

REVIEW ARTICLE

Mercury exposure from fish consumption: A systematic review and meta-analysis of health risks and effects in urban vs. rural settings

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ABSTRACT

Mercury presents a significant environmental health hazard due to its ability to bioaccumulate in the food chain, posing risks through the consumption of contaminated fish. This systematic review aims to analyze and compare mercury levels in human populations, specifically focusing on the health risks associated with fish consumption in urban versus rural areas. The review followed PRISMA guidelines and included articles published between January 1, 2020 and March 15, 2025 from PubMed, Scopus, and ScienceDirect. A total of 768 articles were identified, and seven studies met the inclusion criteria. Data extraction was performed, and study quality was assessed using the JBI checklist and risk of bias assessment with ROBINS-E. Data were extracted and synthesized using RevMan 5.4 for the meta-analysis. The meta-analysis showed substantially higher mercury levels in rural populations (SMD 2.76; 95% CI: 2.63–2.89), largely influenced by dietary patterns, predominant fish species, and environmental contamination levels. Health effects associated with elevated mercury exposure included neurodevelopmental risks, elevated mercury levels in pregnant women, and increased vulnerability among populations with high reliance on freshwater fish. These findings highlight the need for targeted public health strategies to mitigate mercury exposure while maintaining the nutritional benefits of fish consumption.

Keywords:

exposure, fish, mercury, rural, urban

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INTRODUCTION

Mercury is a silent but dangerous threat in the complex web of environmental health hazards.¹ Mercury is a persistent environmental toxin that bioaccumulates in the food chain and poses significant health risks, particularly in populations with high fish consumption.² In populations that consume fish, methylmercury (MeHg) contamination of fish continues to be a major source of mercury compound exposure for humans.³ Mercury toxicity in humans is highly dependent on the type of mercury, dosage, and exposure rate. Although the brain is the primary target organ for inhaled mercury vapor,⁴ mercurial compounds can damage both the intestinal and renal epithelial lining,⁵ and methylmercury is extensively dispersed throughout the body.³

The concentration of methylmercury in hair is roughly 250 times higher than that in blood because it readily accumulates in hair. As a result, hair mercury levels are frequently used as exposure indicators.⁶ A higher consumption of fish and marine biota correlates with higher Hg concentrations in the hair and blood of pregnant women.^{7,8} Methylmercury, which is the most common form of dietary Hg, can also cross the placenta.⁹ The concentration of mercury in the neonatal umbilical cord is higher than that in the mother's blood, suggesting that the fetus may be exposed to a significant amount of the mother's circulating mercury.^{10–12} Because the developing infant has both higher levels of mercury crossing the blood-brain barrier and less effective clearance than adults,^{13–15} harmful concentrations may accumulate during a critical window of neurological development.¹⁶

The US Environmental Protection Agency uses a blood mercury concentration of 5.8 ng/mL as a reference level, and concentrations below this threshold are regarded as safe.¹⁷ A study confirms that

the control population's blood mercury level is roughly 1 ng/mL, while levels of 7–10 ng/mL have been reported in workers and residents exposed to mercury in Guizhou (China), an area that is known to suffer mercury contamination.¹⁸ A recent biomonitoring study conducted in New York City found that adults who regularly ate fish had blood mercury concentrations of 2.73 ng/mL and 5.65 ng/mL. According to WHO, human hair can contain less than 6 µg/g of mercury.^{19,20} In the Amazon basin, where fish is the main source of dietary protein, mercury concentrations in hair reached up to 150 µg/g.²⁰

Globally, around 450 contaminated sites have been identified, and an estimated 20 million people are at risk of mercury exposure.²¹ Despite extensive scientific evidence describing mercury toxicokinetic and its health impacts, there is considerable uncertainty about how exposure patterns differ between urban and rural populations. These groups vary widely in fish consumption habits, environmental conditions, and sources of dietary mercury. Understanding these differences is essential to contextualize population-level risks and to guide targeted mitigation strategies.

Therefore, this systematic review and meta-analysis aims to dissect the complex landscape of mercury exposure through fish consumption by comparing urban versus rural populations. By synthesizing emerging evidence from diverse geographical and socioeconomic contexts, we seek to (1) quantify differences in mercury burden and associated health effects, (2) identify key determinants influencing exposure disparities, and (3) provide actionable insights to inform environmental and nutritional health policies. Understanding these distinctions is essential for targeted public health interventions and policy formulation.

METHODS

This systematic review was compiled using three databases, namely PubMed, Scopus, and ScienceDirect. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were used to ensure the quality and relevance of the studies used in this review.^{22–24} This review used Boolean operators such as AND, OR to obtain relevant studies. Bias control is strictly controlled and managed to ensure the quality of the studies used in the study. The review protocol was registered with PROSPERO International prospective register of systematic reviews (registration number: CRD420251039763).

Screening Protocol

We included all relevant studies that discussed mercury levels from fish consumption and compared rural and urban areas. The discussion is related to its implications for the health of exposed communities. Eligible studies were indexed in PubMed, Scopus, and ScienceDirect and published within the last five years. The search included records published from January 1, 2020 to March 15, 2025, the date on which the final search was completed. The studies used in this review are studies that measured mercury levels in humans using hair, urine or blood biomarkers and presented the results in the form of THg concentrations. Mercury exposure is also closely tied to geographical location. It is thus important to ensure that a clear location is specified in the studies due to differences in the frequency of fish consumption in rural or urban areas.

In this review, we excluded all studies that were not in English, studies using in vitro, in vivo methods or measurements of Hg levels in the environment. Studies without available full-texts, those with irrelevant topics and

studies with <5 participants, were also excluded from this review.

Data Sources and Search Strategy

To ensure the relevance of the studies used in this review, we used Boolean operators. The keywords used in each database are: (“Mercury” OR “Methylmercury”) AND (“Fish” OR “Fish Consumption”) AND (“Urban” OR “City”) AND (“Rural” OR “Village”). In addition, during the search process for relevant studies in each database (PubMed, Scopus, and ScienceDirect), the keywords used were a combination of keywords from Medical Subject Headings (MeSH). All studies were carefully searched and selected by independent reviewers. The studies were stored in the author’s library using the Mendeley group reference manager. During this process, to ensure that no studies were duplicated, we removed any identical studies.

Outcome Measure

This review comprehensively compares mercury levels in humans living in urban or rural areas. Mercury exposure outcomes from fish consumption can vary depending on the population's location. Differences may include the level of mercury exposure, differences in health risks based on location, and the resulting health effects. Exposure levels are measured through mercury levels in the body, such as in blood, hair, or urine, as well as the content of methylmercury (MeHg) in the fish consumed. Confounding factors (age, sex, pregnancy status, and dietary intake) were not included in the reports. Due to methodological variability, these confounding factors could not be statistically reconciled and were instead evaluated qualitatively in the synthesis.

Study Process

Three authors (A.A.S.S, J.C.S. and T.J.) independently conducted searches and screened all studies obtained from each database based on the titles and abstracts. The screening criteria were observational studies in humans that measured mercury levels and could later be compared between rural and urban populations. Inclusion and exclusion criteria were used to ensure that only relevant studies were included in the review. The entire search and screening process was recorded in the PRISMA flow chart. This review removed studies that were unclear about exposure assessment to provide a more accurate, valid, and free from bias conclusion on the relationship between fish consumption, mercury exposure, and associated health effects.

Discrepancies were resolved through group discussion until consensus was achieved, and when needed, MM and EDN were consulted to assist in reaching the final decision. Due to a small number of eligible studies and the use of a three-reviewer system, formal inter-rater reliability statistics were not calculated.

Extraction and Quality Assessment

After relevant studies were identified, studies that met the inclusion criteria were determined. The data recorded include (1) authors, (2) years, (3) methods, (4) country, (5) population, (6) mercury levels and (7) key findings. The extracted data was also organized in a table that shows the studies in this review. Furthermore, the mercury level results are identified and separated according to population location (rural or urban). Quality assessment was undertaken to ensure the quality of the studies. The assessment used the Joanna Briggs Institute (JBI) Critical Appraisal, which was used according to the study's research method, and the Risk of Bias in Non-randomized Studies of Exposures (ROBINS-E) assessment tool from the Cochrane Collaboration. Each of these tools was used

to assess the quality and bias of the studies used in this review. We present the results and findings with a narrative approach in the synthesis process, which can provide detailed information about the comparison of mercury exposure based on the findings of this systematic review.

Synthesis Method

This meta-analysis was conducted using a fixed-effect model approach to combine the results from multiple studies. A fixed-effect model was used because the number of included studies was small, and this approach provided more stable estimates. The effect size used was the Standardized Mean Difference (SMD) with 95% confidence interval (95% CI) to compare mercury levels in rural and urban areas. To assess heterogeneity between studies, statistical tests were performed using the Chi² test and I². All statistical tests for this meta-analysis were conducted using Review Manager (RevMan) v5.4 (Cochrane Collaboration, UK).

RESULTS

Characteristics of the Included Studies

The search results of relevant studies in each database revealed published literature related to mercury exposure from fish consumption in urban and rural areas. From the keyword search results, a number of articles were identified in this review. The initial keyword search identified a total of 768 articles. The initial search revealed that most articles were found in the SCOPUS database (n=748), followed by the PubMed database (n=10), and the ScienceDirect database (n=10). However, after screening and eligibility analysis, only seven articles were included in this review. Figure 1 shows the flow of the systematic review with the PRISMA diagram.

In the systematic review, the included studies employed a variety of research designs to investigate the relationship between mercury exposure and

location, specifically comparing urban and rural settings. Six studies utilized a cross-sectional study design. Cross-sectional studies provide a snapshot of mercury exposure and related factors within a population at a single point in time. These studies are valuable for assessing the prevalence of mercury exposure in different locations and identifying potential associations between residence (urban or rural) and mercury levels. For example, cross-sectional studies included in this review assessed mercury levels in specific communities or population groups within urban and rural areas to compare exposure levels. Additionally, one study used a case-control design. Case-control studies compare individuals with a particular condition or outcome (in this context,

perhaps high mercury levels or related health effects) to a control group without the condition. This design is useful for exploring potential risk factors associated with mercury exposure, with the study design comparing mercury levels of the two groups. By including both cross-sectional and case-control studies, this review offers a more comprehensive analysis of mercury exposure patterns and potential health risks across urban and rural settings. The included studies showed significant variation in methodology, sample size, and biomarkers of mercury exposure. An overview of these characteristics is presented before the pooled analysis. The extracted data from these studies are summarized in Tables 1, 2 and 3.

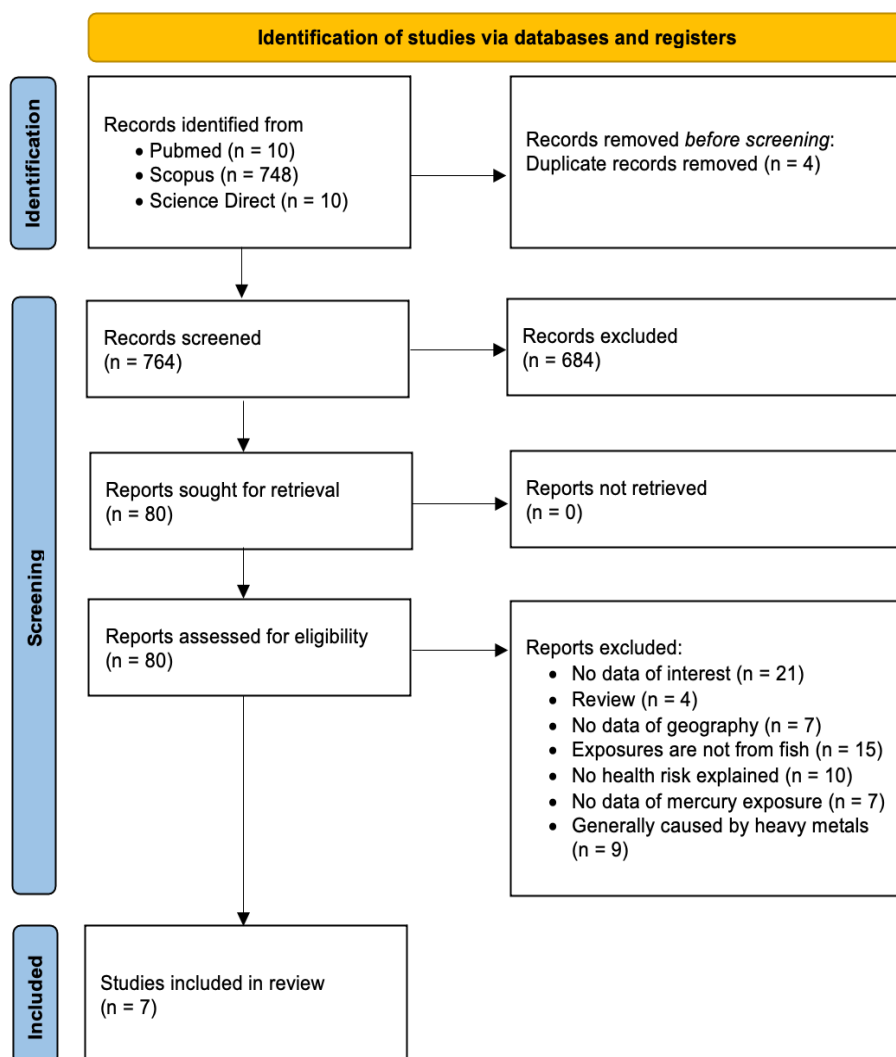


Figure 1. Study selection with PRISMA flowchart

These studies were conducted in various countries, including Brazil, Russia, Indonesia, China, Korea, and the United States (Alaska). These countries have different levels of mercury exposure, depending on factors such as dietary habits and environmental conditions. The publication time span of the studies reviewed is between 2020 and 2024. Among these studies, cross-sectional and

case-control studies are the most commonly used to assess mercury levels. In addition, most journals used methods such as hair, urine, and blood analysis to record the mercury levels of each participant in the study, which is then followed up by a statistical analysis of the data. Figure 2 shows the distribution of locations and mercury exposure in the studies.

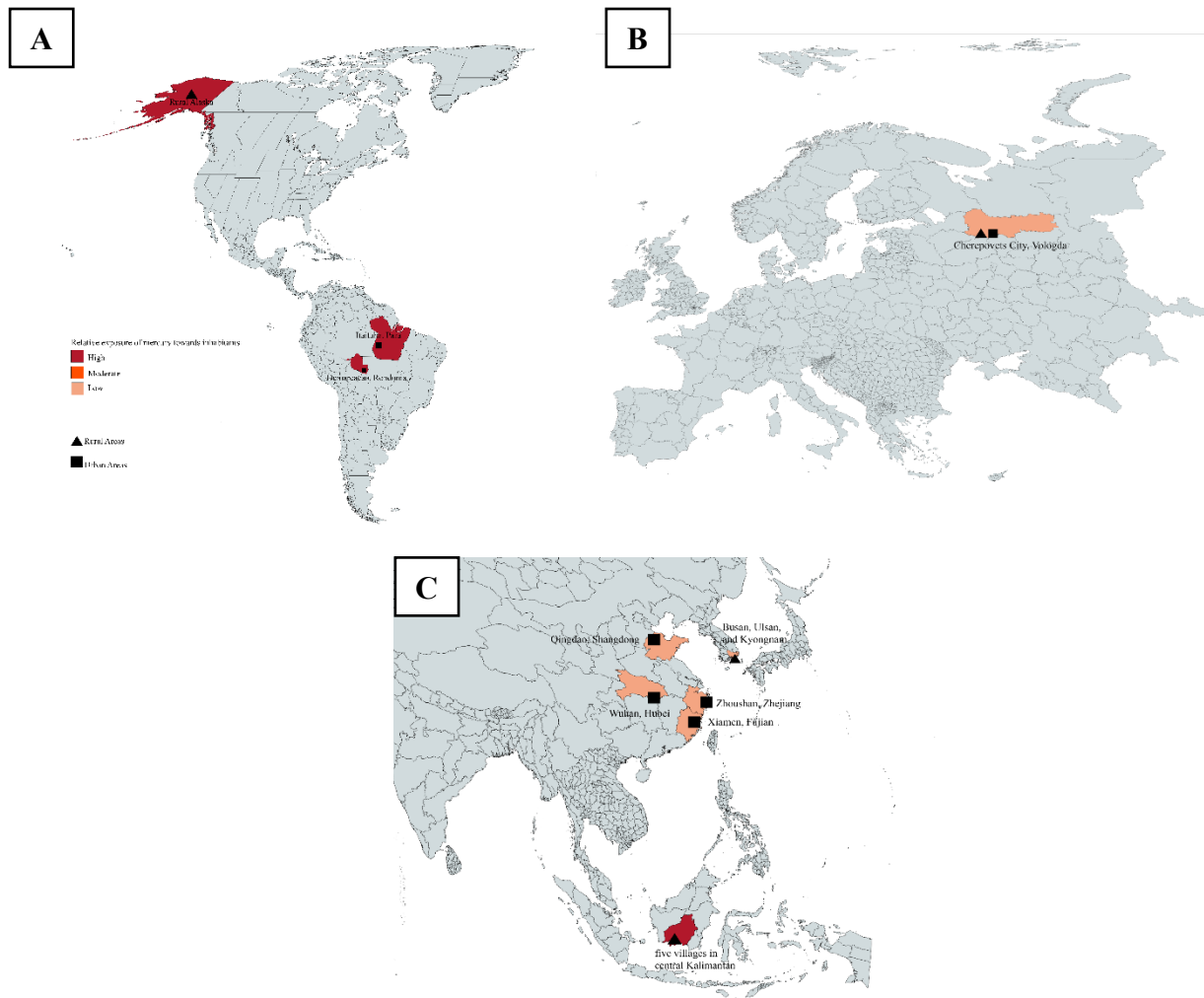


Figure 2. The distribution of locations and mercury exposure in the studies
(A) the Americas, (B) Europe, and (C) Asia

Figure 2 illustrates the geographical distribution of the included studies across the Americas, Europe, and Asia. Notably, the highest concentrations of mercury exposure were reported in regions with strong reliance on freshwater or riverine fish, such as the Amazon basin and certain Indonesian and Russian rural areas. In contrast, some coastal or urban regions demonstrated relatively lower mercury levels, reflecting differences in environmental contamination, fish species distribution, and dietary patterns across continents.

Mercury Level Comparison

The meta-analysis results in Figure 3 show that mercury levels in rural areas are significantly higher than in urban areas, with a Standardized Mean Difference (SMD) = 2.76 (95% CI: 2.63–2.89, $P < 0.00001$). The pooled effect size (SMD = 2.76) represents a large and clinically meaningful difference, indicating that individuals living in rural areas have substantially higher mercury exposure than those in urban areas. Although heterogeneity was high ($I^2 = 100\%$), the direction of effect was consistent across studies. A simple sensitivity check

excluding the study with the largest effect size did not change the overall conclusion,

suggesting robustness of the pooled estimate.

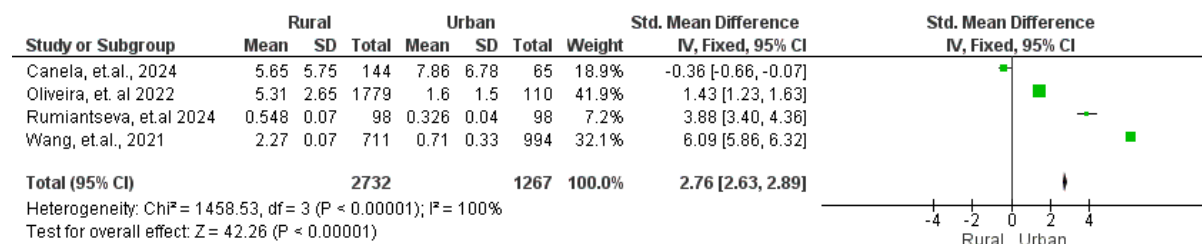


Figure 3. Mercury Levels between Rural and Urban Areas

Risk of Bias Assessment

Figure 4 shows the risk of bias assessment of the studies analyzed using the Risk of Bias in Non-randomized Studies of Exposures (ROBINS-E) tool. The assessment was based on seven main domains. Overall, the majority of studies in this meta-analysis had a low risk of bias. However, there were several domains with "some concerns," especially in exposure measurement (D2), missing data (D5), and

outcome measurement (D6). These risks of bias need to be considered in interpreting the results of the meta-analysis. The overall level of risk of bias indicates that the results of these studies are still reliable, but further studies with more standardized methods for measuring exposure and controlling for missing data are recommended to improve the reliability of the findings. All included studies met the critical appraisal criteria as presented in Tables 4 and 5.

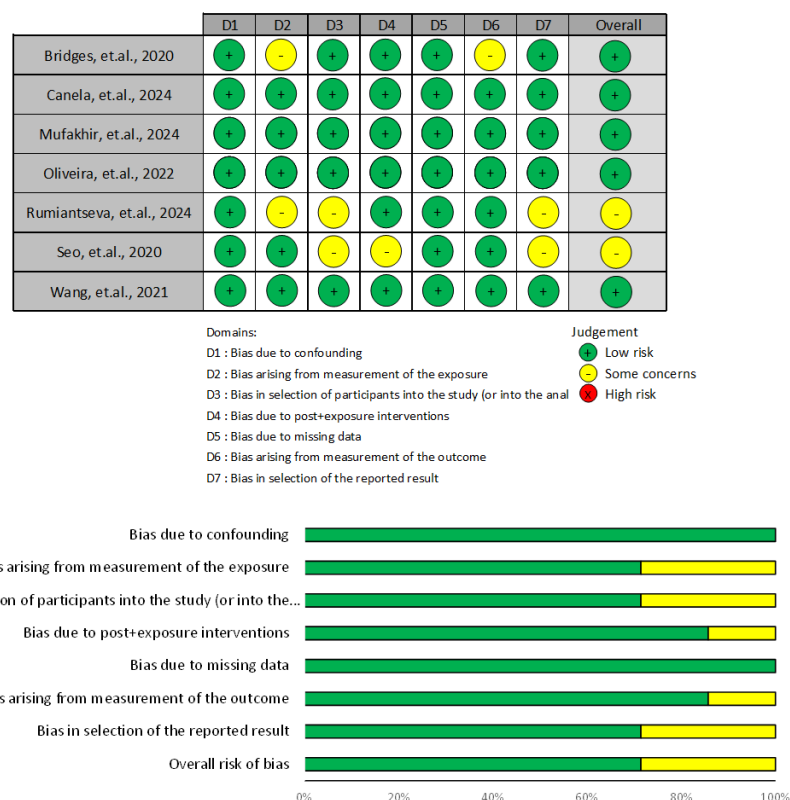


Figure 4. Risk of bias assessment results for each study.

Table 1. Characteristics and Summary of the Studies

No	Authors, Years	Methods	Country	Population	Mercury Level (mg/kg) (Mean $\pm$ SD)	Key Finding
1	Bridges et al., 2020 ²⁵	Cross-sectional	USA (Alaska)	n=1779 females aged 6 to 95 years old	5.31 $\pm$ 2.65	This research indicates that the methylmercury content in Pacific salmon does not pose a significant health risk to average subsistence consumers in Alaska.
2	Canela et al., 2024 ²⁶	Cross-sectional	Brazil	n=65 males and females in Demarcação.	7.86 $\pm$ 6.78	Residents of the Demarcação District in the Brazilian Amazon experience high mercury exposure, primarily from fish consumption. This exposure is higher in males and increases with age.
3	Mufakhir et al., 2024 ²⁷	Cross-sectional	Indonesia	n=144 adult residents	5.65 $\pm$ 5.75	This study was conducted to assess the risk of mercury exposure from Katingan fish consumption. The results confirm that variations in fish consumption patterns have a significant impact on mercury exposure levels.
4	Oliveira et al., 2022 ¹³	Cross-sectional	Brazil	n = 110, pregnant women 18–40 y.o; mean age 24.6 $\pm$ 4.8 years	1.6 $\pm$ 1.5	The results showed that 48% of the population had mercury levels exceeding safe limits. The commonly consumed fish, <i>Cichla spp.</i> and <i>P. squamosissimus</i> , had high THg.
5	Rumiantseva et al., 2024 ²⁸	Case-control	Russia	n = 98 pregnant women 18-45 y.o	Rural: 0.548 $\pm$ 0.07 Urban: 0.326 $\pm$ 0.04	Mercury levels in rural areas are higher than those in urban areas. Freshwater fish consumption leads to higher mercury levels compared to saltwater fish.

No	Authors, Years	Methods	Country	Population	Mercury Level (mg/kg) (Mean ± SD)	Key Finding
6	Seo et al., 2020 ²⁹	Cross-sectional	Korea	n = 711 women of child bearing age	Blood mercury: 4.11 ± 0.11 Hair Mercury: 0.97 ± 0.03 Urine Mercury: 1.72 ± 0.06	Total mercury concentrations in blood and hair were higher in groups with greater fish and shellfish consumption. Seafood consumption is a major factor in increased mercury exposure in women of childbearing age.
7	Wang et al., 2021 ³⁰	Cross-sectional	China	n=994 adult residents	• WH: 0.41 ± 0.55 • QD: 0.49 ± 1.36 • XM: 0.81 ± 2.31 • ZS: 1.14 ± 2.05	Hg concentrations in human hair increased significantly in Zhoushan (ZS), Xiamen (XM), Qingdao (QD), and the Zinc Smelting Area (ZSA). Fish consumption was the main source of MeHg exposure in coastal cities (>85%).

Note: Elevated Hg levels were defined as: blood ≥5.8 µg/L (US EPA), hair >2 µg/g (WHO), and urine >4 µg/L (WHO).

Table 2. Characteristics and results of mercury levels from urban areas

No	Author, Years	Location	Hg Levels (mg/kg) (Mean ± SD)	Measurement Sample	Source
1	Rumiantseva, et al., 2024 ²⁸	Cherepovets City, Rusia	0.326 ± 0.04	Hair	Fish consumption
2	Oliveira, et al., 2022 ¹³	municipality of Itaituba, Brazil	1.6 ± 1.5	Hair	Fish consumption
3	Canela, et al., 2024 ²⁶	Demarcação District, Brazil	7.86 ± 6.78	Hair	Water and fish consumption
4	Wang, et al., 2021 ³⁰	Zhoushan, Xiamen, Qingdao, Wuhan, China	0.71 ± 0.33	Hair	Fish consumption

Table 3. Characteristics and results of mercury levels from rural areas

No	Author, Years	Location	Hg Levels (mg/kg) (Mean $\pm$ SD)	Measurement Sample	Source
1	Rumiantseva, et al., 2024 ²⁸	Cherepovets City, Rusia	0.548 $\pm$ 0.07	Hair	Fish consumption
2	Mufakhir, et al., 2024 ²⁷	Five villages, i.e.: Tampelas, Telaga, Jahanjang, Asem Kumbang and Talingke. Kalimantan, Indonesia	5.65 $\pm$ 5.75	Hair	Fish consumption
3	Seo, et al., 2020 ²⁹	Coastal areas of Busan, Ulsan, and Kyongnam in Korea	2.27 $\pm$ 0.07	Hair	Fish consumption
4	Bridges, et al., 2020 ²⁵	Rural Alaska	5.31 $\pm$ 2.65	Hair	Fish consumption

Table 4. Critical appraisal for Cross-Sectional Studies

Criteria	Oliveira, et al., 2022	Seo, et al., 2020	Bridges, et al., 2020	Canela, et al., 2024	Wang, et al., 2021	Mufakhir, et al., 2024
Were the criteria for inclusion in the sample clearly defined?	Y	Y	Y	Y	Y	Y
Were the study subjects and the setting described in detail?	Y	Y	Y	Y	Y	Y
Was the exposure measured in a valid and reliable way?	Y	Y	Y	Y	Y	Y
Were objective, standard criteria used for measurement of the condition?	Y	Y	Y	Y	Y	Y
Were confounding factors identified?	Y	Y	Y	Y	Y	Y
Were strategies to deal with confounding factors stated?	Y	Y	Y	Y	Y	Y
Were the outcomes measured in a valid and reliable way?	Y	Y	Y	Y	Y	Y
Was an appropriate statistical analysis used?	Y	Y	Y	Y	Y	Y
Overall appraisal	I	I	I	I	I	I

Table 5. Critical appraisal for Case-control Studies

Criteria	Rumiantseva, et al., 2024
Were the groups comparable other than the presence of disease in cases or the absence of disease in controls?	Y
Were cases and controls matched appropriately?	Y
Were the same criteria used for the identification of cases and controls?	Y
Was exposure measured in a standard, valid and reliable way?	Y
Was exposure measured in the same way for cases and controls?	Y
Were confounding factors identified?	Y
Were strategies to deal with confounding factors stated?	Y
Were outcomes assessed in a standard, valid and reliable way for cases and controls?	Y
Was the exposure period of interest long enough to be meaningful?	Y
Was an appropriate statistical analysis used?	Y
Overall appraisal	I

DISCUSSION

This systematic review aimed to compare mercury (Hg) levels in human populations in urban and rural areas, focusing on fish consumption as a primary exposure source. The review identified seven studies conducted across various countries, including Brazil, Russia, Indonesia, China, Korea, and the United States (Alaska). These studies employed cross-sectional and case-control designs, utilizing hair, urine, and blood samples to measure Hg concentrations. Overall, the review reveals a complex picture of Hg exposure, with variations observed across different geographical locations and between urban and rural settings.

The populations examined in these studies vary and include adult males and females, pregnant women, and residents of specific regions. The studies focus on measuring mercury levels in human populations and comparing exposure levels in rural and urban areas. Mercury levels were measured using biomarkers such as hair, urine, and blood. The studies included in this review can be classified based on the measurement of mercury levels (THg) from fish consumption in human populations. All mercury concentrations reported in the meta-analysis are expressed in hair mercury (mg/g). According to WHO guidelines,³¹ hair mercury levels $>2 \mu\text{g/g}$ are considered high. The results showed variations in mercury levels across different geographical locations and different urban and rural settings.

Figure 3 shows the results of a meta-analysis comparing mercury levels in rural and urban areas in four studies. The total Standardized Mean Difference (SMD) value was 2.76 (95% CI: 2.63–2.89, $P < 0.00001$), indicating that mercury levels were significantly higher in rural areas compared to urban areas. The results of the heterogeneity analysis showed $\text{Chi}^2 = 1458.53$, $\text{df} = 3$, $P < 0.00001$ and $I^2 = 100\%$, indicating very high heterogeneity in the

results of the studies analyzed. Factors explaining the high level of heterogeneity include differences in mercury level measurement methods between studies, variations in study population characteristics, including fish consumption patterns and environmental exposure, and differences in the main sources of mercury contamination between rural and urban areas.

The results of the meta-analysis showed a general pattern where mercury levels in rural areas were higher than in urban areas, except in the study by Canela et al.²⁶ (2024), which showed the opposite trend. They reported an SMD of -0.36 (-0.66, -0.07), indicating that mercury levels in urban areas are higher than in rural areas, although the difference is small. In contrast, Oliveira et al.¹³ (2018) showed that mercury levels were higher in rural areas with a significant difference (SMD = 1.43, 95% CI: 1.23, 1.63). Rumiantseva et al.²⁸ (2024) reported a large difference in mercury levels, with rural areas showing much higher concentrations than urban areas (SMD = 3.88, 95% CI: 3.40, 4.36). Wang et al.³⁰ (2021) showed the largest difference, with rural areas showing very high mercury levels (SMD = 6.09, 95% CI: 5.86, 6.32). The difference in mercury levels between rural and urban areas can be explained by several main factors. Industrial pollution and coal burning are usually higher in urban areas, but mercury contamination can be more concentrated in certain areas. Fish and seafood consumption is also a major factor, with rural communities often relying on local food sources, including fish from waters that may be contaminated with mercury. In addition, small-scale gold mining activities in some rural areas use mercury in the gold extraction process, increasing exposure of local residents.

Across the included studies, consistent patterns emerged when comparing mercury levels between rural and urban settings. Rumiantseva et al.²⁸

(2024) reported substantially higher hair mercury levels in rural pregnant women than their urban counterparts, largely due to greater reliance on freshwater fish. Similar trends were observed in Korea,²⁹ Indonesia,²⁷ Alaska,²⁵ and some parts of China,³⁰ where communities dependent on local fish demonstrated higher exposure levels. In contrast, a study by Canela et al.²⁶ (2024) found a unique pattern, with slightly higher mercury concentrations in urban residents, likely attributed to the consumption of commercially sourced piscivorous species with high trophic levels. Oliveira et al.¹³ (2022) also highlighted significant exposure among Amazonian pregnant women, particularly those consuming predatory fish species. Taken together, these findings show that while the majority of studies indicate higher exposure in rural populations, specific dietary patterns and fish species can lead to exceptions in certain urban contexts.

Socio-economic and lifestyle factors also influence differences in mercury levels.³² Rural communities may be more vulnerable to mercury exposure due to limited access to clean water and good sanitation. Rural dietary patterns that rely more on local catches also contribute to increased mercury levels. In addition, awareness of the dangers of mercury is generally higher in urban areas than in rural areas, making urban communities more likely to take preventive measures. The studies included in this review confirm that fish consumption is a significant pathway for Hg exposure in both urban and rural populations.²⁵ This finding is in line with existing scientific literature, which has consistently identified contaminated fish as a major source of MeHg exposure. However, the review also highlights that the relationship between fish consumption, Hg levels, and location (urban versus rural) is not straightforward and is influenced by several factors.

The review found considerable variability in mercury (Hg) levels across the studies, influenced by several factors. Dietary habits play a crucial role, as differences in the types and amounts of fish consumed significantly impact Hg exposure. Populations in rural or coastal areas, where fish is a primary protein source, are at a higher risk of Hg accumulation. Additionally, different fish species contribute to this variability,³³ with predatory fish such as *Cichla spp.* and *Plagioscion squamosissimus*, as identified in Oliveira et al.¹³ (2018), containing higher Hg concentrations. Another major factor is environmental contamination, where Hg pollution in aquatic ecosystems varies due to industrial discharge, mining activities, and natural geological sources, directly affecting Hg levels in fish. Geographical location further influences Hg exposure. Rumiantseva et al.²⁸ (2024) found that rural areas exhibited higher Hg levels than urban regions, which is likely due to proximity to contaminated water sources and a higher intake of freshwater fish, which generally have greater Hg concentrations than saltwater species.

Despite these observations, the review provides mixed evidence regarding urban-rural differences in Hg exposure. While some studies, such as a study by Rumiantseva et al.²⁸ (2024), reported higher Hg levels in rural areas, others did not find a consistent distinction. This inconsistency suggests that the urban-rural gradient alone is not a sufficient predictor of Hg exposure. Instead, other factors such as specific dietary habits and local environmental conditions play a more significant role. More concerning, health risks associated with Hg exposure remain a critical issue,²⁷ as several studies reported Hg levels exceeding safe limits, particularly in vulnerable populations such as pregnant women, developing fetuses, and young children. Findings from Oliveira

et al.¹³ (2018) and Canela et al.²⁶ (2024) underscore the need for public health interventions to mitigate Hg exposure in affected communities.

The review confirms that fish consumption is a primary contributor to MeHg exposure, with studies such as those by Seo et al.²⁹ (2020) and Wang et al.³⁰ (2021) highlighting the importance of considering fish consumption patterns when assessing Hg exposure risks. These findings have significant implications for dietary recommendations and public health policies, emphasizing the need to balance the nutritional benefits of fish consumption with the potential risks of Hg exposure.^{29,30}

The findings of this systematic review are consistent with a large body of literature that has investigated Hg exposure and its associated health risks. Previous studies have also reported variations in Hg levels across different populations and geographical locations,³⁴ with fish consumption being a primary source of exposure. This review also highlights some important nuances. The comparison between urban and rural areas is complex, and the relationship between location and Hg exposure is often mediated by other factors. This finding suggests that public health interventions should be tailored to specific local conditions and dietary habits, rather than relying on broad generalizations about urban versus rural settings.

However, the review is limited by the number of included studies ($n=7$), which may restrict the statistical power and the ability to draw firm conclusions. The heterogeneity of the included studies in terms of study design, population characteristics, and methods of Hg measurement may also limit the comparability of the findings. Although this meta-analysis provides important insights, there are some limitations that need to be considered. As high heterogeneity ($I^2 = 100\%$) indicates large differences between studies, the results should be interpreted with caution. The

number of studies analyzed was only four, which may limit the generalizability of the results. In addition, this analysis did not consider confounding factors such as age, gender, and fish consumption habits that may affect mercury levels. Furthermore, the review focused primarily on studies published in English, potentially introducing language bias.

Despite the high heterogeneity ($I^2 = 100\%$), all studies demonstrate a consistent direction of effect, justifying the use of a pooled analysis, although conclusions must be interpreted cautiously. Narrative synthesis remains crucial to contextualize inter-study differences. This review also has notable strengths, including adherence to PRISMA guidelines, PROSPERO registration, and the use of validated appraisal tools. The inclusion of multiple biomarkers and geographically diverse populations further enhances the robustness and relevance of the findings.

The findings of this systematic review have significant implications for public health and policy, especially in regions with high fish consumption. One of the key priorities is monitoring Hg levels, both in fish and human populations, particularly among vulnerable groups. Regular monitoring should be conducted across urban and rural areas, considering local dietary habits and environmental conditions to provide a comprehensive risk assessment.³⁵ Additionally, dietary guidelines must be developed and disseminated by public health agencies to offer clear, evidence-based recommendations on safe fish consumption. These guidelines should take into account the Hg content of different fish species and provide specific advisories for at-risk populations, including pregnant women and young children.

Beyond individual dietary choices, environmental regulations play a crucial role^{36,37} in mitigating Hg exposure.³⁸ Stricter policies on industrial discharge, mining activities, and other pollution sources are essential to reducing Hg

contamination in aquatic ecosystems. Furthermore, risk communication strategies must be enhanced to effectively inform the public about the potential risks and benefits of fish consumption. These communication efforts should be tailored to specific populations and cultural contexts to ensure clarity and accessibility.

Lastly, further research is necessary to deepen our understanding of the intricate relationship between fish consumption, Hg exposure, and health outcomes across urban and rural settings.³⁹ Future studies should employ standardized Hg measurement methods and explore additional factors such as genetics, nutrition, and socioeconomic status, which may influence Hg absorption and toxicity. Addressing these aspects will be essential for designing more effective public health interventions and policies.

RECOMMENDATIONS

This systematic review reveals a complex relationship between mercury exposure, fish consumption, and geographic setting. These findings highlight the necessity for tailored public health interventions that address local environmental conditions and cultural dietary practices rather than broad geographic generalizations. Moving forward, comprehensive monitoring programs, culturally-sensitive dietary guidelines, stricter environmental regulations, and effective risk communication strategies are essential to protect vulnerable populations, particularly pregnant women and children, from the neurological and developmental consequences of mercury exposure while preserving the nutritional benefits of fish consumption. Due to the limited number of studies and substantial methodological heterogeneity, future research should apply standardized exposure assessments and better confounder control to improve

comparability and strengthen evidence quality.

AUTHOR CONTRIBUTION

AASS: Conceptualization, Methodology, Data Curation, Formal Analysis, and Writing-Original Draft. TJ: Data Curation, Visualization, and Writing-Original Draft. JCS: Data Curation, Formal Analysis, Visualization and Writing-Original Draft. SB: Methodology, Validation and Writing-Review & Editing. EDN: Formal Analysis, Supervision, and Writing-Review & Editing. MM: Formal Analysis, Supervision, and Writing-Review & Editing.

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CONFLICT OF INTEREST

The authors declare no conflict of interest associated with the materials presented in this paper.

SUPPLEMENTARY MATERIAL

Supplementary tables are available.

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