y.-S., Osman, A. I., Hosny, M., Elgarahy, A. M., Eltaweil, A. S., Rooney, D. W., Chen, Z., Rahim, N. S., Sekar, M., Gopinath, S. C. B., Mat Rani, N. N. I., Batumalaie, K., & Yap, P.-S. (2024). The Toxicity of Mercury and Its Chemical Compounds: Molecular Mechanisms and Environmental and Human Health Implications: A Comprehensive Review. *ACS Omega*, 9(5), 5100–5126. <https://doi.org/10.1021/acsomega.3c07047>
- Yang, L., Xu, J., Song, Y., Ackom, E., He, Y., Namu, D. M., Wang, A., Zhang, H., & Xia, J. (2026). Vegetation-driven soil organic carbon regulates mercury accumulation in karst soil profiles. *Journal of Hazardous Materials*, 506, 141626. <https://doi.org/https://doi.org/10.1016/j.jhazmat.2026.141626>
- Yang, X., Mao, K., Chang, C., Wang, J., Wu, Q., Shao, Y., Huang, J.-H., Zhang, H., & Feng, X. (2024). Interactions of selenium and mercury in soil–plant systems: Characterizations, occurrences, and mechanisms. *Critical Reviews in Environmental Science and Technology*, 54(21), 1527–1545. <https://doi.org/10.1080/10643389.2024.2332135>
- Yoshimura, A., Suemasu, K., & Veiga, M. M. (2021). Estimation of Mercury Losses and Gold Production by Artisanal and Small-Scale Gold Mining (ASGM). *Journal of Sustainable Metallurgy*, 7(3), 1045–1059. <https://doi.org/10.1007/s40831-021-00394-8>
- Youssef, A. N., Janssen, S. E., Lamborg, C., Tate, M. T., Despins, M., Doting, E. L., Poulin, B. A., McCabe, D., Hopf, L. M., Ferrer, E. K., Doroshov, A., Lamarche-Gagnon, G., Delaney, I., Gevers, M., Hatton, J., Kubler-Dudgeon, I., Murphy, J. G., Schartup, A. T., Stibal, M., ... Hawkings, J. R. (2026). Mercury mobilization and export from the Greenland Ice Sheet using an ice-to-ocean approach. *Communications Earth & Environment*. <https://doi.org/10.1038/s43247-026-03818-z>
- Yu, G., Chen, F., Zhang, X., & Wang, Z. (2025). Mercury contamination alters soil microbial communities and functional traits in farmland soils of a mining region, south-western China. *Frontiers in Microbiology*, Volume 16-2025. <https://doi.org/10.3389/fmicb.2025.1721310>
- Yuan, T., Huang, S., Zhang, P., Song, Z., Ge, J., Miao, X., Wang, Y., Pang, Q., Peng, D., Wu, P., Shao, J., Zhang, P., Wang, Y., Guo, H., Guo, W., & Zhang, Y. (2024). Potential decoupling of CO₂ and Hg uptake process by global vegetation in the 21st century. *Nature Communications*, 15(1), 4490. <https://doi.org/10.1038/s41467-024-48849-2>
- Zhan, Z., Lv, D., Zhou, H., Wu, Q., Cui, Y., & Duan, L. (2025). Forest Mercury Deposition Observation in Chongqing: Evaluating Effectiveness of Mercury Pollution Control over the Past Decade in South-western China. *ACS ES&T Air*, 2(2), 286–294. <https://doi.org/10.1021/acsestair.4c00269>

- Zhang, J., Li, C., Tang, W., Wu, M., Chen, M., He, H., Lei, P., & Zhong, H. (2023). Mercury in wetlands over 60 years: Research progress and emerging trends. *Science of the Total Environment*, 869, 161862. <https://doi.org/https://doi.org/10.1016/j.scitotenv.2023.161862>
- Zheng, L., Li, Y., Shang, W., Dong, X., Tang, Q., & Cheng, H. (2019). The inhibitory effect of cadmium and/or mercury on soil enzyme activity, basal respiration, and microbial community structure in coal mine-affected agricultural soil. *Annals of Microbiology*, 69(8), 849–859. <https://doi.org/10.1007/s13213-019-01478-3>
- Zhou, J., Obrist, D., Dastoor, A., Jiskra, M., & Ryjkov, A. (2021). Vegetation uptake of mercury and impacts on global cycling. *Nature Reviews Earth & Environment*, 2(4), 269–284. <https://doi.org/10.1038/s43017-021-00146-y>