



DOI: <https://doi.org/10.38035/dijemss.v7i2>
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Mercury Exposure and Health Effects in Humans: A Systematic Review of Biomarker Evidence

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Abstract: Mercury remains a long-lasting pollutant in the environment, known for its toxic effects on humans, especially from long-term exposure. This systematic review compiles recent findings on how mercury exposure affects human health, focusing on studies using biological markers. Research articles from 2000 to 2025 were retrieved from PubMed, Scopus, and Web of Science. Included studies were observational or experimental, involving human subjects with mercury detected in blood, hair, or urine, alongside health impact assessments. The review followed PRISMA standards, and risk of bias was evaluated using the Newcastle-Ottawa Scale. Out of all results, 40 studies met the criteria. Most showed increased health risks such as neurotoxic, kidney, and heart problems in people living near gold mining sites, industrial areas, or those frequently eating seafood. Blood and hair were the most used biomarkers. Sensitive groups like pregnant women and children showed greater vulnerability even at low exposure levels. Overall, mercury continues to pose a public health threat, highlighting the urgent need for stricter environmental policies and targeted protective actions.

Keyword: Biomarkers, Human Health, Mercury Exposure, Neurotoxicity

INTRODUCTION

Mercury (Hg) is a widespread and persistent environmental pollutant that poses serious threats to public health. It is the only metal that is liquid at room temperature and can easily volatilize when exposed to air.(Chikhladze et al., 2023) Although naturally found, its toxicity

and ability to build up in the body make it dangerous even at low levels.(Wen, 2022) Methylmercury (MeHg), the most harmful form, is often found in fish and seafood.(Ayensu K et al., 2023) This compound can cross the placenta and blood–brain barrier, affecting brain development in fetuses and young children. Mercury is also linked to hormone, kidney, immune, and heart problems.(Kimáková et al., 2018)

The global urgency to reduce mercury exposure is reflected in the adoption of the Minamata Convention, which aims to limit mercury emissions and releases. However, evaluating mercury-related health risks in humans is still difficult, especially in areas with weak monitoring systems(Mostafalou & Abdollahi, 2013). Human activities like small-scale gold mining, burning coal, and industrial operations have led to a rise in mercury emissions in recent years. (Feng et al., 2021) Once released, mercury contaminates air, water, and soil, and enters the food chain mainly through tainted seafood.(Dragan et al., 2023)

Even at low concentrations, mercury can accumulate in the human body and exert toxic effects on vital organs, particularly the central nervous system. Vulnerable populations, including pregnant women and children, are especially at risk due to mercury’s interference with neurodevelopment, leading to cognitive and motor impairments.(González-Estechea et al., 2024) Moreover, chronic exposure is known to adversely affect renal function, immune responses, and reproductive health.

Despite increasing research on mercury exposure, there is limited synthesis that focuses specifically on biomarker-based assessments in human populations. Most prior reviews rely on indirect estimations of exposure, such as environmental measurements or dietary intake data, which may not accurately reflect internal mercury burden. Biomarkers found in samples like blood, hair, and urine provide a more accurate and personal way to evaluate mercury exposure.(Raju et al., 2022) (Zulaikhah et al., 2020)

This review aims to summarize recent evidence linking mercury exposure to health problems in humans, focusing on biomarker-based research. It explores two key questions: How well do biomarkers represent mercury exposure and its effects, and what do the findings mean for public health efforts and risk management?

METHOD

This study used a systematic review method to assess the impact of mercury exposure on human health through biomarker analysis. The study followed the 2020 PRISMA guidelines to maintain clear and reproducible research methods.

A thorough search was done using databases like PubMed, Scopus, Web of Science, MDPI, and Google Scholar with keywords including "mercury exposure", "biomarker", "neurotoxicity", and "health impact". Boolean terms (AND, OR) helped refine results. Only English articles from 2020–2025 were included, while gray literature, non-peer-reviewed works, and studies unrelated to mercury’s health effects on humans were excluded.

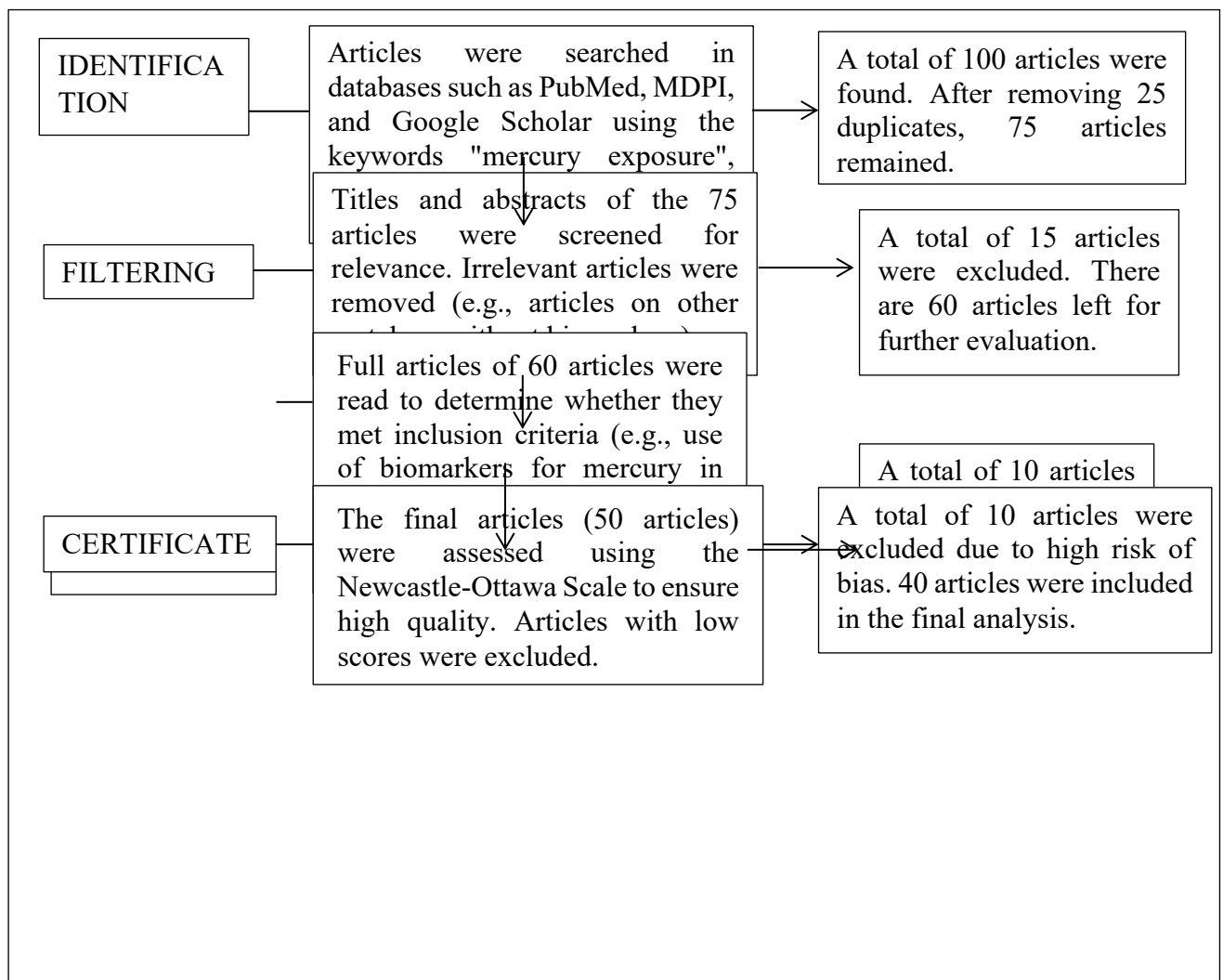
Eligible studies included observational or experimental designs involving human participants, in which mercury levels were assessed using biological matrices such as blood, urine, or hair. Studies were excluded if they involved animal models, lacked primary data, were opinion-based reviews, had sample sizes below 10 participants, or did not use biomarkers as the primary tool for exposure assessment.

The selection process was conducted in three stages: identification, screening, and eligibility. Duplicates were removed during the identification stage. Titles and abstracts were first reviewed for relevance, followed by full-text checks based on set inclusion and exclusion criteria. Two reviewers independently screened and extracted data, resolving any differences through discussion and agreement.

The Newcastle-Ottawa Scale (NOS) was used to assess bias, focusing on participant selection, group comparability, and how exposure and outcomes were measured. Articles scoring below 5 out of 9 on the NOS were excluded from further analysis.

Data were extracted using a standardized form and synthesized narratively. Data taken included population details, biomarker types, mercury levels, health effects, and vulnerable groups like pregnant women, children, and miners. Because of differences in study design and outcomes, meta-analysis wasn't conducted.

Since the review used only public data without involving participants, ethical approval wasn't needed. However, all selected studies were checked to confirm they had proper ethical clearance.



Suriname, for instance, pregnant women near gold mines had high blood methylmercury linked to fetal development risks.(Elwaleed et al., 2024) Another review(Dack et al., 2022) reported that even low prenatal mercury exposure may delay neurological development in young children.(Taux et al., 2022)

Types of Biomarkers

In toxicology, biomarkers are key for measuring mercury exposure in individuals. Blood, urine, and hair are the main types used, each suitable depending on mercury form, exposure time, and how it enters the body.(WHO, 2020)

1. Blood

Blood is a common biomarker used to assess short to medium term mercury exposure. Mercury that enters the body, especially in the form of methylmercury from seafood consumption, will circulate in the bloodstream before being distributed to other body tissues. (Vogel et al., 2021) Studies have found a strong link between mercury in maternal blood and a child's brain development, even at levels under WHO limits. This makes blood a useful biomarker for tracking both short- and long-term mercury exposure in sensitive groups like pregnant women and children. (Lee et al., 2023)

2. Urine

Urine is used as the primary biomarker for detecting inorganic and elemental mercury exposure, especially in the context of exposure through inhalation or direct contact. This type of mercury generally comes from industrial activities and traditional gold mining using amalgamation techniques. Urinary mercury levels reflect excretion over a relatively short period of time (days to weeks), and are very effective in monitoring mine workers or populations living close to sources of inorganic mercury emissions. (Yawei et al., 2021).

3. Hair

Hair is a very useful biomarker for assessing long-term mercury exposure, especially methylmercury. Because hair grows gradually and is able to absorb mercury circulating in the blood, hair segment analysis can provide a chronological picture of mercury exposure over the past few months. Research shows that mercury levels in pregnant women's hair are strongly linked to fetal growth problems. (Muniroh et al., 2022) This makes hair an ideal biomarker in population epidemiological studies examining the long-term impact of environmental exposures on health. (B. Wang et al., 2021)

Observed Health Outcomes

Mercury can lead to serious health issues, influenced by its type, exposure method, amount, duration, and a person's condition. It mainly harms the nervous system, kidneys, reproductive organs, and heart.

1. Neurological Effects

One of the most prominent effects of mercury exposure, particularly methylmercury, is disruption of the central nervous system. Prenatal and early life exposure has been shown to disrupt brain and nerve development, characterized by decreased IQ, speech delays, impaired memory, and other cognitive functions. (Yorifuji et al., 2023) This effect is irreversible, especially if it occurs during a period of active growth of the nervous system, such as in utero or childhood. (Dack et al., 2022)

2. Effects on the Kidneys

Inorganic and elemental mercury tend to accumulate in the kidneys, which are the main organs in the excretion process. Chronic exposure to mercury through inhalation in the workplace, such as in gold miners, can cause kidney cell damage, filtration disorders, and kidney inflammation. (Basu et al., 2023) Several studies have also noted that increased levels of mercury in urine are associated with decreased kidney function, especially in groups exposed over the long term. (Dack et al., 2022)

3. Cardiovascular Effects

Mercury exposure is also linked to poor heart health. (Hu et al., 2021) Recent reviews show that high body mercury levels, especially methylmercury, raise the risk of hypertension

and heart disease.(Hu et al., 2018) A meta-analysis of over 34,000 people found that those with the most exposure had higher rates of high blood pressure and heart problems. Hair mercury above 1–2 µg/g is also linked to greater risk of ischemic heart disease and cardiovascular death, (Houston, 2011) (Wu et al., 2024) These effects may result from oxidative stress,(Nucera et al., 2024) blood vessel inflammation, and endothelial dysfunction (Balali-Mood et al., 2021). All of which harm the cardiovascular system.(Dack et al., 2022)

4. Reproductive Effects

Mercury is known to cross the placental barrier and affect the fetus in the womb. Exposure during pregnancy, especially in the first trimester, has been linked to the risk of miscarriage, premature birth, and impaired development of organs and the nervous system in the fetus. Babies born to mothers with high levels of mercury in their blood or hair tend to have low birth weight and stunted growth.(Dack et al., 2021)

High Risk Population

Mercury exposure does not affect the entire population equally. Certain groups are more vulnerable due to biological, social, and environmental factors. Population groups most at risk for mercury exposure include:

1. Pregnant Mother and Fetus

Pregnant women are especially at risk from mercury, since it can pass through the placenta and reach the fetus’s bloodstream. Fetuses exposed to mercury are at risk of developing impaired brain growth, delayed neurodevelopment, and congenital abnormalities. Even relatively low levels of mercury can have serious effects in the highly sensitive phase of fetal development.(Dack et al., 2022)

2. Children

Children’s developing nervous systems make them particularly sensitive to mercury toxicity. The effects of this exposure are not only short-term, but can have lifelong effects in the form of reduced learning ability, concentration, and motor function. Children who live in coastal areas or consume mercury-contaminated fish are at higher risk.(Dack et al., 2021)

3. Gold Miner

Communities living around small-scale gold mines or in coastal areas that depend on marine fish consumption are also at high risk. Mining activities using mercury as an amalgamation material produce elemental mercury vapor that can be inhaled and enter the workers' bodies. At the same time, methylmercury in seafood is a key exposure source for people living in coastal areas.(Jiang et al., 2020)

Table 1: General Characteristics of the Research

Author & Study Year	Study Location	Population	Types of Biomarkers	Observed Health Effects	Population at Risk	Study Methods
Zhou et al. (2025)	Global (Seafood dataset)	Seafood consumers	Hair	Neurological and cardiovascular risks	Coastal communities, fish consumers	Estimation model
Charkiewicz et al. (2025)	Global (Review)	Pregnant women,	Blood, Hair, Urine	Neurological disorders,	Pregnant women,	Reviews

Author & Study Year	Study Location	Population	Types of Biomarkers	Observed Health Effects	Population at Risk	Study Methods
Packull-McCormick et al. (2023)	Canada	fetuses, children Preschool age children	Blood	cardiovascular risk Decreased IQ due to prenatal mercury exposure	fetuses, children Children	Cohort Study
Dragan et al. (2022)	Regional	Seafood consumers	Hair	Effects on child development due to methylmercury	Children	Comparative
Lee et al. (2022)	Global	Newborn baby	Umbilical cord blood	Growth disorders in infants	Newborn baby, in pregnant mother	Cohort Study

Summary in Narrative

Mercury exposure has been a major focus of studies across locations and populations. Recent research by(Zhou et al., 2025) used an estimation model approach to analyze neurological and cardiovascular risks in coastal communities consuming seafood, highlighting the importance of monitoring hair biomarkers for long-term exposure.

In a review study by(Charkiewicz et al., 2025), it was found that pregnant women, fetuses, and children are the groups most susceptible to neurological disorders due to mercury exposure. This study also emphasizes the importance of a multi-biomarker approach (blood, urine, hair) in evaluating health risks.

Studies(Packull-McCormick et al., 2023) examined the association between prenatal mercury exposure and IQ development in Canadian preschool children. The study used data from a longitudinal cohort (MIREC) to analyze the association between blood mercury levels and children's intellectual performance. Results showed that fish consumption during pregnancy modified this association, with increased IQ scores in girls despite mercury exposure. The study also showed gender differences in response to mercury exposure, with boys with low fish consumption more susceptible to decreased IQ scores.

Studies(Dragan et al., 2023) using a quantitative approach with comparative data analysis and surveys. By involving local populations, this study highlights the impact of fish consumption on mercury exposure, using questionnaires as the main instrument.

A study in South Korea used a PBPK model to estimate fetal mercury exposure.(Lee et al., 2023) It included 334 pregnant women, measuring mercury in both maternal and cord blood. Results showed higher mercury levels in cord blood (7.35 µg/L) than in maternal blood (4.47 µg/L), suggesting mercury builds up in the fetus through the placenta. Higher mercury levels were linked to longer birth length, but not significantly to birth weight.

Discussion

Exposure to mercury—whether as methylmercury (MeHg), inorganic (IHg), or elemental (Hg⁰) is now a major global health issue. Research shows it can cause a wide range of effects, from nerve and kidney damage to immune and reproductive problems. This section reviews those impacts, emphasizing biomarkers, at-risk groups, and public health policy relevanc.

The complexity of neurological impact

Neurological effects are the most consistent finding in mercury exposure studies. Research showed that coastal communities that consume fish as a major source of protein are at high risk for neurological disorders due to methylmercury exposure. (Zhou et al., 2025) Methylmercury can cross the blood–brain barrier, harming neurons, blocking signals, and impairing brain activity. The risk is greater during pregnancy, as mercury can reach the fetus and affect brain development. Long-term effects include lower cognitive skills, motor delays, and behavioral issues. Hair and urine samples from communities near gold mines show mercury levels well above safe limits, with symptoms like tremors, poor sleep, and fatigue often reported. This highlights the urgency of local policies and routine health checks. (Jayanti et al., 2025)

The results of this study revealed that methylmercury (methylmercury) exposure through fish consumption in the Amazon river community has a significant impact on the human immune system, reflected by increased antinuclear antibodies (ANA) titers as an indicator of autoimmune immune system activation and potential chronic immune disorders. An interesting finding showed that individuals with high ANA levels had decreased pro- and anti-inflammatory cytokines, indicating a vulnerable subgroup that shows an atypical immune response to methylmercury exposure, which may indicate damage to immune regulatory mechanisms and potentially trigger or exacerbate autoimmune conditions. This study also showed that selenium didn't provide protection, highlighting how complex nutrient–metal interactions are and that nutrients alone can't fully prevent methylmercury's toxic effects on the immune system.

This adds to the understanding that mercury exposure not only causes neurological and cardiovascular damage, but can also significantly disrupt the immunological balance, thus requiring special attention to the long-term health risks in communities that depend on fish consumption from mercury-contaminated waters. This study also underscores the importance of monitoring immunological biomarkers and developing more effective mitigation strategies to protect vulnerable populations from the cumulative and multisystemic effects of mercury toxicity.

Research strengthens these findings by stating that prenatal mercury exposure has long-term consequences that not only affect the child but also the next generation. (Charkiewicz et al., 2025) Multisystemic impacts, such as reduced IQ, impaired neurodevelopment, and potential risk of neurodegenerative diseases later in life, are of major concern in this vulnerable population. The importance of early detection through blood and hair biomarkers to identify exposure levels is an emphasized recommendation.

This study shows that even low-level mercury exposure can harm health, especially in pregnant women, unborn babies, and children. Mercury found in blood, hair, urine, and cord blood is linked to issues like fetal brain injury, neurological problems in kids, and higher risk of heart disease.

Methylmercury is extremely toxic and offers no benefit to the body. Long-term exposure can lead to lasting damage to the brain, heart, kidneys, liver, and reproductive organs, and may also cause miscarriage or growth problems. (Packull-McCormick et al., 2023)

With the continued widespread use of mercury in industry, agriculture, and medicine, and ongoing environmental pollution, the authors emphasize the importance of ongoing monitoring, control, and public health interventions to protect vulnerable groups, such as pregnant women and children, from the cumulative and multisystemic hazards of mercury. (Nascimento et al., 2022)

Research found that prenatal mercury exposure affects boys' IQ differently based on fish intake. (Goodman et al., 2023) In low fish consumers, higher cord mercury was linked to lower performance IQ. But with moderate to high fish intake, PIQ scores improved, indicating that nutrients in fish might help counter mercury's toxicity

Among girls, higher mercury in cord blood was linked to better FSIQ and PIQ scores in those who ate a lot of fish. This supports the idea that nutrients like omega-3 in fish may help lessen mercury's harmful effects. Also, blood mercury in girls was generally tied to higher IQ, though the PIQ link wasn't significant.

The study also stresses the importance of looking at how mercury and fish nutrients interact when assessing fish intake during pregnancy. While fish can expose people to mercury, their nutrients offer protective benefits especially when mercury levels are low, like in Canada.

However, this study has several limitations. Fish consumption was only measured in the first trimester of pregnancy, so it may not reflect consumption patterns throughout pregnancy. In addition, mercury exposure was measured as total mercury, without distinguishing between methylmercury and other forms. In addition, the limited sample size and low mercury exposure in the subgroup analysis reduce how broadly the findings can be applied.

The study found that 55% of respondents didn't realize mercury risks from eating fish.(Dragan et al., 2023) Around 65% believed their fish intake was too low to be harmful. Children were noted as a vulnerable group due to methylmercury's impact on brain development. Interestingly, 41% of parents avoided giving fish to their kids, choosing supplements like fish oil and vitamin D instead

Fish provide key nutrients like omega-3, vitamin D, and protein, but the risk of methylmercury contamination is still a major concern. In the context of children's health, methylmercury can cause neurological developmental disorders, including mental retardation, tremors, and behavioral changes. In addition, the risk of exposure may be exacerbated by the lack of information provided to consumers about the levels of mercury in the fish they purchase.

This study emphasizes the need to raise public awareness about mercury risks, especially for pregnant women and children. Many participants supported better access to information, such as clearer labels or public campaigns. It also calls for global efforts to reduce mercury use and switch to safer options to protect future generations. While fish is still a key part of a healthy diet, limiting mercury exposure and improving public education are essential to lower health risks.

The study found that mercury levels were higher in umbilical cord blood (7.35 $\mu\text{g/L}$) than in maternal blood (4.47 $\mu\text{g/L}$), showing clear placental transfer.(Lee et al., 2023) Researchers also examined how these mercury levels related to infant growth like weight, length, and head size—at birth and up to age two, while adjusting for factors such as maternal age, BMI, smoking, alcohol use, and secondhand smoke during pregnancy.

Interestingly, higher mercury in cord blood was linked to longer birth length and faster growth in infants. But researchers cautioned that this doesn't suggest mercury is beneficial—rather, it may act as an obesogen that disrupts metabolism and raises the risk of future metabolic disorders.

The study highlights the need to reduce mercury exposure in pregnant women, mainly by limiting fish with high mercury content.(Schaefer et al., 2019) This aligns with South Korea's guidelines that restrict certain fish for expectant mothers.(Beasant et al., 2023) It also calls for more research on how prenatal mercury affects child health over time, considering diet, fish intake, and other environmental exposures.(Asif, M., Umair, M., & Shehryar, 2022)

Overall, this cohort study adds valuable insight into how mercury exposure during pregnancy affects newborn growth.(Shah et al., 2024) Although higher exposure seemed linked to faster growth, it may pose long-term metabolic health risks. That's why minimizing mercury exposure in pregnant women is essential for improving maternal and child health

CONCLUSION

Mercury exposure especially as methylmercury, elemental, and inorganic forms is a major global health issue that affects many body systems. Neurological problems are the most

common, especially in pregnant women, unborn babies, and children. Prenatal mercury exposure can harm brain development, causing learning, movement, and behavior issues later on.

Besides nerve damage, mercury also harms the immune, kidney, heart, and reproductive systems. Some studies link mercury to immune disorders and increased autoimmune risk, especially in people who eat a lot of fish. Still, nutrients like omega-3 in fish may help reduce mercury's harm, depending on exposure levels.

The study also revealed the importance of biomarkers such as blood, hair, and umbilical cord blood in identifying mercury exposure levels, especially in groups that rely on fish as a major source of protein.(Y. Wang et al., 2021) Although fish consumption has nutritional benefits, such as omega-3 and vitamin D content, education about the risks of mercury contamination is still needed to reduce adverse health impacts.

Policy implications resulting from these findings include the importance of controlling the consumption of mercury-contaminated fish, monitoring environmental mercury levels, and banning the use of mercury in certain industries. In addition, mitigation approaches such as information labels on fish products and public education campaigns need to be strengthened to protect future generations.

Overall, efforts to protect against mercury exposure require a holistic approach that includes policy interventions, public education, and further research to understand long-term impacts and develop effective prevention strategies.

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