

Mercury in Amazonian fish: chemical speciation, environmental drivers and implications for food security and human health: a 36-year scientometric review

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**Mercury in Amazonian fish: chemical speciation, environmental drivers
and implications for food security and human health: a 36-year
scientometric review**

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Abstract

Mercury contamination in aquatic ecosystems is a major environmental and public health concern, particularly in the Amazon, where natural and anthropogenic processes promote mercury mobilization, methylation, bioaccumulation, and biomagnification in aquatic food webs. This scientometric study assessed temporal and spatial patterns of mercury concentrations in Amazonian fish and their implications for food security. We analyzed 98 articles indexed in Web of Science and Scopus, published between 1988 and 2024, following PRISMA-based screening criteria. Publication trends, mercury chemical forms, sampling locations, feeding habits, and species exceeding reference limits for human consumption were evaluated. Scientific production increased significantly over the study period ($R^2=0.56$; $p<0.001$), with peaks in 2018 and 2021. Brazil accounted for 79 studies (approximately 80% of publications), whereas other Amazonian countries were underrepresented. Total mercury (THg) was the most frequently assessed chemical form, reported in 90 studies evaluating a single mercury form, while methylmercury (MeHg) and inorganic mercury were less frequently investigated. This gap limits dietary-exposure assessments because MeHg is the form of greatest toxicological relevance. A total of 436 fish species were identified. Mercury concentrations were generally higher in carnivorous and piscivorous species, consistent with trophic biomagnification, although elevated values also occurred in some omnivorous, herbivorous, and detritivorous species. Median concentrations above 1.6 mg/kg were more frequent in Brazilian states, while values reached approximately 3.0 mg/kg in French Guiana and 1.5 mg/kg in Colombia. Of the assessed species, 218 (48.23%) exceeded 0.5 mg/kg and 144 exceeded 1.0 mg/kg. These findings highlight risks for riverine and Indigenous communities reliant on fish and reinforce the need for integrated biomonitoring, regional dietary data, and policies to reduce mercury emissions and protect Amazonian biodiversity, food security, and human health.

Keywords: Ecotoxicology; Mercury contamination; Methylmercury; One Health; Riverine populations

INTRODUCTION

Mercury (Hg) contamination in aquatic ecosystems is widely recognized as a global environmental and public health issue. This metal is introduced into the environment through natural processes, such as rock weathering (Veiga; Meech; Onate, 1994; Lacerda, 1995; Malm, 1998), and by anthropogenic activities, including artisanal gold mining, deforestation, burning, and the construction of hydroelectric power plants (Dórea; Barbosa, 2007; Bastos et al., 2008; Crespo-Lopez et al., 2021, 2023). Once in aquatic systems, mercury undergoes complex biogeochemical transformations and tends to accumulate along the food chain through the processes of bioaccumulation and biomagnification, resulting in higher concentrations at higher trophic levels (Driscoll et al., 2013).

In the Amazon, mercury dynamics are strongly influenced by specific environmental conditions. Studies conducted in regions such as the Upper Rio Negro have recorded mercury concentrations in water (4.5 ng/L) and soil (172 µg/kg) that are associated, in part, with natural sources (Fadini; Jardim, 2001). However, the availability and transformation of Hg in aquatic environments can also be controlled by physicochemical characteristics of the water, such as pH, redox potential, dissolved oxygen, turbidity, and dissolved organic matter concentration (Driscoll et al., 1994; Barbosa et al., 2003). These factors regulate microbial activity and directly influence methylation rates - the process responsible for the formation of methylmercury (MeHg), the most toxic and bioavailable form of mercury in aquatic ecosystems (Malm, 1998; Dórea, Barbosa, 2007; Crespo-Lopez et al., 2021).

MeHg is rapidly absorbed and widely distributed in tissues, exhibiting slow elimination and a high potential for bioaccumulation, especially in fish muscle (Bloom, 1992; World Health Organization - WHO, 2008). Due to its neurotoxic properties, mercury exposure poses a significant risk to human health - particularly for vulnerable groups such as pregnant women and children - potentially causing neurodevelopmental changes as well as cardiovascular and renal effects (Goyer; Clarkson, 2008; Crespo-Lopez et al., 2023).

In the Amazonian context, where fish consumption constitutes the primary route of human exposure to mercury and is strongly linked to the local population's way of life, the situation is further aggravated. Riverine and indigenous populations in

the Amazon region exhibit consumption rates that can exceed 100 to 200 kg per person per year - that is, up to ten times higher (Isaac et al., 2011; Hacon et al., 2020) the global average, estimated at approximately 20 kg per person per year (The State of World Fisheries and Aquaculture-FAO, 2024). This high consumption is linked to the central role of fishing as a traditional activity and the foundation of food security for these populations (Alho et al., 2015; Dias et al., 2023).

Fishing in the Amazon is strongly influenced by environmental factors - such as the hydrological regime, food availability, and food web structure - which also drive variability in concentrations across species and regions (Barbosa et al., 2003; Brito et al., 2017), having a direct influence on the capture of these organisms (Isaac et al., 2011). Furthermore, ecological and biological factors - such as feeding habits, trophic position, body size, and age - influence Hg absorption and accumulation, with higher concentrations generally observed in carnivorous and piscivorous species (Blom, 1992; WHO, 2008).

There is a growing number of studies on mercury in fish in the Amazon, yet significant gaps remain regarding the temporal evolution of scientific output, the spatial distribution of studies across Amazonian countries, and the integration of ecological and chemical data with implications for food security. In this context, the present study employs a scientometric approach to analyze scientific literature on mercury contamination in Amazonian fish, focusing on temporal and spatial variations, chemical forms of mercury, and ecological patterns of contamination. The study seeks to answer the following questions: (i) has there been an increase in scientific output regarding Hg in the Amazon over time? (ii) which chemical forms of Hg have been most investigated? (iii) which Amazonian countries account for the highest scientific output? (iv) where were the highest mercury concentrations in fish recorded? (v) which fish species and feeding habits exhibit the highest levels of contamination? and (vi) which species - and what proportion of them - exceed the safety limits established by the World Health Organization for human consumption?

Integrating a scientometric approach with ecological and public health perspectives aims to provide a comprehensive overview of mercury contamination in Amazonian fish and contribute to understanding its impacts on biodiversity conservation and human health protection.

METHODS

Databases and Selection of Keywords

Scientific articles indexed in the Web of Science (WoS, Clarivate Analytics, <https://access.clarivate.com>) and Scopus (Elsevier, <https://www.scopus.com>) databases were retrieved through the Brazilian platform *Periódicos Capes* (<https://www.periodicos.capes.gov.br>). The search terms were “Mercury,” “Amazon,” and “fish,” searched as the main topic across “all fields” using the Boolean operator “AND”: ((ALL= mercury) AND (ALL= amazon) AND (ALL= fish)). Thus, we gathered studies ranging from the date of the earliest publication found during the search up to the year 2024.

Screening and Inclusion Criteria

The screening of articles followed the PRISMA protocol (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) (Moher et al. 2009). We excluded duplicates, reviews, and studies that did not directly address Amazonian fish or provide the scientific name of the species. Only studies reporting mean concentrations of Hg in fish muscle with quantitative data and species identified by their scientific names were included (Figure 1).

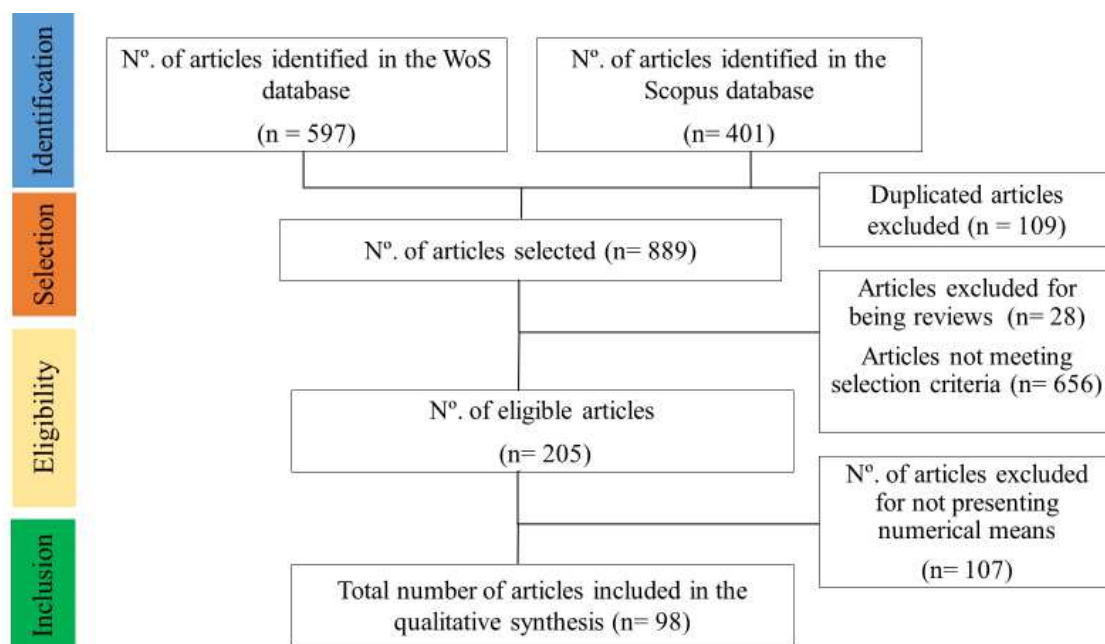


Fig. 1 Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram of the selection process for studies included in the scientometric analysis, adapted from Moher et al. (2009)

Selection of Scientometric Indicators

We included the following scientometric indicators in this study: (i) year of publication, (ii) chemical form of mercury analyzed (Hg, THg, IHg, MeHg), (iii) country and state of sampling, (iv) feeding habits of the species, and (v) species with values above the World Health Organization (WHO) thresholds. Feeding classifications were standardized according to Ferreira et al. (2007), Santos et al. (2009) and FishBase. The Hg and THg records were consolidated into a single category, designated as THg, to ensure greater consistency in comparative analyses and reduce ambiguity in data interpretation.

Data analysis

Mercury concentrations were expressed in mg/kg. To evaluate the effects of country and dietary habits on mercury concentrations, a two-way analysis of variance (two-way ANOVA) was performed, considering country and dietary habits as fixed factors, as well as the interaction between these factors. Additionally, descriptive statistics (mean, median, minimum and maximum values) were used to characterize mercury concentrations across species, dietary habits, and countries. The distribution of mercury concentrations in Amazonian fish was categorized by country of occurrence, feeding habit, chemical form of mercury (IHg, MeHg, and THg), and was represented by heat maps. For each combination of species, country, and chemical form, the median concentration was calculated - a measure of central tendency chosen for its robustness against extreme values and the skewed distributions frequently observed in environmental data. Hg concentrations were represented by a continuous logarithmic ($\log_{10}$) color scale to allow for the simultaneous visualization of values distributed across different orders of magnitude. The species with the highest number of records were selected and ordered according to their median mercury concentrations for the generation of heatmaps. Due to the predominance of records from Brazil and the high number of species associated with that country, the results were presented in two independent

heatmaps: (i) containing records from Amazonian countries excluding Brazil (Bolivia, Colombia, Ecuador, French Guiana, Peru, and Suriname), and (ii) containing exclusively records from Brazil. This strategy was adopted to enhance the figure's readability and allow for a better visualization of mercury concentration distribution patterns across species, feeding habits, and geographic regions.

Peixes com maiores concentrações de mercúrio foram identificados e selecionados para calcular a proporção de espécies que excederam os limites de referência estabelecidos para consumo humano. Todas as análises foram realizadas no ambiente R (Core Team 2025), com uso do RStudio para geração gráfica e modelagem estatística, utilizando os pacotes “dplyr, ggplot2, ggpubr, broom, tidyr, readxl, tidyverse, rnatualearth, rnatualearthdata”.

RESULTS

Scientific output regarding mercury in Amazonian fish showed an upward trend between 1988 and 2024, totaling 98 analyzed publications (Table SI). During the initial period of the series (late 1980s to early 2000s), scientific activity was characterized by a low frequency of annual publications and an absence of records for the years 1990, 1992, 1993, 1996, 2002, and 2003. From the 2000s onwards, a gradual increase in output is evident, with greater publication regularity in subsequent years. In more recent years -particularly the last decade - a higher concentration of studies per year is observed (2018 and 2021, both with $n=7$) (Figure 2). Brazil accounted for 80% of the studies ($n = 79$), followed by Bolivia ($n = 5$), Colombia and French Guiana (a French territory) ($n = 4$); the lowest numbers of publications were observed for Peru ($n = 3$), Suriname ($n = 2$), and Ecuador ($n = 1$).

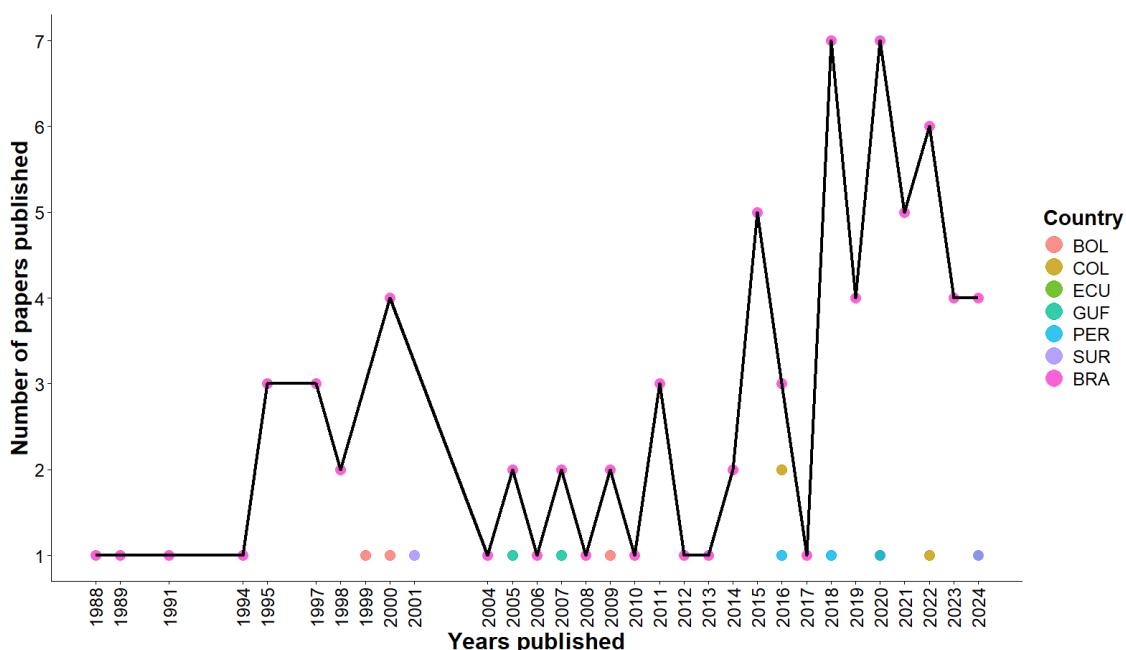


Fig. 2 Temporal distribution of published articles on mercury in fish from the Amazon (1988–2024). Brazil produced 80% of publications analyzed in this review (highlighted by the continuous line). BOL - Bolivia; BRA- Brasil; COL - Colombia; ECU - Ecuador; GUF - Guiana Francesa; PER - Peru; SUR - Suriname

Studies on Amazonian fish evaluated the following chemical forms: Hg, THg, IHg (inorganic forms), and MeHg (organic form). Temporal analysis revealed a predominance of the term Hg between 1988 and 2005. From the year 2000 onwards, the use of the term THg increased, accounting for 91.8% (n = 90) of the studies that analyzed only a single chemical form of mercury. A small number of publications (6.1%; n = 6) simultaneously evaluated two chemical forms (MeHg and THg), while only 2% of the studies (n = 2) conducted analyses covering three chemical forms of mercury (IHg, MeHg and THg).

The THg form was the most frequently cited; meanwhile, methylmercury - though less commonly reported - was primarily associated with locations recording higher THg concentrations, particularly within Brazilian territory. Most recorded mercury concentrations fall within the 0.6–1 mg/kg range, distributed across Brazil, Peru, Bolivia, Colombia, Ecuador, Suriname, and French Guiana. Higher values (>1.6 mg/kg) were registered more frequently in the Brazilian states of Acre (AC), Amazonas (AM), Amapá (AP), Mato Grosso (MT), Pará (PA), Rondônia (RO), and Roraima (RR), as well as in a few isolated locations within French territory (Figure 3).

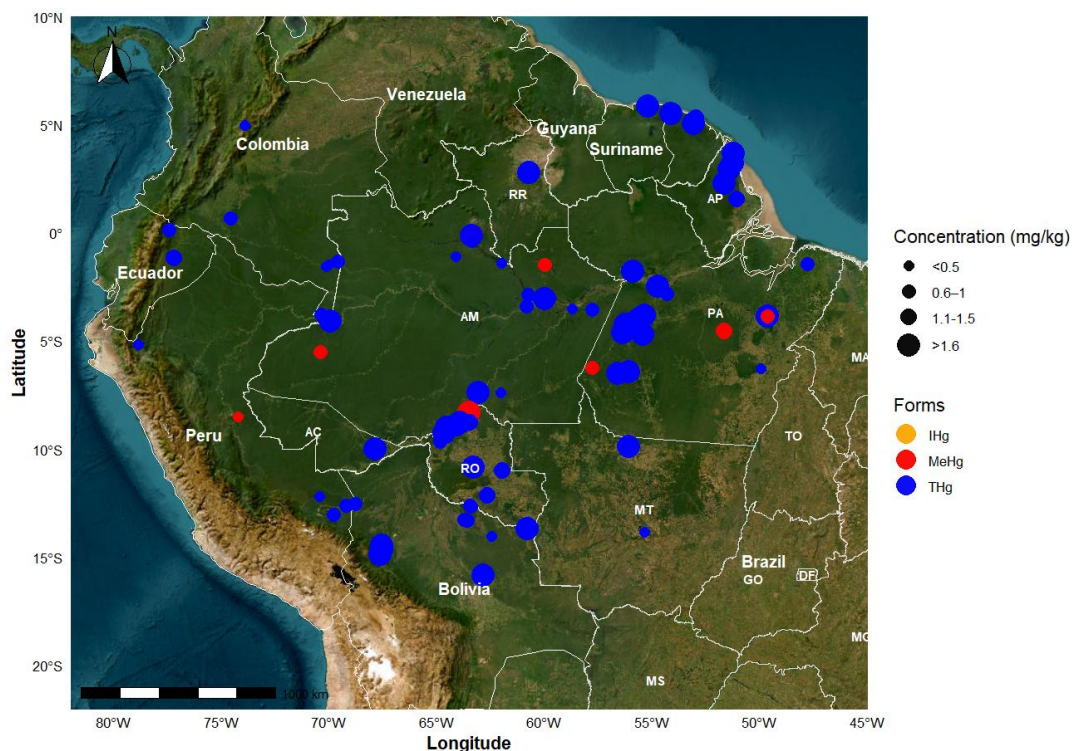


Fig. 3 Mean concentrations of different mercury forms (mg/kg) in fish muscle across Amazonian countries. Colors indicate each chemical form, and circle size represents the magnitude of the concentration

The distribution of median mercury concentrations in Amazonian fish analyzed in Bolivia, Colombia, Ecuador, French Guiana, Peru, and Suriname covered two chemical forms: methylmercury and total mercury. Regarding MeHg, the two most frequently cited species were *Calophysus macropterus* in French Guiana and *Prochilodus nigricans* in Peru; however, their median values did not exceed 0.30 mg/kg.

Regarding THg, the carnivorous species *Plagioscion squamosissimus* showed one of the highest medians, reaching values close to 3.0 mg/kg in French Guiana, 1.5 mg/kg in Colombia, and values near 0.3 mg/kg in Peru and Suriname. In Bolivia, *Pseudoplatystoma fasciatus* showed a median close to 1.2 mg/kg, and approximately 0.2 mg/kg in Suriname. *Hoplias malabaricus* showed values ranging from 0.03 mg/kg in Ecuador to 0.4 mg/kg in Bolivia and Suriname. In contrast, species belonging to the herbivorous, omnivorous, and detritivorous groups showed lower concentrations in most of the countries analyzed. In Peru and Colombia, the median concentrations for these categories were below 0.10 mg/kg (Figure 4).

In Brazil, median mercury concentrations varied by approximately four orders of magnitude, from 10^{-4} to 10^0 mg/kg. For THg, carnivorous species showed medians predominantly between 0.3 and 1.0 mg/kg. *Pelona flavipinnis*, *Brachyplatystoma flavicans*, *Acestrorhynchus falcistrotris* and *Brachyplatystoma filamentosum* exhibited medians close to 0.8 mg/kg. Among omnivores, *Triportheus albus* showed a median close to 0.6 mg/kg, while *Colossoma macropomum* showed approximately 0.1 mg/kg.

For MeHg, *P. flavipinnis* showed a median close to 3.0 mg/kg, representing one of the highest values observed in Brazil. *Brachyplatystoma flavicans* showed approximately 2.5 mg/kg, while *Hoplias aimara* and *A. falcistrotris* showed values close to 1.0 mg/kg. Among the piscivores, *Pelona castelnaeana* showed a median close to 0.3 mg/kg.

Regarding THg, *Pygocentrus nattereri*, *P. castelnaeana*, *A. falcistrotris*, *Pseudoplatystoma sp.* and *P. squamosissimus* stood out, with medians ranging from 1.0 to 3.0 mg/kg. Among the omnivores, concentration variations were observed between species: *Leporinus fasciatus* had a median close to 1.0 mg/kg, whereas *Leporinus friderici* ranged between 0.1 and 0.3 mg/kg. *Hemiodus unimaculatus* showed the lowest value recorded in the entire dataset, close to 0.0001 mg/kg. *Colossoma macropomum* had a median close to 0.1 mg/kg, while *Pimelodus blochii* showed approximately 0.3 mg/kg.

Detritivorous species such as *P. nigricans* and *Curimata inornata* showed medians between 0.1 and 0.5 mg/kg. Among herbivores, *Mylossoma duriventre* showed medians close to 0.05 mg/kg, while *Leporinus friderici* showed values close to 0.2 mg/kg (Figure 5).

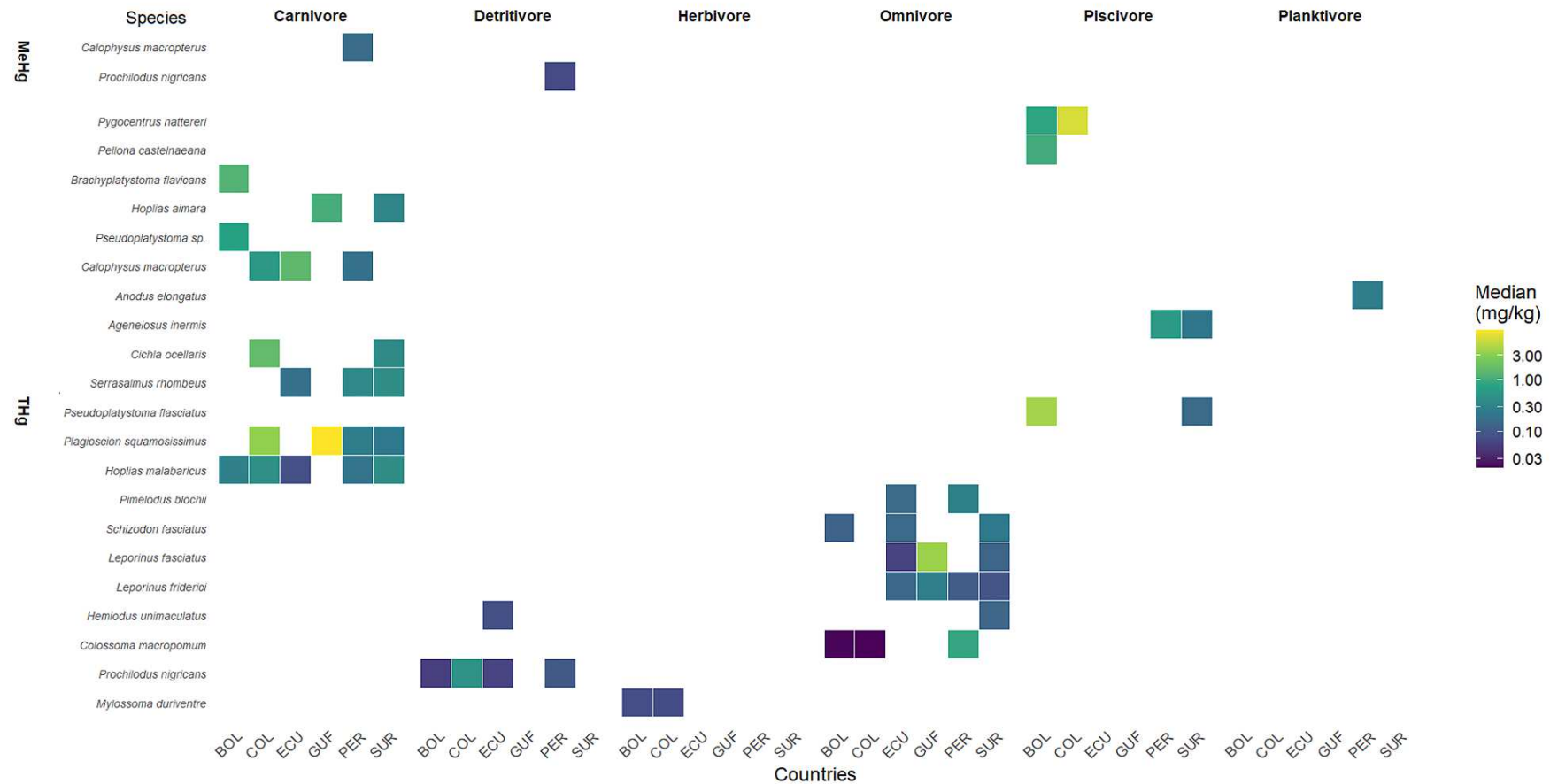


Fig. 4 Median concentrations of total mercury and methylmercury in fish species from six Amazonian countries: Bolivia (BOL), Colombia (COL), Ecuador (ECU), French Guiana (GUF), Peru (PER), and Suriname (SUR). The vertical axis (Y) indicates the species analyzed, while the horizontal axis (X) groups the species from each country by feeding habit: Carnivore, Detritivore, Herbivore, Omnivore, Piscivore, and Planktivore. The color scale represents the median concentration in mg/kg, ranging from 0.03 (dark blue) to 3.0 (yellow) on a logarithmic scale. The data are organized by trophic guild (top axis) and by species (vertical axis). Data on inorganic mercury (IHg) were unavailable for regions outside Brazil



Fig. 5 Median concentrations of total mercury, methylmercury, and inorganic mercury in fish species collected in Brazil, categorized by feeding habit. The vertical axis (Y) indicates the species analyzed, while the horizontal axis (X) groups the species by feeding habit: Carnivore, Detritivore, Herbivore, Omnivore, Piscivore, and Planktivore. The color scale represents the median concentration in mg/kg, ranging from 10^{-4} (purple) to 1.0 (yellow) on a logarithmic scale. The data are organized by trophic guild (top axis) and by species (vertical axis)

Mercury contamination in Amazonian fish has reached critical levels across several countries, with nearly half of the analyzed species exceeding the safety limits established by the World Health Organization (WHO). Of the 436 species identified, 218 (48.23%) showed concentrations exceeding 0.5 mg/kg across all evaluated countries, and of these, 144 species surpassed the 1.0 mg/kg limit (Table SII, Figure 6). Values exceeding 1.6 mg/kg occur most frequently in Brazilian states; however, outside Brazilian territory, median values of 3.0 mg/kg were recorded in French Guiana and 1.5 mg/kg in Colombia, with ranges of 0.6 to 1.2 mg/kg observed in Bolivia, Peru, Ecuador, and Suriname.

Most records regarding mercury in Amazonian fish are concentrated in Brazil, which accounted for the majority of observations included in the review. Furthermore, total mercury represents the largest share of the flows across countries and dietary habits. Among trophic guilds, carnivores showed the highest proportion of records (38.9%), followed by omnivores (24.8%), detritivores (15.4%), and piscivores (14.8%). This pattern observed in the Sankey diagram is consistent with the heatmap results, which show not only a greater number of species evaluated among carnivores and piscivores but also higher median concentrations of Hg and MeHg in these groups.

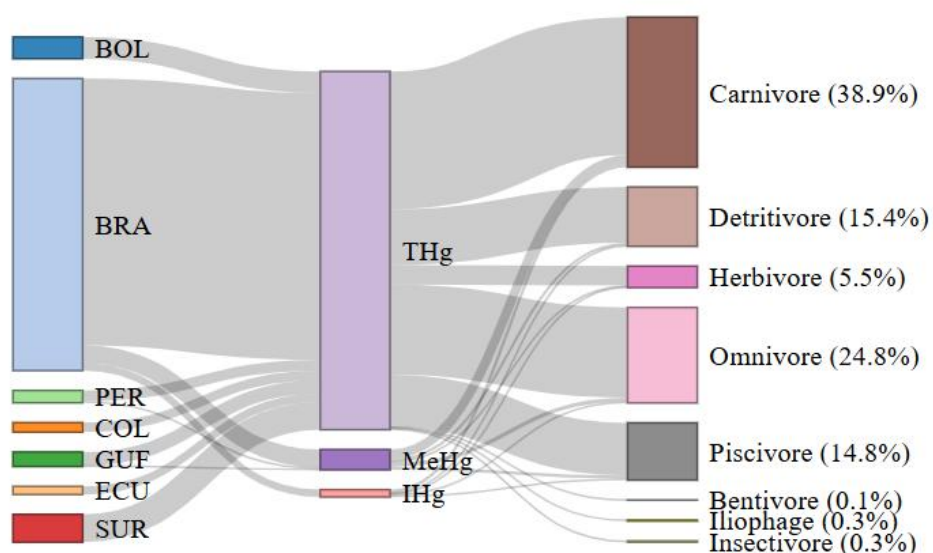


Fig. 6 Sankey diagram showing the flow between countries, feeding habits, and mercury chemical forms, between non-carnivorous and carnivorous. Values in parentheses indicate the percentage of species studied for each chemical form

DISCUSSION

Chemical forms of mercury in Amazonian fish

The results of this study showed that scientific production on mercury in Amazonian fish is predominantly focused on the determination of total mercury, while a small number of studies simultaneously evaluated other chemical forms, especially methylmercury, a topic on which there were fewer than 10 studies throughout the analyzed period. This predominance was also observed temporally, with the use of the term THg becoming more frequent from the year 2000 onwards. Studies involving the quantification of THg represented more than 90% of the studies that investigated only one chemical form of mercury.

The development and refinement of analytical techniques have contributed to expanding the characterization of Hg in Amazonian fish, enabling not only the determination of THg but also the identification and quantification of different chemical species. The incorporation of extraction and separation procedures combined with more sensitive instrumental techniques has allowed for the expanded determination of MeHg and inorganic Hg, providing information that cannot be obtained through THg analysis alone. The use of different analytical approaches, such as direct mercury analyzers and atomic absorption spectrometry techniques, for the determination of THg and MeHg in Amazonian fish reflects improvements in sample preparation and analysis methods (Rodríguez Martín-Doimeadios et al., 2014; Pierezan et al., 2024).

The determination of THg provides useful information as an indicator of exposure but may not adequately represent the dynamics of different Hg chemical species in organisms, given that MeHg and inorganic Hg can exhibit distinct accumulation patterns depending on the species, trophic level, and hydrological period (Paiva et al., 2022). These authors found that THg, MeHg, and inorganic Hg concentrations exhibited seasonal variations in six fish species from Lake Catalão (Amazonas, Brazil) (Paiva et al., 2022).

Although the determination of THg allows for the estimation of the overall contaminant load in fish tissues, the specific determination of MeHg becomes particularly relevant in studies aimed at assessing human exposure to Hg (Souza-Araújo et al., 2016; Mussý et al., 2023). Studies conducted in various Amazonian river basins demonstrate that MeHg constitutes the primary fraction of mercury

accumulated in fish muscle tissue. Fish from the Bacajá River, a tributary of the Xingu River (496 individuals belonging to 22 species), showed that approximately 96% of the mercury present in the fish was in methylated form (Souza-Araujo et al., 2016). In the Madeira River basin, 3,182 individuals representing 84 fish species were evaluated, and MeHg:THg ratios ranging from 70% to 92% were recorded, with variation associated with trophic level (Bastos et al., 2015). These results demonstrate that the predominance of MeHg in Amazonian fish is significant, exceeding 70%, and shows a strong relationship with the species' positions in food webs and the environmental conditions controlling its production and transfer.

The dynamics of Hg speciation occur across different compartments of Amazonian ecosystems. In the Tapajós River basin, THg and MeHg levels were assessed in water, sediment, particulate matter, plankton, and fish, demonstrating that the distribution of these chemical forms is linked to the processes of Hg transport, transformation, and transfer among environmental compartments (Lino et al., 2019).

The simultaneous occurrence of ecological biomagnification processes and human exposure to MeHg in the muscle tissue of Amazonian fish has significant implications for populations that rely on fish as a food source, such as riverine and indigenous communities. Fish intended for human consumption can contain significant levels of Hg, particularly among species at higher trophic levels (Lino et al., 2019; Hacon et al., 2020; Vasconcellos et al., 2022). This highlights the importance of increasing biomonitoring studies to generate a robust dataset on mercury (Hg) levels in fish, enabling risk assessments that incorporate regional consumption data reflecting the actual fish consumption patterns of isolated Amazonian populations, given their high reliance on fish. Thus, it is important to expand studies that combine the quantification of THg and MeHg with the integration of data on trophic level and consumption. Studies addressing environmental characteristics and transfer between compartments are also highly relevant for aiding the understanding of bioaccumulation and biomagnification processes (Lino et al., 2019; Bastos et al., 2015; Mussu et al., 2023) in different regions of the Amazon basin.

Environmental influences on the transformation and dispersion of mercury in the Amazon

The interaction among hydrological, biogeochemical, and ecological factors determines the conversion of inorganic mercury into methylmercury, its most toxic form, facilitating its incorporation into aquatic food chains (Driscoll et al., 2013). These processes are strongly influenced by natural processes characteristic of the Amazon, which are quite distinctive and vary markedly across different river basins.

The flood pulse is considered the primary structuring factor of Amazonian aquatic ecosystems and, as such, warrants special attention among natural processes. The alternation between high- and low-water periods drives significant fluctuations in connectivity among rivers, lakes, and floodplain forests, altering the dynamics of sediments, organic matter, and nutrients (Junk et al., 2011; Forsberg et al., 2017). These changes favor the mobilization of Hg previously accumulated in soil and sediments, increasing its availability for biogeochemical transformation (Kasper et al., 2017; Paiva et al., 2022).

The extensive floodplain areas of the Amazon create environmental conditions favorable to the activity of methylating microorganisms, primarily sulfate- and iron-reducing bacteria, which are responsible for converting inorganic mercury into methylmercury (Caballero-Gallardo, Palomares-Bolaños, Olivero-Verbel, 2022). This process is intensified in environments with high availability of organic matter, low dissolved oxygen levels, acidic pH, and high concentrations of dissolved organic carbon, characteristics frequently observed in floodplain areas and blackwater rivers from the Amazon basin (Belger & Forsberg, 2006; Brito et al., 2017; Crespo-Lopez et al., 2021; 2023). High percentages of flood-prone areas, low pH levels, and high concentrations of dissolved organic carbon have been reported as important factors contributing to Hg bioaccumulation and biomagnification in Amazonian fish (Belger & Forsberg, 2006).

The occurrence of thermal stratification and the reduction of dissolved oxygen concentrations in the deeper layers of Amazonian lakes can favor mercury methylation processes (Kasper et al., 2014) and its initial incorporation by planktonic organisms (Brito et al., 2017). This demonstrates that lacustrine environments can exhibit a greater potential for Hg transfer and biomagnification

along food webs (Almeida et al., 2014; Kasper et al., 2017; Paiva et al., 2022). Data obtained in the Madeira River basin demonstrated that Hg biomagnification factors in fish tend to be higher in lakes than in rivers (Mussy et al., 2023), reinforcing the importance of these environments in Hg dynamics and transfer within aquatic ecosystems.

Mercury dynamics in the Amazon are multifactorial, depending on the interaction between soil characteristics, the flood pulse, the physicochemical conditions of water and sediments, and microbial activity, mobility, and availability for incorporation into food webs. An integrated assessment of these mechanisms is essential to explain the spatial and temporal heterogeneity of Hg concentrations in Amazonian fish, given that these mechanisms are strongly modulated by the flood pulse and rainfall - which define seasonality - and can vary across different regions (sub-basins) due to the wide range of physicochemical conditions found in the Amazon.

Anthropic impacts on the origin, transformation and dispersion of mercury in the Amazon

Despite the fact that Amazonian soils constitute important natural reservoirs of mercury (Roulet et al., 1998; Fadini; Jardim, 2001), the majority of the environmental burden has been attributed to anthropogenic sources (Lechler et al., 2000; Wasserman, Hacon, Wasserman, 2003). The Artisanal and Small-Scale Gold Mining (ASGM) is identified as the anthropogenic activity that contributes most to mercury emissions in the Amazon (UNEP, 2013; Fischer et al., 2023). This activity has been growing since the 1980s, with a notable 55% increase in artisanal mining areas in the Amazon between 2019 and 2022 (Ferreira Neto et al., 2024).

In addition to the direct use of metallic mercury in the gold extraction process (UNEP, 2018), there are profound alterations to the landscape that ultimately contribute to the contamination of aquatic and terrestrial environments (Esdaile & Chalker, 2018; UNEP, 2018). The Hg used during gold processing can be released into the environment through volatilization during the burning of the amalgam and through the deposition and transport of contaminated waste, reaching soils, sediments, and water bodies (Teixeira et al., 2021; Fritz et al., 2024). Deforestation, the removal of vegetation cover, intense soil disturbance,

and the excavation of alluvial deposits increase erosion and the transfer of large volumes of particles into aquatic systems (Martinez et al., 2018). In the Tapajós River, it has been demonstrated that Hg associated with suspended sediments constitutes a major transport pathway and that the physical mobilization of floodplain soils and Hg-rich sediments, intensified by excavation and dredging operations, can represent the primary source of river-transported Hg, surpassing, under certain conditions, the contribution resulting from direct Hg loss during amalgamation (Telmer et al., 2006).

In addition to soil disturbance, the formation of flooded pits and waterlogged areas following extraction significantly alters local hydrological, sedimentary, and biogeochemical conditions (Obrist et al., 2018). In the Amazon, tailings consisting of water and sediments can be directed into small ponds and depressions formed by mining activity, creating new environments for the deposition and retention of contaminated particles (Lourenço et al., 2026). The results of this review show that the majority of the studies were conducted in Brazilian areas historically influenced by gold mining, especially in the Madeira River basins (Bastos et al., 2008, 2015, 2020; Reuther, 1994) Tapajós (Roulet et al., 1998, 2000; Berzas Nevado et al., 2010), Negro (Magarelli, Fostier, 2005; Belger, Forsberg, 2006) and Uraricoera (Corrêa, 2024; Galvis, 2018). However, mercury contamination is not limited to regions directly impacted by gold mining. Recent studies demonstrate that the atmospheric transport of elemental mercury allows for its dispersal over hundreds or thousands of kilometers prior to deposition, reaching regions far from emission sources and contributing to the contamination of ecosystems considered to be preserved (Obrist et al., 2018; UNEP, 2018). Therefore, some of the mercury being detected originates in other regions of the planet and reaches the Amazon via the global Hg cycle (Selin et al., 2007; Obrist et al., 2018).

Deforestation constitutes a significant mechanism for the remobilization of mercury naturally accumulated in Amazonian soils. Studies conducted in Guyana and Peru observed that the removal of vegetation cover increases mercury leaching and alters soil redox conditions, promoting environments favorable to methylation (Gallay et al., 2018; Diringer et al., 2019; Mestanza-Ramón et al., 2022). This occurs because deforestation and agricultural land use promote the loss of fine particles enriched with Hg and their transfer to aquatic systems,

497 facilitating the export of Hg from soils to aquatic environments (Roulet et al., 1998;
498 Farella et al., 2006). Deforestation acts as a secondary source of Hg, capable of
499 increasing its mobilization even in regions where there is no significant local
500 anthropogenic source of metallic Hg. Furthermore, with the loss of vegetation
501 cover, the soil tends to become more alkaline, reducing the capacity to retain
502 mercury in organic complexes and promoting its mobility and dispersion (Farella
503 et al., 2006). The conversion of forest areas to pasture was associated with a
504 reduction in soil Hg stocks, indicating their loss and redistribution following the
505 change in land use (Lacerda, Souza, Ribeiro, 2004; Almeida et al., 2005),
506 facilitating transfer to other environmental compartments.

507 Deforestation also alters the soil-atmosphere interface, as in deforested areas,
508 the rise in soil temperature and changes in physicochemical conditions can
509 promote Hg volatilization and its transfer to the atmosphere (Almeida et al., 2009).
510 Thus, deforestation can simultaneously contribute to Hg mobilization via surface
511 runoff and to increased atmospheric emissions, creating mechanisms for the
512 regional redistribution of the element.

513 Biomass burning constitutes another important mechanism for Hg remobilization.
514 During combustion, mercury accumulated in vegetation and soil organic matter
515 is volatilized, returning to the atmosphere and potentially undergoing
516 redistribution. Scenarios involving increased deforestation and a higher
517 frequency of forest fires are playing an increasingly significant role in mercury
518 cycling between terrestrial and atmospheric compartments (Friedli et al., 2009;
519 Obrist et al., 2018).

520 Another activity capable of altering mercury dynamics is the construction of
521 hydroelectric reservoirs. In the areas of the Balbina and Tucuruí hydroelectric
522 plants in the Brazilian Amazon (in the states of Amazonas and Pará,
523 respectively), vast tracts of forest were flooded, resulting in the significant release
524 of organic carbon into the reservoirs and contributing to the establishment of ideal
525 conditions for the microbial methylation of mercury (Forsberg et al., 2017). The
526 influence of the hydroelectric plant can extend beyond the flooded area and have
527 consequences downstream of the dam. The bioaccumulation of MeHg in fish
528 (*Cichla* spp.) was greater in areas up to 250 km downstream of the Balbina Dam
529 than in the reservoir itself, demonstrating that a reservoir's influence on Hg

dynamics is not necessarily limited to the directly flooded area but can extend to downstream riverine environments (Kasper et al., 2014).

Although the majority of studies identified in this review focus on the Brazilian Amazon, evidence from other Amazonian countries demonstrates that the impacts of mining and land-use changes extend across national borders (Selin et al., 2007; Obrist et al., 2018; Diringer et al., 2019). The basin's high hydrological and atmospheric connectivity facilitates the transfer of Hg between regions, while the expansion of mining activities in various parts of the Amazon could increase the exposure of ecosystems and populations that rely heavily on aquatic resources for their daily diet (Organização do Tratado de Cooperação Amazônica - OTCA, 2024; UNEP, 2018). In this context, regional monitoring must simultaneously consider direct Hg emissions, the mobilization of natural pools present in soils, atmospheric deposition, fluvial transport, and the biogeochemical processes that determine its bioavailability.

Taken together, the available evidence demonstrates that the anthropogenic dynamics of Hg in the Amazon cannot be explained by a single source. Although gold mining constitutes an important direct source of Hg, deforestation, soil erosion, wildfires, and the presence and construction of new reservoirs are highly relevant because they modify the flows, mobility, and biogeochemistry of Hg, potentially remobilizing stocks from natural or anthropogenic sources and favoring its transfer between environmental compartments. Therefore, strategies to reduce mercury contamination in the Amazon must combine the control of mining-related emissions with forest conservation policies - including the reduction of deforestation and soil degradation, fire prevention, and the monitoring of impacts from large hydroelectric projects - as well as the promotion of alternative sources of electricity, such as solar energy. An integrated approach is necessary to understand and reduce Hg emissions and mobilization in Amazonian ecosystems and their negative effects on biota and human populations, especially those that are more isolated and highly dependent on fish.

Feeding Habits and Mercury Bioaccumulation

The highest mercury levels were recorded in piscivorous and carnivorous fish, followed by omnivores, herbivores, detritivores, and planktivores. This pattern confirms the occurrence of Hg biomagnification along the food chain, one of the

ecological processes widely associated with Hg in aquatic ecosystems (Bloom, 1992; Lavoie et al., 20213; Hacon et al, 2020). The high concentration of mercury in predatory fish is linked to high assimilation and retention efficiency within the organisms and the consequent difficulty in eliminating this metal. A significant fraction of the ingested Hg is present as MeHg, a compound that exhibits a high affinity for muscle proteins and a strong potential for transfer between trophic levels (Bloom, 1992; Kehrig; Malm; Moreira, 1998; Driscoll et al., 2013).

Although trophic position is identified as the primary factor associated with the higher concentrations observed in this region, other ecological factors can influence mercury bioaccumulation. Species belonging to the same feeding group may exhibit distinct concentrations depending on habitat characteristics, food availability, migratory patterns, age, and body size, as well as ontogenetic dietary shifts (Power et al., 2002; Kasper et al., 2007; Lavoie et al., 2013). Thus, trophic classification alone does not explain the full range of variability that may occur among the analyzed species.

The flood pulse, characteristic of the Amazon region, regulates connectivity between aquatic environments and resource availability, altering food web structures and, consequently, patterns of mercury exposure throughout the year (Kasper et al., 2007; Junk et al., 2011). These natural seasonal changes influence the exposure of organisms to Hg and can modify bioaccumulation rates between high-water and low-water periods (Brito et al., 2017; Azevedo et al., 2020; Paiva et al., 2022). Physicochemical water parameters - such as pH, turbidity, dissolved organic matter, and redox conditions - modulate mercury methylation processes and its bioavailability to aquatic organisms (Barbosa et al., 2003; Belger & Forsberg, 2006; Driscoll et al., 2013; Bastos et al., 2020; Bravo & Cosio, 2020). Connectivity among rivers, lakes, floodplains, and seasonally flooded forests alters both the physicochemical conditions of the water and the availability and composition of food resources (Bastos et al., 2007; Hurd et al., 2016). Hg concentrations in detritivorous, herbivorous, and omnivorous fish from the Madeira River varied across different hydrological periods, indicating that the flood cycle influences exposure even in species at relatively low trophic levels (Azevedo et al., 2020). The influence of seasonality and trophic position on Hg bioaccumulation has also been observed in fish from Lake Catalão (Amazonas, Brazil). It has been shown that biomagnification is more pronounced during the

falling water season and decreases in high- and rising-water seasons (Paiva et al., 2022). In the Madeira River, positive correlations were found between body length and THg concentration in species belonging to different feeding guilds, including piscivorous, carnivorous, planktivorous, detritivorous, and herbivorous fish (Bastos et al., 2015). High trophic magnification factors were observed in fish from the Juruá River (Amazonas, Brazil), with values of 10.1 during the dry season and 5.4 during the receding-water period, both exceeding the estimated global average for freshwater environments (Nyholt et al., 2022). The combination of food web structure, hydrological dynamics, and Hg availability can produce high rates of biomagnification, even in tropical environments lacking significant anthropogenic sources (Nyholt et al., 2022).

Although studies show that the relationship between Hg and trophic position can be modified throughout the hydrological cycle, individual characteristics also contribute to the observed variability. Species classified within the same guild may exhibit different exposure levels depending on specific diet composition and differential habitat use (Belger & Fosberg, 2006; Bastos et al., 2007; Souza-Araújo et al., 2016).

Food security and implications for human health

The identification of Amazonian fish species with mercury concentrations above the limits established by the WHO and Brazilian legislation reveals a concerning scenario for the food security of human populations in the region. The highest mercury concentrations have been recorded predominantly in predatory species at higher trophic levels, many of which are of high importance for fishing and food sources for Amazonian populations, such as the large catfish of the genera *Brachyplatystoma* spp. and *Pseudoplatystoma* spp. and the peacock bass (*Cichla* spp.) (Dórea et al., 2007; Bastos et al., 2008; Vasconcellos et al., 2021). High concentrations of total mercury (THg) were also reported in carnivorous and piscivorous species marketed in the Upper Solimões region, including *Cichla ocellaris* and *Pseudoplatystoma fasciatum* (Silva & Lima, 2020). In these species, mean THg concentrations exceeding the 1.0 mg/kg reference limit applicable to predatory fish were observed, indicating a potential risk associated with

consumption, particularly in situations of high intake frequency (Silva & Lima, 2020).

Predatory fish species generally exhibit higher Hg concentrations; however, human health risk assessments should not be limited to these species. Omnivorous, detritivorous, and herbivorous species can also constitute a significant portion of the diet of Amazonian populations and, in certain regions, may be consumed frequently (Dórea, Barbosa, 2007; Santos, Ferreira, Zuanon, 2009). In Suriname, the tambaqui (*C. macropomum*) showed a median methylmercury (MeHg) level of 0.86 mg/kg, whereas in Peru, the curimatã (*P. nigricans*) showed a median of 0.30 mg/kg. These results demonstrate that human exposure to mercury in the Amazon is not determined solely by the trophic position of the consumed species, but rather by the interaction between fish contamination levels, their importance in the local diet, the quantity ingested, and the frequency of consumption (Martín-Doimeadios et al., 2014; Hacon et al., 2020).

Even when frequently consumed species have relatively low concentrations, high fish intake can result in significant dietary exposure to Hg (Passos et al., 2008). This aspect is particularly relevant for riverine and indigenous populations in the Amazon, for whom fish is a primary source of animal protein and consumption can exceed 200 g per person per day, a figure substantially higher than the global average (Dórea, 2003; FAO, 2024). Although fish is an important source of high-quality protein, omega-3 fatty acids, vitamins, and other essential nutrients, frequent consumption of species with high mercury concentrations can increase the risk of adverse effects, including neurotoxic, cardiovascular, and developmental changes, raising particular concern for pregnant women, fetuses, and children, who are more susceptible to the harmful effects of Hg (WHO, 2021; Crespo-Lopez et al., 2021).

The results obtained in this study reinforce that risk assessment and management strategies must take regional consumption patterns into account. Frequency of intake, quantity consumed, fishing seasonality, and the composition of consumed and available species vary across different regions of the Amazon and directly influence the magnitude of human exposure to mercury (Passos & Mergler, 2008; Isaac & Almeida, 2011; Hacon et al., 2020). Continuing studies that demonstrate regional patterns of bioaccumulation and the periods of the year

when bioaccumulation is most critical is essential for implementing management measures and providing guidance to Indigenous and riverine populations regarding fish consumption. A more comprehensive approach must integrate information on the dietary habits of local populations, the concentrations of different chemical forms of Hg, and the presence of nutrients capable of modifying its bioavailability and toxicity.

The Hg:Se ratio is a relevant aspect for understanding the effects associated with Hg exposure, given that Se is a micronutrient identified as a potential modulator of its toxicity (Lemire et al., 2006). The Se:Hg ratio was evaluated in fish from the Tapajós River (Pará, Brazil); most carnivorous fish exhibited an Hg:Se ratio > 1 , indicating reduced protection, whereas non-carnivorous fish showed an excess of Se relative to Hg, suggesting a protective effect of Se in these species (Lino et al., 2018).

In the Colombian Amazon, Hg, Cd, and Se levels were evaluated in fish and the population of Puerto Nariño. The study showed higher Hg concentrations in species at higher trophic levels, such as *Rhaphiodon vulpinus* (880 ± 130 ng/g) and *Pseudoplatystoma tigrinum* (920 ± 87 ng/g), associated with lower Se molar ratios and higher risk indices for consumers (Alcalá-Orozco, Caballero-Gallardo & Olivero-Verbel, 2020). Furthermore, the authors found mean total mercury (THg) concentrations of $5.31 \mu\text{g/g}$ in hair and $13.7 \mu\text{g/L}$ in blood among the participants, with 93% exhibiting blood concentrations exceeding $5 \mu\text{g/L}$. Fish consumption was significantly associated with Hg concentrations in hair and blood, highlighting the importance of diet as an exposure pathway in this population (Alcalá-Orozco, Caballero-Gallardo & Olivero-Verbel, 2020).

Experimental and epidemiological evidence suggests that Se may attenuate certain effects associated with Hg exposure and can also be obtained through dietary intake (Lemire et al. 2006; Ralston & Raymond, 2018; Sørmo et al. 2011). In the Amazon, this micronutrient is present in several foods commonly consumed by riverine populations, including nuts, poultry, meat, and eggs, with Brazil nuts (*Bertholletia excelsa*) standing out as a particularly rich source of Se (Lemire et al. 2010).

However, the presence of Se in the diet or in fish itself should not, in isolation, be interpreted as evidence of protection against the adverse effects of mercury. The relationship between Se and Hg depends on several factors, including their

concentrations, chemical forms, bioavailability, molar ratio, dietary patterns, and characteristics of exposure. Thus, although Se intake may contribute to modulating certain effects associated with Hg exposure, the magnitude and relevance of this effect in Amazonian human populations remain insufficiently understood. Further studies are therefore needed to elucidate Hg–Se interactions under real-world exposure conditions and to improve risk assessment and food safety criteria applicable to Amazonian populations.

CONCLUSIONS

This study provides a comprehensive overview of 36 years of research on mercury in the Amazon. Scientific production on mercury in fish from the Amazon has grown substantially over the last five years, consolidating the issue as central to discussions on public health, environment and food security.

The mapping of mercury distribution in the Amazon is heterogeneous, with most studies and evidence of contamination concentrated in Brazil, the low number and absence of studies in some areas probably underestimate mercury concentrations in under-sampled countries from the Amazon. International cooperation and integrated research monitoring is needed to assess and mitigate risks to both human and environmental health.

Artisanal and small-scale gold mining represent the primary contamination vector across Amazon, but agricultural expansion, deforestation, hydroelectric dam construction, biomass burning, disposal of mercury-containing waste, and waste incineration, combined with insufficient enforcement, exacerbate the problem.

The low number of studies addressing methylmercury highlights the need to move beyond approaches focused solely on total mercury to obtain more accurate risk assessments for human and environmental health. The relationship between feeding habits and mercury concentrations confirmed trophic risk patterns: piscivorous and carnivorous fish tend to exhibit the highest Hg concentrations, yet some herbivorous, omnivorous, and detritivorous species from the Amazon also exceeded WHO thresholds for human consumption. These findings emphasize the vulnerability of communities that rely on fish as a primary food source and reinforce the need to use local consumption data in regional risk assessments.

Therefore, it is urgent to promote research grounded in a systems-based One Health framework, integrating ecology, toxicology, public health and the social sciences to address mercury pollution. Collaboration among scientific institutions, governments and local communities is essential to translate knowledge into concrete actions that protect both the environment and Amazonian human populations. This requires integrated local, regional and international public policies aligned with the UN Sustainable Development Goals and the Minamata Convention, together with stricter, effectively enforced monitoring of mining activities and mercury use to prevent the intensification of environmental contamination. Expanding international cooperation and strengthening support for research on mercury dynamics, biomonitoring, selenium–Hg interactions, risk assessment and the effectiveness of management strategies are likewise essential to safeguard human health and conserve Amazonian aquatic biodiversity.

Credit authorship contribution statement

Cristiane Oliveira de Jesus: Conceptualization, Data curation, Formal analysis, Writing – original draft, Visualization

Maiby Glorize da Silva Bandeira: Conceptualization, Formal analysis, Methodology, Writing – review and editing

Sandro Loris Aquino-Pereira: Conceptualization, Funding acquisition, Supervision, Writing – review and editing

Fabíola Xochilt Valdez Domingos-Moreira: Conceptualization, Funding acquisition, Supervision, Writing – review and editing

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Declaration of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary data

The following is the supplementary data to this article.

Data availability

Data will be made available upon request.

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