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Review Article

Systematic review of mercury contamination in aquatic organisms of Sepetiba Bay, RJ, Brazil

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ABSTRACT

Sepetiba Bay is an ecologically and economically significant lagoon for Rio de Janeiro, Brazil. However, the development of this region has been linked to numerous environmental contaminations, leading to the accumulation of trace metals across various ecosystems. Mercury is particularly concerned for public health due to its propensity to bioaccumulate and biomagnify in marine organisms, subsequently entering the human body through consuming contaminated fish. Six studies were identified, with their findings indicating that mercury concentrations in fish from Sepetiba Bay do not exceed the maximum limits set by national legislation (Brazilian Health Regulatory Agency) and the World Health Organization. This systematic review sought to compile research related to mercury contamination in fish from Sepetiba Bay between 2000 and 2024, following the PRISMA-P protocol. A total of six studies were selected, with an additional 27 articles included because of their relevance in understanding the feeding habits of fish, bringing the total to 33 articles. Our findings suggest that, despite the low risk to human consumption, there is a need for the development of public policies focused on the continuous monitoring and control of mercury contamination in the bay's fish, intending to decontaminate the environment and prevent a progressive increase in mercury levels in species that constitute a significant part of the local diet.

Keywords: Seafood; Environmental contaminants; Aquatic biota; Trace metals.

Revisão sistemática da contaminação mercurial em organismos aquáticos da Baía de Sepetiba, RJ, Brasil

RESUMO

A Baía de Sepetiba é uma laguna de grande importância ecológica e econômica para o estado do Rio de Janeiro, Região Sudeste do Brasil, no entanto o desenvolvimento dessa região está associado a inúmeros casos de contaminação ambiental que resultaram no acúmulo de metais traço no ambiente e na biota aquática. O mercúrio tem grande importância para a saúde pública por causa das capacidades de acumular e biomagnificar na biota aquática e entrar no organismo humano por meio da ingestão de pescado contaminado. Foram identificados seis estudos, cujos resultados indicam que as concentrações de mercúrio nos peixes da Baía de Sepetiba não excedem os limites máximos estabelecidos pela legislação nacional (Agência Nacional de Vigilância Sanitária) nem pela Organização Mundial de Saúde. Essa revisão sistemática teve como objetivo compilar estudos relacionados à contaminação por mercúrio em peixes da Baía de Sepetiba entre 2000 e 2024, seguindo o protocolo PRISMA-P. Foi selecionado o total de seis estudos, tendo sido incluídos mais 27 artigos em razão de sua relevância para a compreensão dos hábitos alimentares dos peixes, elevando o total para 33 artigos. Os nossos resultados sugerem que, apesar do baixo risco para o consumo humano, é necessário o desenvolvimento de políticas públicas centradas nos monitoramento e controle contínuos da contaminação por mercúrio nos peixes da baía, com os propósitos de descontaminar o ambiente e prevenir um aumento progressivo dos níveis de mercúrio em espécies que constituem uma parte significativa da dieta local.

Palavras-chave: Frutos do mar; Contaminantes ambientais; Biota aquática; Metais traço; Rio de Janeiro.

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INTRODUCTION

Sepetiba Bay, situated in Rio de Janeiro State, Brazil, holds substantial ecological significance owing to its rich biodiversity (Fig. 1). The bay's mangrove ecosystems and estuarine zones provide critical habitats for the development of numerous species, including mollusks, crustaceans, and fish, while also supporting economic activities such as fishing and tourism. Its strategic location has transformed the region into a key industrial and economic center within the state.

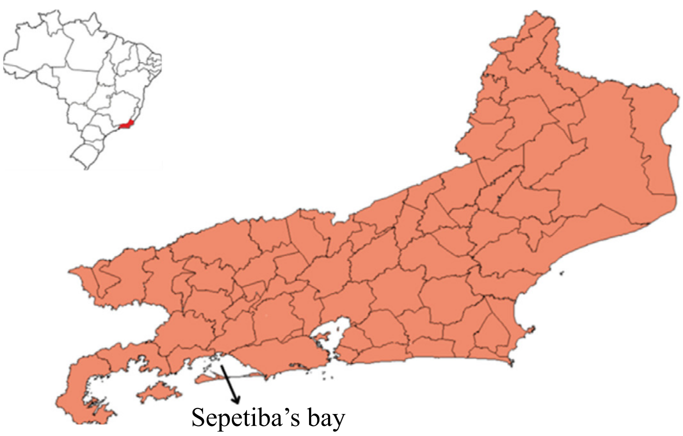
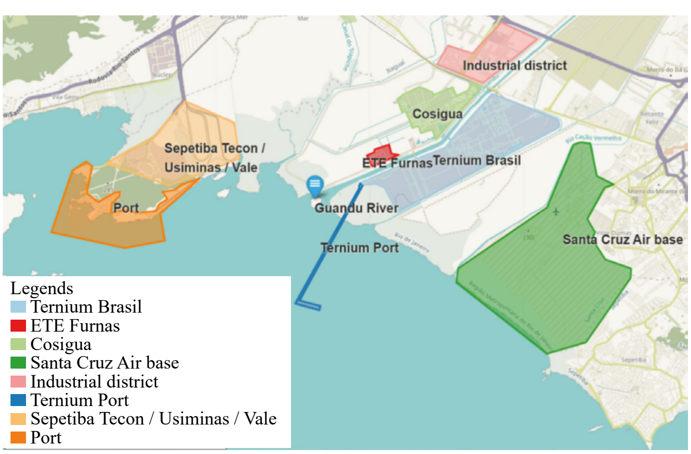


Figure 1. Map of the state of Rio de Janeiro, Brazil, highlighting the Sepetiba Bay region.

The development of various industries, such as steel manufacturing and mining (Fig. 2), coupled with the increased discharge of untreated urban effluents, has greatly contributed to the region's environmental degradation (Dourado et al., 2012).



Source: PACS (2015, p. 8).

Figure 2. Location of the Sepetiba Industrial Hub, Sepetiba Bay.

The transposition of the Paraíba do Sul River to the tributaries of the Guandu River played a pivotal role in altering the bay's ecological conditions, while also introducing significant mercury loads into the area (Molisani et al., 2004; Molisani et al., 2006). The rupture of the waste reservoir at the Ingá Industrial and Mercantile Company metallurgical plant in the early 2000s further aggravated the accumulation of metals, including mercury, in the bay (Nascimento et al., 2021). Mercury (Hg), which naturally occurs at low concentrations in aquatic environments, can see its levels rise due to anthropogenic activities (Silva et al., 2016). Like most metals, mercury exists in various chemical forms, both inorganic and organic, and exhibits high environmental persistence. These forms include elemental or metallic mercury, inorganic or ionic mercury, and organic mercury, with methylmercury being of the greatest toxicological concern.

The described process, known as the biogeochemical cycle, allows mercury to interact with both the environment and aquatic biota, with its effects varying based on the metal's chemical form, the route of exposure (ingestion, inhalation, or dermal absorption), and the intensity of exposure. Inorganic mercury, when bound to aquatic organic matter, is converted into methylmercury (MeHg) by anaerobic bacteria in aquatic environments. Methylmercury, the most toxic form of mercury, is readily absorbed by aquatic organisms and has a high capacity to bioaccumulate in tissues and biomagnify throughout the aquatic food chain, posing a significant public health risk (Ferreira et al., 2012).

Predatory fish accumulate higher levels of mercury than other species in the food chain, absorbing the metal through adsorption, respiration, and feeding. The metal accumulates primarily in their tissues, particularly in the muscle, which is the most consumed part by humans (Rodrigues et al., 2019). However, mercury can also accumulate in organs such as the kidneys, liver, gills, gastrointestinal tract, gonads, and brain (Zulkipli et al., 2021).

Methylmercury enters the human body primarily through the consumption of contaminated food, especially fish. Once absorbed, it binds to red blood cells and nervous tissue, crossing both the blood-brain barrier and the placenta, thereby posing a serious risk to pregnant women and fetuses. Neurological disorders, such as paresis, ataxia, tremors, and difficulty walking, are the primary symptoms of mercury poisoning in humans. Children born to mothers exposed to methylmercury during pregnancy may suffer from intellectual disabilities, cerebral palsy, and seizures (Cardoso et al., 2009).

Bivalves are considered effective bioindicators of water quality, playing a crucial role in monitoring environmental pollution. These organisms accumulate essential and non-essential elements from their surroundings in their muscle tissues. However, due to their filter-feeding habits, bivalves tend to accumulate lower levels of methylmercury compared to predatory fish (Kehrig et al., 2006).

Given the history of metal contamination in Sepetiba Bay, numerous studies have been conducted over the years to assess the contamination of sediments, water, and fish in the region. This study aimed to conduct a systematic review of mercury contamination in the aquatic biota of Sepetiba Bay, Rio de Janeiro, Brazil, from 2000 to 2024.

METHOD

This systematic review followed the Preferred Reporting Items for Systematic Review and Meta-Analysis Protocols (PRISMA-P) 2020 guidelines to map the existing research on mercury contamination in fish from Sepetiba Bay and to identify potential knowledge gaps (Page et al., 2022).

Search strategy and study selection

Relevant publications were reviewed and indexed in the ScienceDirect, Scientific Electronic Library Online (SciELO), Google Scholar, Scopus, and PubMed databases between June 12 and 14, 2024. The Population, Intervention, Comparison, Outcome-Study design (PICO-S) framework was employed for the keyword search. The search terms included “Sepetiba Bay,” “mercury,” “fish,” “seafood,” and “methylmercury,” using the Boolean operators “and” / “AND,” “OR,” and “IN” for studies published between 2000 and 2024 (Table 1).

Table 1. Databases used in the research.

Database	Terms and connectors used	Number of papers returned	Number of papers selected from the inclusion criteria
ScienceDirect	Sepetiba Bay and mercury and fish	59	3
ScienceDirect	“Sepetiba bay” AND “seafood” AND “mercury”	13	1
SciELO	Sepetiba Bay and mercury and fish	0	0
Google Scholar	Sepetiba Bay and mercury and fish	976	6
Google Scholar	“Sepetiba bay” AND “seafood” AND “mercury”	146	3
Google Scholar	“Fish” and “methylmercury” “ and “ Sepetiba Bay”	337	1
Google Scholar	“Fish” AND “methylmercury” OR “mercury” IN “ Sepetiba Bay”	768	4
Scopus	Sepetiba Bay and mercury and fish	0	0
PubMed	Sepetiba Bay and mercury and fish	0	0

SciELO: Scientific Electronic Library Online.

Subsequently, two authors (L.M. and E.M.) independently conducted a preliminary selection of the identified abstracts and paper titles, followed by a thorough review of the abstracts of all the selected articles.

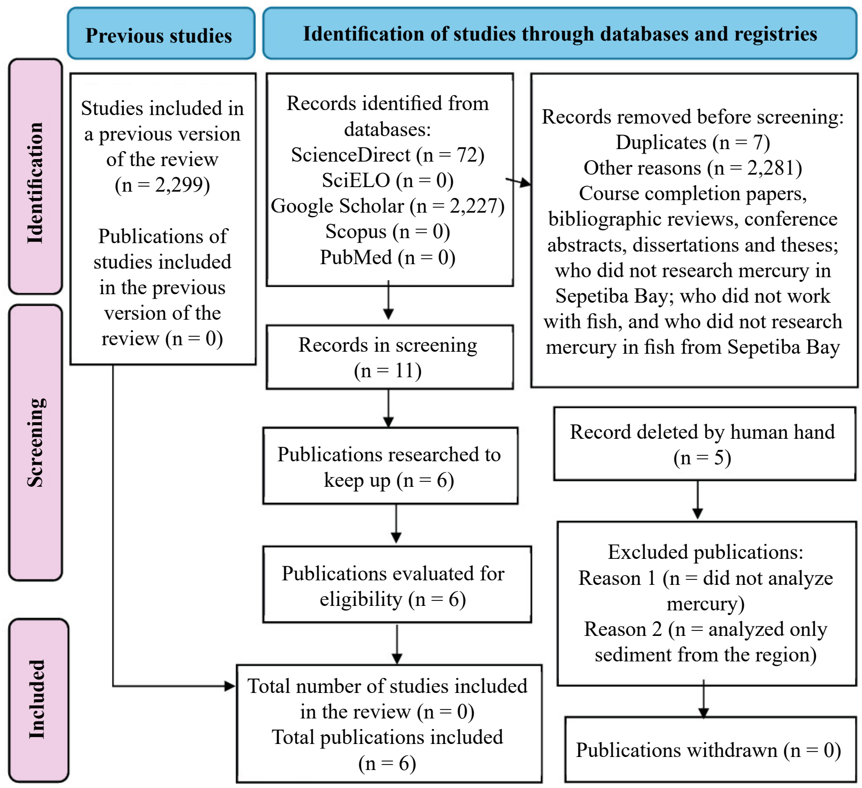
Study inclusion criteria

The inclusion criteria for the documents were as follows: studies focused on mercury contamination in Sepetiba Bay, Rio de Janeiro, Brazil; studies assessing mercury levels in the muscle and/or organs of fish from Sepetiba Bay; studies published between 2000 and 2024; and articles available in English and/or Portuguese.

Study exclusion criteria

Exclusion criteria encompassed articles categorized as undergraduate final papers, literature reviews, conference abstracts, dissertations, or theses; studies that did not explore mercury in Sepetiba Bay; studies that did not involve fish; and studies that did not analyze mercury in fish from Sepetiba Bay. Moreover, only studies conducted between 2000 and 2024 were considered eligible for inclusion. The document selection process is depicted in Fig. 3.

During the eligibility phase, the full texts of the studies were scrutinized, resulting in the identification of six studies pertinent to the research theme. Tables 2 and 3 present the fundamental information of the selected articles.



SciELO: Scientific Electronic Library Online.

Figure 3. Flow diagram for systematic review adopted from Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA).

Table 2. Summary of studies on mercury contamination in Sepetiba Bay.

Authors	Title	Research location	Species analysed and sample
Kehrig et al. (2006)	"Total and methyl mercury in different species of mollusks from two estuaries in Rio de Janeiro state"	Sepetiba Bay: Madeira Island and Island Guaíba); Guanabara Bay	*Perna perna* (40), *Crassostrea rhizophorae* (30), *Anomalocardia brasiliana* (30), *Perna perna* (41) and 15 L of water from Guanabara Bay
Bisi et al. (2012)	"Trophic relationships and mercury biomagnification in Brazilian tropical coastal food webs"	Sepetiba Bay; Guanabara Bay; Ilha Grande	44 *Sotalia guianensis* and 813 fishes from species identified in the stomach of *Sotalia guianensis*
Ferreira et al. (2012)	"Total mercury in marine fish traded in Brazil"	Fishing warehouses in different regions of Brazil. *Litopenaeus vannamei* was collected in Sepetiba Bay	*Thunnus albacares* (56) *Thunnus* sp. (35) *Xiphias gladius* (83) *Trichiurus lepturus* (58) *Micropogonias furnieri* (58) *Litopenaeus vannamei* (20) *Pteroplatytrygon violacea* (5)
Carneiro et al. (2013)	"Total mercury bioaccumulation in tissues of carnivorous fish (*Micropogonias furnieri* and *Cynoscion acoupa*) and oysters (*Crassostrea brasiliana*) from Sepetiba Bay, Brazil"	Sepetiba Bay	*Micropogonias furnieri* and *Cynoscion acoupa* (80); *Crassostrea brasiliana* (86)

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Silva et al. (2016)	"Spectrometric method for determination of inorganic contaminants (arsenic, cadmium, lead and mercury) in Smooth weakfish fish"	Pedra de Guaratiba	*Cynoscion leiarchus* (10)
Fiori et al. (2018)	"An alternative approach to bioaccumulation assessment of methyl-Hg, total-Hg, Cd, Pb, Zn in bivalve Anomalocardia brasiliana from Rio de Janeiro bays"	Sepetiba Bay, Ribeira Bay, Guanabara Bay, Mamanguá Bay	*Anomalocardia brasiliana* (72) and sediment of the bays

Table 3. Mercury contamination and the main techniques used in the analyzed studies.

Authors	Risk assessment	Technique	Results
Kehrig et al. (2006)	-	HgT: CV-AAS MeHg: GC-ECD	*Perna perna* 75.5 ± 7.1 (μg·kg^{-1}) *Crassostrea rhizophorae* 18.5 ± 3.6 (μg·kg^{-1}) *Anomalocardia brasiliana* 1.1 ± 0.1 (μg·kg^{-1})
Bisi et al. (2012)	-	CV-AAS	The lowest average concentration of HgT in *Litopenaeus schmitti* (4.2 ng/g in Sepetiba Bay) and the highest in the *Sotalia guianensis* (269.2 ng/g)
Ferreira et al. (2012)	No risk of consumption	EAA-VF with Bacharach Coleman analyzer, MAS-50 B1	Higher average HgT concentration in *Xiphias gladius* (0.393 μg·g^{-1}); the lowest average in *Litopenaeus vannamei* (0.058 μg·g^{-1})
Carneiro et al. (2013)	-	CV-AAS	The lowest concentrations were found in the gills (0.004 ± 0.005 μg/g HgT) and the highest in the kidneys (0.048 ± 0.06 μg/g HgT)
Silva et al. (2016)	-	Direct Hg analyzer (Teledyne Leeman, model Hydra C, Hudson, NH, United States of America)	HgT levels were lower than the levels established by Brazilian regulatory agencies
Fiori et al. (2018)	-	HgT: Portable atomic absorption spectrophotometer (LUMEX) MeHg: GC-ECD	The concentration of HgT and MeHg in the bivalves of Sepetiba Bay was three to six times higher than in the other bays evaluated, but five times below the safe level for human consumption

EAA-VF: cold vapor atomic absorption spectrophotometry, in Portuguese; CV-AAS: cold vapor-atomic absorption spectrophotometry; GC-ECD: gas chromatograph with electron capture detector.

RESULTS

The total of 2,299 studies were identified across the two databases, being 72 in ScienceDirect and 2,227 in Google Scholar. No studies aligned with the research theme were discovered in the SciELO, Scopus, and PubMed databases. Before screening, 2,281 studies were eliminated from consideration based on the exclusion criteria, resulting in 18 papers. Seven were discarded due to duplication, yielding a final count of 11 papers. Following a comprehensive review of the papers, five were excluded based on the criteria, either for failing to address mercury or for focusing on mercury in water rather than in fish. Figure 3 illustrates the screening stages, which culminated in the selection of six articles for this review. Table 1 provides a summary of the included studies.

Statistical analysis

The statistical analysis was conducted in Python 3.13, primarily using four libraries: Pandas (2.3.2) for tabular data manipulation, including file reading, filtering, and sorting; NumPy (2.3.2) for numerical operations; and Seaborn (0.13.2) together with Matplotlib (3.10.7) for data visualization (bar charts). The analyzed data were extracted directly from the articles selected in the systematic review and manually consolidated into a spreadsheet, in which the mean and standard deviation values of mercury concentration reported in the references were recorded and organized by author and species.

The metrics presented in the studies synthesize two measures: the arithmetic mean of mercury concentrations ($\mu g \cdot g^{-1}$), which represents the average value reported by each study, and the standard deviation, which quantifies the dispersion of values around the mean and the heterogeneity among samples. These data gave rise to graphs in which the horizontal bars, shown in red, represent the mean values, while the error bars, shown in black, indicate the standard deviation, allowing a direct visual assessment of uncertainty and variability for each species and author.

Study characteristics

The consulted authors evaluated the concentrations of total mercury (Bisi et al., 2012; Carneiro et al., 2013; Ferreira et al., 2012; Fiori et al., 2018; Kehrig et al., 2006; Silva et al., 2016) and methylmercury (Fiori et al., 2018; Kehrig et al., 2006) in fish from Sepetiba Bay (Tables 2 and 3).

Among the six authors, three conducted studies comparing Sepetiba Bay with other bays in the state of Rio de Janeiro, such as Guanabara Bay, Ilha Grande, Saco do Mamanguá, and Ribeira Bay (Bisi et al., 2012; Fiori et al., 2018; Kehrig et al., 2006). One author compared fish from various trading posts across the country, including one situated in Sepetiba Bay (Ferreira et al., 2012). Conversely, Carneiro et al. (2013) and Silva et al. (2016) focused their research exclusively on Sepetiba Bay.

Despite being an environment subjected to significant anthropogenic pressure, a comparative analysis of Sepetiba Bay with other bays, such as Guanabara Bay, indicates that the region exhibits a lower level of degradation than anticipated. The authors noted that the region's food web is complex, characterized by high biodiversity compared to other areas, and the fish from this region, under the studied conditions, are deemed safe for consumption.

To elucidate the region's environmental status, Kehrig et al. (2006) assessed the concentrations of total mercury and methylmercury in three species of mollusks (*Perna perna*—mussel, *Crassostrea rhizophorae*—oyster, and *A. brasiliana*—clam) collected from Sepetiba Bay and Guanabara Bay.

P. perna exhibited the highest average concentration of mercury, followed by *C. rhizophorae* and *A. brasiliana*. The capacity to filter larger particles may have influenced the mercury concentration in *P. perna*, as it ingests food from higher trophic levels compared to oysters, whose feeding habits are analogous to those of clams. The values recorded were consistent with those previously documented in other studies involving marine bivalves collected in coastal regions worldwide.

In another study, Bisi et al. (2012) investigated mercury biomagnification in food webs across three bays: Guanabara Bay, Sepetiba Bay, and Ilha Grande Bay, each characterized by varying levels of degradation, with Guanabara Bay being the most severely affected. Mercury in Sepetiba Bay appeared to be less bioavailable than in the other studied bays, demonstrating lower efficiency in trophic transfer within the region's food web.

Similarly, Ferreira et al. (2012) assessed the degree of mercury contamination in fish species sourced from areas with a history of contamination consumed in Brazil and the international market. One of the selected species was the white shrimp (*Litopenaeus vannamei*) from Sepetiba Bay, which exhibited the lowest mercury concentrations. When calculating the human consumption risk by simulating elevated consumption levels, *L. vannamei* was also determined to pose no risk to consumers.

Expanding the scope of mercury contamination research, Carneiro et al. (2013) investigated the total mercury levels in the muscle and organs of two carnivorous fish species, the croaker (*Micropogonias furnieri*) and the yellow sea bass (*Cynoscion acoupa*), as well as in the soft tissues of the oyster *Crassostrea brasiliana*, collected near Madeira Island, in Sepetiba Bay. The authors concluded that the oysters demonstrated a higher mercury concentration compared to the fish, attributable to their filter-feeding habits, which capture suspended particles in the water known to contain elevated mercury concentrations. Consequently, oysters were identified as superior bioindicators of metal contamination compared to predatory fish.

In terms of methodology, Silva et al. (2016) examined 10 specimens of white sea bass (*Cynoscion leiarchus*) obtained from fish markets in Pedra de Guaratiba to develop and validate a direct analyzer method for assessing mercury in fish, achieving satisfactory results for the technique. The analyzed samples exhibited low mercury concentrations, but the author emphasized that these results provide insufficient data to serve as indicators of the environmental conditions in the region.

Finally, Fiori et al. (2018) investigated the bioaccumulation of trace metals, including mercury and methylmercury, in the bivalve *A. brasiliana* across four bays in Rio de Janeiro:

Sepetiba, Ribeira, Ilha Grande, and Mamanguá. They detected concentrations of cadmium, lead, and zinc exceeding safety levels, and mercury and methylmercury levels in Sepetiba Bay were below the established limits, despite it being considered the most polluted among the studied bays.

Only one author evaluated the human health risk associated with consuming the analyzed species. The shrimp *L. vannamei* studied by Ferreira et al. (2012) was determined to pose no health risk even with daily high consumption (300 g/day), concluding that this species is safe for human consumption.

Among the analyzed papers, cold vapor atomic absorption spectrophotometry was the predominant method employed for total mercury analysis. The remaining authors quantified mercury using a Teledyne Leeman direct mercury analyzer, model Hydra C, Hudson, NH, United States of America (Silva et al., 2016), and a portable atomic absorption spectrophotometer from LUMEX (Fiori et al., 2018). These techniques offer the advantage of eliminating the need for acid digestion of the sample before analysis.

Concerning the evaluation of methylmercury, both authors employed the gas chromatography with electron capture detector technique, with Kehrig et al. (2006) integrating this method with ditizone-toluene-based extraction, while Fiori et al. (2018) utilized the technique in conjunction with an electron capture detector.

Food chain and mercury

Understanding the dynamics of trophic relationships in an ecosystem is crucial for analyzing the flow of mercury across trophic levels. Mercury, a non-essential element, accumulates in concentration as one ascends the trophic hierarchy. Its organic form, methylmercury, is primarily responsible for this biomagnification in aquatic environments. Consequently, organisms positioned at the top of the food chain are anticipated to exhibit the highest concentrations of mercury.

To investigate the trophic relationships, present in the food webs of Sepetiba Bay, Bisi et al. (2012) measured carbon and nitrogen isotopes in muscle tissue samples of Guiana dolphins (*Sotalia guianensis*), fish, and invertebrates from the region, calculating the trophic magnification factors for total mercury and methylmercury (Bisi et al., 2012).

Elevated carbon isotope values suggest that the carbon source is derived from coastal or benthic food webs, while lower values indicate that the primary contribution originates from pelagic food webs. Nitrogen isotopes reflect the organism's trophic position: higher values correspond to elevated trophic levels. This phenomenon is evident in species that prey on fish, benthic invertebrates, and organisms from the demersal-pelagic habitat (Bisi et al., 2012). From this assessment, it was determined that some species utilize carbon sources from outside the bay, specifically from the neritic zone, as observed in certain cephalopods that exhibited no carbon isotopes in their composition. Conversely, fish species such as *Mugil spp.* displayed high carbon isotope values, indicating that they feed on carbon-enriched sources, such as macroalgae and microalgae prevalent in coastal areas (Bisi et al., 2012).

The same authors noted that detritivorous species and invertebrates exhibit low nitrogen isotope values, including plankton-feeding fish and species that consume benthic invertebrates. In contrast, demersal-pelagic species display elevated nitrogen values, as evidenced by evaluations of *Trichiurus lepturus*, a top predator in Sepetiba Bay, and *Chloroscombrus chrysurus*, which primarily preys on fish, despite variations in feeding habits among different populations. Contrary to expectations, the Guiana dolphin (*S. guianensis*) did not occupy the highest trophic level in Sepetiba Bay; nitrogen isotopes indicated intermediate values for this species, suggesting that it likely feeds on organisms at lower trophic levels than anticipated. The high biodiversity of this environment facilitates a diverse array of prey available to each predator.

These authors assert that the food web in Sepetiba Bay is complex, complicating the determination of trophic relationships among fish species—a common characteristic in tropical environments in which each predator has access to a wide variety of prey. Nevertheless, upon assessing total mercury levels in muscle tissue, they discovered that the lowest concentrations were found in *Litopenaeus schmitti* and *Sardinella brasiliensis*, whereas the highest concentrations were observed in the Guiana dolphin. Carneiro et al. (2013) reported similar findings, noting elevated mercury concentrations in the muscle tissue of predatory species *M. furnieri* and *C. acoupa* compared to the oyster species *C. brasiliana*, thereby confirming the trend of increasing mercury concentration with ascending trophic levels.

Detritivorous species and invertebrates exhibited low mean values for nitrogen and total mercury (HgT), whereas piscivorous benthic fish and invertebrates demonstrated higher mean values for both nitrogen and HgT. Demersal-pelagic species, despite possessing elevated nitrogen values, did not follow the same trend of increasing HgT (Bisi et al., 2012).

In Sepetiba Bay, no linear correlation was observed between nitrogen and HgT concentrations. This relationship may be attributed to the reduced bioavailability of mercury in the region, as much of the mercury present in Sepetiba Bay is ultimately transported to adjacent areas, such as Ilha Grande Bay.

Mercury in mollusks and crustaceans

Mollusks are recognized as bioindicators of water quality due to their capacity to accumulate both essential (Cu, Zn, Mn, and Co) and non-essential elements (Cd, Ag, Hg, Pb, and Cr) within their tissues. Kehrig et al. (2006) investigated the presence of total mercury (HgT) and methylmercury (MeHg) in the muscles of mollusks, specifically *P. perna*, mussels (*Crassostrea rhizophorae*), and oysters (*A. brasiliana*), collected from Sepetiba and Guanabara Bays in Rio de Janeiro. They concluded that the concentrations of HgT and MeHg detected were not considered high. In Sepetiba Bay, the mollusk *P. perna* exhibited a higher average total mercury concentration (0.0755 ± 0.0071 $\mu g \cdot g^{-1}$ dry weight) compared to the other species evaluated in the region, which recorded concentrations of 0.0185 ± 0.0036 $\mu g \cdot g^{-1}$ dry weight for *C. rhizophorae* and 0.0011 ± 0.0001 $\mu g \cdot g^{-1}$ dry weight for A. brasiliana.

The mollusk *P. perna* and the oyster *A. brasiliana* collected from the Guaíba River, a tributary of Sepetiba Bay, exhibited methylmercury (MeHg) concentrations of 48.1 ± 5.1 and 6.9 ± 0.4 $\mu g \cdot kg^{-1}$, respectively, on a dry weight basis. Soft tissues from *C. rhizophorae* collected from Guaíba Island demonstrated higher mean total mercury (HgT) levels than those from Madeira Island. However, the percentage of MeHg was consistent at 32% in samples from both locations. The authors inferred that the dietary habits of mollusks, which primarily consist of organic detritus, sludge, and nanozooplankton, contrasted with the more selective feeding habits of oysters that primarily consume phytoplankton; this difference may have influenced the concentrations of mercury and methylmercury found in these species.

In 2018, Fiori et al. reported that under the conditions of their study, the mercury concentrations in *A. brasiliana* from Sepetiba Bay were three to six times higher than those recorded in the same bivalve species from Ilha Grande, Ribeira, and Saco do Mamanguá bays. Nevertheless, these concentrations did not exceed safety limits for human consumption. When compared to sediment, mercury concentrations in the bivalves increased in accordance with the levels present in the surrounding soil (Fiori et al., 2018).

The industrial region of Sepetiba Bay is situated near the mouths of the Guandu and Guarda rivers. Recognizing the significance of understanding the dynamics of chemical pollutants in these areas, Ferreira et al. (2012) posited that species within the genus *Penaeus* could serve as indicators of pollution, given their habitat in estuarine sediments near river mouths and drainage areas (Ferreira et al., 2012). This consideration is crucial, as mercury can remain sequestered in sediment and act as a substrate for methylation for decades.

The shrimp species *L. vannamei* and *L. schmitti* were assessed for total mercury concentration in their muscle tissue. In *L. vannamei*, the average concentration observed was 0.058 $\mu g \cdot g^{-1}$, with a maximum concentration of 0.101 $\mu g \cdot g^{-1}$, which is approximately four times below the limit established by Brazilian Health Regulatory Agency (ANVISA) and World Health Organization (WHO) (0.5 $\mu g \cdot g^{-1}$) for non-predatory species. *L. schmitti* was collected during both the summer and winter seasons, yielding mercury concentrations comparable to those of *L. vannamei*, recorded at 0.0042 ± 0.0021 $\mu g \cdot g^{-1}$ in summer and 0.0065 ± 0.0015 $\mu g \cdot g^{-1}$ in winter (Bisi et al., 2012; Ferreira et al., 2012).

Regarding the feeding habits of the species studied, *Lolliguncula brevis* is a carnivorous species that prey on fish, small crustaceans, and zooplankton (Bisi et al., 2012; Coelho et al., 2010). The species *L. schmitti* and *L. vannamei* are omnivorous, consuming organic matter, microalgae, small mollusks, and invertebrates (Bisi et al., 2012; Cavalcante & Câmara, 2008; Ferreira et al., 2012; Santos et al., 2004). Bivalves feed through filtration and may exhibit varying capacities for metal accumulation, excretion, and metabolism. The mussel *P. perna* feeds on sediments, organic matter, and nanozooplankton (Evangelista-Barreto et al., 2008; Kehrig et al., 2006). Conversely, *C. rhizophorae*, *C. brasiliana*, and *A. brasiliana* feed exclusively on phytoplankton and are classified as herbivorous species (Table 4). The feeding behaviors of filter-feeding species directly influence the concentration of absorbed metals, impacting their efficacy as bioindicators of mercury methylation present in sediment.

The mussel *P. perna* has been identified as the species with the highest capacity for mercury accumulation among mussels. However, Kehrig et al. (2006) also emphasized the need for caution when utilizing this species to assess long-term mercury exposure due to its ability to rapidly purify its tissues and reduce mercury concentrations.

The total mercury concentration ($\mu g \cdot g^{-1}$) in the mollusks and crustaceans analyzed by the authors is illustrated in Fig. 4, with data from Bisi et al. (2012) categorized according to samples collected during winter and summer. Notably, both the highest and lowest mercury concentrations were recorded in specimens of *A. brasiliana*. In 2006, Kehrig et al. reported a concentration of 0.001 $\mu g \cdot g^{-1}$ in 30 specimens of *A. brasiliana*, whereas in 2018, Fiori et al. (2018), after evaluating 18 specimens, observed concentrations close to 0.1 $\mu g \cdot g^{-1}$. Although these studies are relevant for representing different periods in the history of the bay, the limited sample size and the long temporal interval between the studies restrict more robust comparisons regarding the temporal evolution of mercury concentrations.

Table 4. Feeding habits and total mercury (HgT) of mollusks and crustaceans studied in Sepetiba Bay between the years 2000 and 2024.

Species	Feed	Eating habits	HgT (µg•g^{-1})	References
Litopenaeus schmitti	Organic matter, microalgae, zooplankton and small invertebrates	Omnivorous	0.0042–0.0065	Bisi et al. (2012) and Santos et al. (2004)
Litopenaeus vannamei	small mollusks, polychaetes and amphipods	Omnivorous	0.058 (± 0.23)	Cavalcante and Câmara (2008) and Ferreira et al. (2012)
Lolliguncula brevis	Zooplankton, small crustaceans and fish	Carnivore	0.0129	Bisi et al. (2012) and Coelho et al. (2010)
Perna perna	Organic debris, sediment and nanozooplankton	Herbivore	0.0755	Evangelista-Barreto et al. (2008) and Kehrig et al. (2006)
Crassostrea rhizophorae	Phytoplankton	Herbivore	0.0185	Evangelista-Barreto et al. (2008) and Kehrig et al. (2006) Oliveira et al. (2014)
Crassostrea brasiliana	Phytoplankton	Herbivore	0.0520	Carneiro et al. (2013) and Oliveira et al. (2014)
Anomalocardia brasiliana	Phytoplankton	Herbivore	0.0011–0.098	Ferraz et al. (2023), Fiori et al. (2018) and Kehrig et al. (2006)

Mercury in fish from Sepetiba Bay

Bisi et al. (2012) evaluated the highest variety of fish species (n = 25) among the consulted studies, with specimens collected during both summer and winter periods. Among these species, the highest concentrations of total mercury were found in the gray dolphin, *S. guianensis* (0.2692 ± 0.3323 µg·g^{-1}), which follows a piscivorous diet. Following this, *M. furnieri*, a carnivorous species exceeding 40 cm in length, exhibited concentrations of 0.1076 ± 0.1340 µg·g^{-1} in winter and 0.1355 ± 0.0995 µg·g^{-1} in summer. The third-highest mercury concentrations were detected in the piscivorous species *Centropomus* spp. during winter (0.0335 ± 0.0231 µg·g^{-1}) and in *Engraulis anchoita* during summer (0.0596 ± 0.0071 µg·g^{-1}) (Bisi et al., 2012) (Fig. 5).

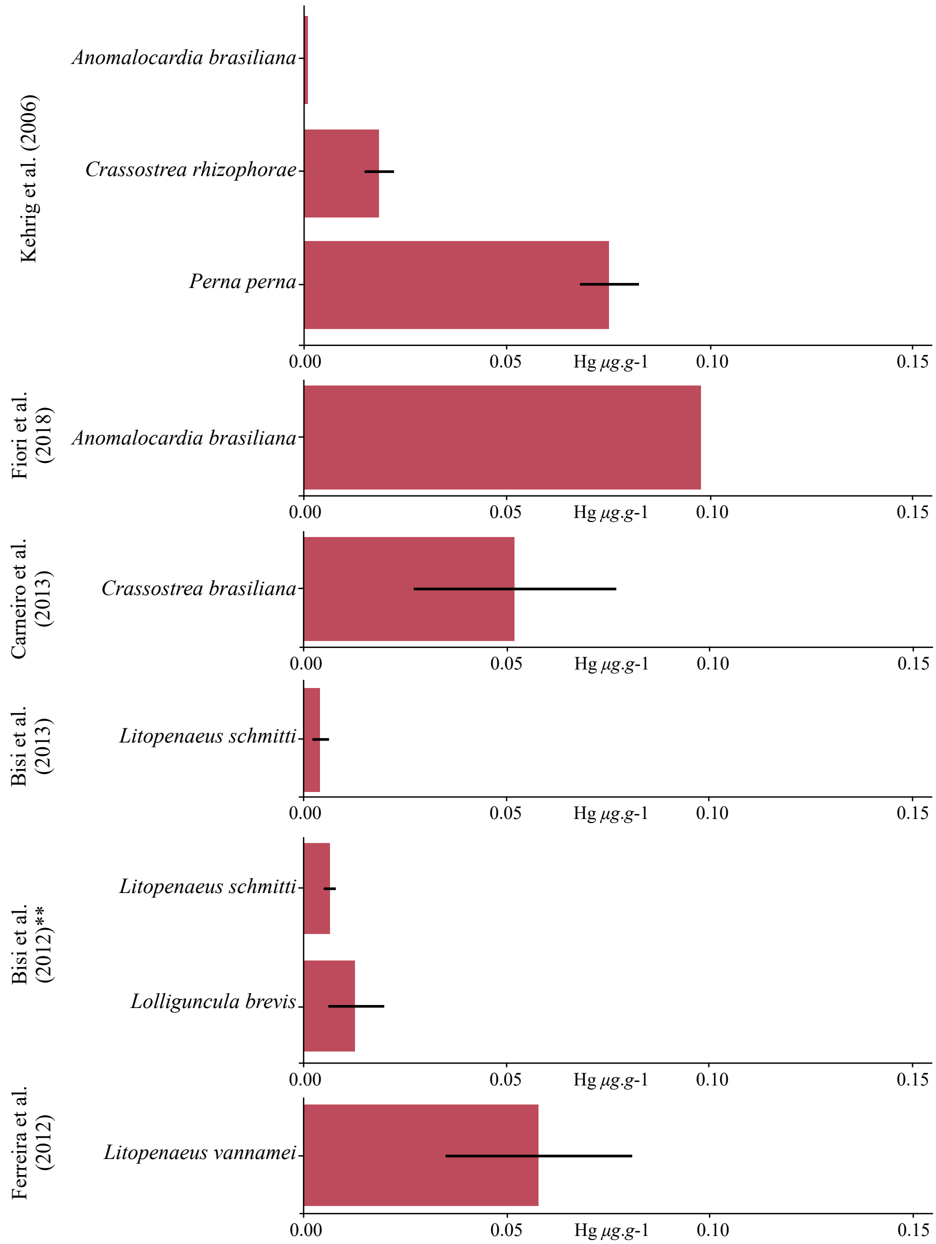
During winter, the lowest concentrations of total mercury were detected in *Symphurus tessellatus* (0.0044 ± 0.0022 µg·g^{-1}). In summer, the species *S. brasiliensis* (0.0058 ± 0.0008 µg·g^{-1}) and *Paralonchurus brasiliensis* (0.0058 ± 0.0015 µg·g^{-1}) exhibited the lowest concentrations (Bisi et al., 2012) (Tables 5 and 6).

Carneiro et al. (2013) collected adult specimens of *C. acoupa* and *M. furnieri* in the Ilha da Madeira region, analyzing total mercury concentrations in the muscle and organs of these fish. Upon conducting biometric measurements, they compared them to the mercury concentrations and observed a positive correlation—mercury concentration increases as fish grow. This relationship is commonly observed in carnivorous fish, such as the species studied in this research (Carneiro et al., 2013).

When evaluating total mercury concentrations in the organs and arranging them in ascending order, the following sequence was obtained: gills, gonads, muscle, intestine, liver, and kidneys. The gills had the lowest mercury levels, while the kidneys exhibited the highest. This result is significant because mercury levels in the gills depend on waterborne concentrations, whereas other organs reflect the bioaccumulation of the metal (Carneiro et al., 2013). This suggests that the primary source of contamination is not the water itself, particularly during periods of low precipitation.

These findings reveal that the gills, which are responsible for gas exchange and in direct contact with water, have lower capacity to retain mercury, while the kidneys play a critical role in filtering and excreting toxic substances. The kidneys' high affinity for heavy metals is due to the proteins present in this organ that can bind to metal ions, forming complexes that are stored in renal tissue. Additionally, while mercury can be excreted via the kidneys, this process is slow and inefficient, leading to metal accumulation, which is consistent with observations in several studies (Carneiro et al., 2013).

The intestines of fish can also show significant mercury concentrations, although usually lower than those found

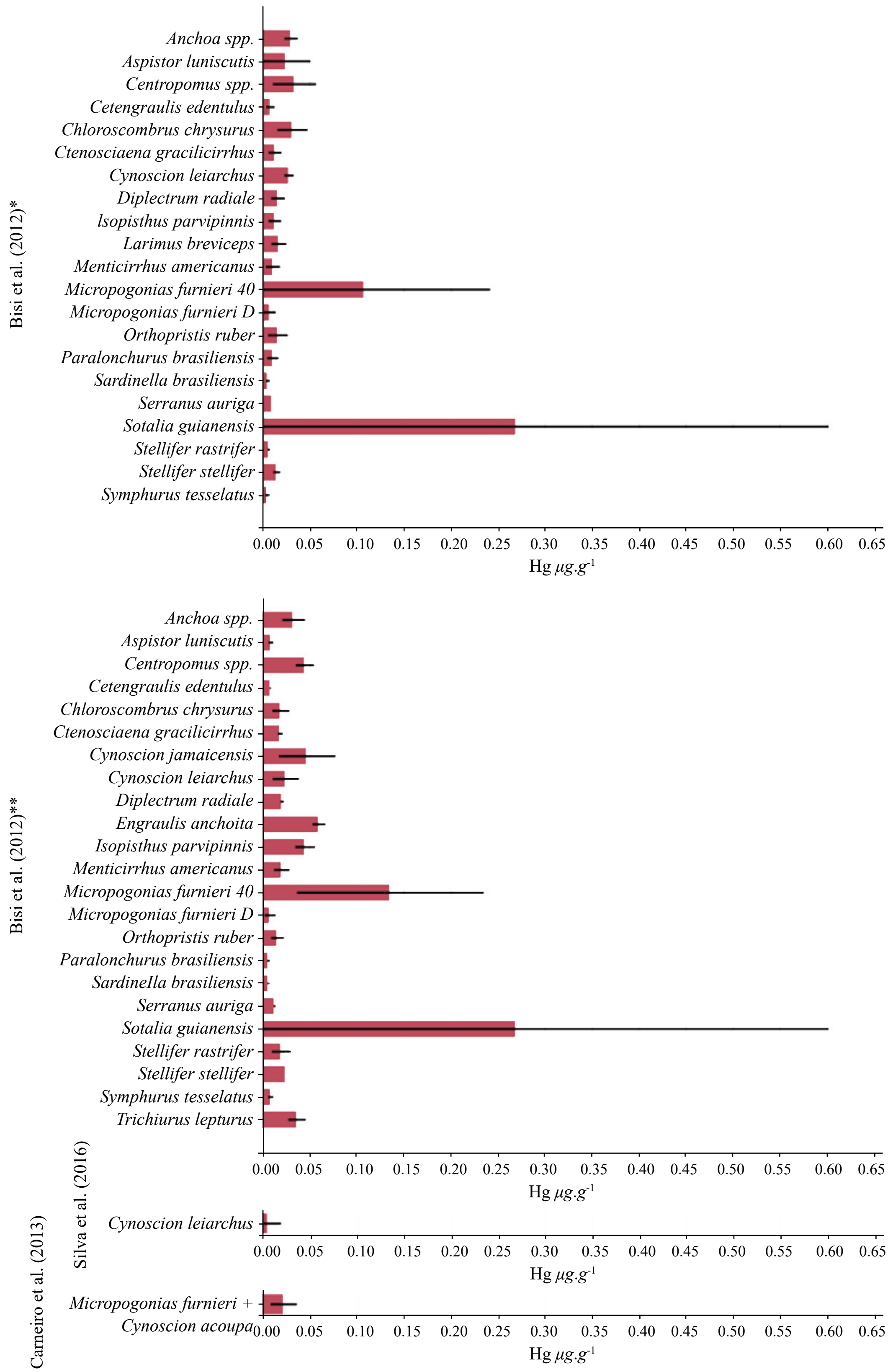


*Data collected during winter; **data collected during summer.

Figure 4. Total mercury concentration ($\mu g \cdot g^{-1}$) in mollusks and crustaceans studied in Sepetiba Bay as reported in the reviewed articles.

in the kidneys, due to their role in nutrient absorption and, consequently, toxic substances. This organ constitutes the first barrier for the absorption of both nutrients and toxins, potentially presenting high concentrations of the metal, especially in fish species at the top of the food chain that accumulates mercury by consuming other contaminated fish. Since the intestines absorb mercury present in the food ingested by the fish, the fact that they exhibited higher mercury values compared to the gills indicates that the contamination of these animals primarily occurs through dietary means, common in carnivorous animals such as *C. acoupa* and *M. furnieri* (Carneiro et al., 2013).

The liver typically shows high concentrations of mercury because of its essential functions in metabolism, detoxification, and chemical storage. Acting as a central filter for toxins, including mercury, the liver binds these toxins to proteins and other molecules, which complicates their elimination. According



*Aquatic organisms collected during winter; **aquatic organisms collected during summer.

Figure 5. Concentration of total mercury ($\mu g \cdot g^{-1}$) in aquatic organisms sampled from Sepetiba Bay as reported in the reviewed articles.

Table 5. Feeding habits and total mercury (HgT) of fishes studied in Sepetiba Bay between the years 2000 and 2024.

Species	Feed	Eating habits	HgT (µg·g^{-1})	Reference
Cynoscion leiarchus	Teleostei	Piscivorous	0.0052–0.0275	Bisi et al. (2012), Capete et al. (2024) and Silva et al. (2016)
Aspistor luniscutis	Scale, polychaete	Omnivorous	0.0085–0.0242	Bisi et al. (2012) and Rodrigues et al. (2010)
Chloroscombrus chrysurus	Copepoda, ostracoda	Carnivore	0.0190–0.0312	Bisi et al. (2012) and Silva and Lopes (2002)
Centropomus spp.	Teleostei, crustaceans	Carnivore	0.0335–0.0447	Bisi et al. (2012), Capete et al. (2024) and Rabelo et al. (2009)
Sardinella brasiliensis	Zooplankton and phytoplankton	Omnivorous	0.0050–0.0058	Bisi et al. (2012) and Souza et al. (2018)
Symphurus tesselatus	Polychaete / crustacean	Carnivore	0.0044–0.0083	Bisi et al. (2012) and Garcia et al. (2018)
Anchoa spp.	Zooplankton	Carnivore	0.0298–0.0326	Araújo et al. (2008) and Bisi et al. (2012)
Cetengraulis edentulus	Phytoplankton	Herbivore	0.0078–0.0080	Araújo et al. (2008), Bisi et al., 2012) and Silva et al. (2003)
Engraulis anchoita	Zooplankton and phytoplankton	Omnivorous	0.0596	Araújo et al. (2008), Bisi et al. (2012) and Sato et al. (2011)
Orthopristis ruber	Annelids, echinoderms, plant and mineral waste	Omnivorous	0.0154–0.0158	Bisi et al. (2012) and Santos et al. (2007)
Ctenosciaena gracilicirrhus	Polychaete / crustacean	Carnivore	0.0127–0.0182	Bisi et al. (2012) and Martins et al. (2017)
Cynoscion jamaicensis	Fish and crustaceans	Carnivore	0.0470	Bisi et al. (2012) and Rondinelli et al. (2007)
Cynoscion leiarchus	Teleostei	Piscivorous	0.0242–0.0275	Bisi et al. (2012) and Capete et al. (2024)
Isopisthus parvipinnis	Teleosts, crustaceans and polychaetes	Carnivore	0.0125–0.0449	Bisi et al. (2012) and Kehrig et al. (2009)
Larimus breviceps	Crustaceans and teleosts	Carnivore	0.0168	Bisi et al. (2012) and Nascimento and Ramos (2020)
Menticirrhus americanus	Polychaete / crustacean	Carnivore	0.0105–0.0199	Bisi et al. (2012), Capete et al. (2024) and Rondinelli et al. (2007)
M. furnieri (smaller than 40 cm)	Polychaeta, crustacea, caprella	Carnivore	0.0071–0.0074	Bisi et al. (2012) and Capete et al. (2024)
M. furnieri (longer than 40 cm)	Polychaeta, crustacea, caprella	Carnivore	0.1076–0.1355	Bisi et al. (2012) and Capete et al. (2024)
Paralonchurus brasiliensis	Polychaetes, crustaceans and fish	Carnivore	0.0058–0.0104	Bisi et al. (2012) and Robert et al. (2007)
Stellifer rastrifer	Copepoda, crustaceans	Carnivore	0.0061–0.0194	Bisi et al. (2012) and Sabinson et al. (2015)
Stellifer stellifer	Microcrustaceans, benthic invertebrates and fish	Carnivore	0.0145–0.0244	
Diplectrum radiale	Polychaeta / crustacea / decapoda / teleostei	Carnivore	0.0158–0.0204	Ferreira and Abilhoa (2005) and Bisi et al. (2012)
Serranus auriga	Small fish, crustaceans	Carnivore	0.0095–0.0125	Bisi et al. (2012) and Roman et al. (2024)
T. lepturus	Teleostei	Piscivorous	0.0363	Bittar et al. (2008), Cardoso et al. (2009) and Bisi et al. (2012)
Sotalia guianensis	Piscivorous	Piscivorous	0.2692–0.3323	Bisi et al. (2012) and Kehrig et al. (2009)
M. furnieri + *C. acoupa*	Polychaeta, crustacea, caprella, crustaceans, fish	Carnivore and piscivorous	0.014–0.022	Capete et al. (2024) and Carneiro et al. (2013)

to Carneiro et al. (2013), the liver ranks as the second-highest organ in mercury accumulation after the kidneys. This high mercury content is attributed to the liver's demethylation capacity, which converts methylmercury, a more toxic form, into less toxic inorganic mercury. This detoxification process results in the liver retaining high levels of mercury.

Muscle tissue, being the primary part consumed by humans, is of particular importance for ongoing monitoring and risk assessments. Brazilian legislation, through ANVISA and WHO, sets a safety threshold for mercury concentrations in fish muscle: 0.5 $\mu g \cdot g^{-1}$ for non-predatory fish and 1 $\mu g \cdot g^{-1}$ for predatory fish (Carneiro et al., 2013). None of the studies reviewed reported mercury levels exceeding these limits in the muscle tissue of the species analyzed.

However, continuous monitoring of mercury levels remains essential, given the region's history of contamination. Such monitoring is necessary to generate consistent and up-to-date data that can contribute to the formulation and improvement of public policies aimed at sustainability and public health, in alignment with the United Nations' 2030 Agenda. Although several studies on environmental contamination have been conducted in the region, few have addressed contamination in fishery products. Among them, only one author analyzed a significant number of species across different seasons, albeit with a low sample size, and only one study identified during this systematic review presented a risk assessment associated with the human consumption of fish from Sepetiba Bay.

From a health perspective within the *one health* framework, which addresses the interdependence of human, animal, and environmental health, the need for integrated public policies becomes evident. These policies should focus on implementing permanent programs for environmental monitoring, monitoring of fishery products, and surveillance of the health of residents in the region, who represent the primary exposed population. Regarding the assessment of local fauna, efforts should include expanding the number of species analyzed, considering different life stages, seasonality, and trophic levels, as well as broadening risk assessments related to the human consumption of the main commercially exploited and consumed species in the region. Furthermore, public policies should promote ongoing environmental education initiatives associated with risk communication, directed at the local community and consumers of fishery products. Additionally, environmental enforcement should be strengthened and expanded to identify, reduce, and control the main sources of contamination.

CONCLUSION

In this systematic review, it was observed that mercury concentrations in Sepetiba Bay followed the trend of increasing with the trophic level of species, confirming the occurrence of biomagnification. Although the risk to public health is considered low, the potential for mercury bioaccumulation remains a concern. Moreover, the review highlighted notable research gaps, with few studies focusing on mercury in fishery products, limitations in sampling due to low species representativeness, small sample sizes, and a lack of risk assessments related to human consumption. The deficiency of research on this topic became evident when comparing the reviewed articles with the volume of excluded studies, which were primarily focused on mercury in sediments or on other metals in fish, without addressing mercury.

In future research, it is recommended to increase the number of species analyzed to ensure greater sample representativeness. Furthermore, sample collection should be prioritized directly from the natural environment, avoiding the collection of samples from fish markets, to reduce uncertainties regarding the origin of the analyzed material. It is further suggested to collect species belonging to different trophic levels that occupy different zones of the water column and are sampled across different seasons of the year, aiming to capture seasonal and spatial variations in contamination levels.

The average total mercury concentrations found in the biotic environment were relatively low, with fish showing 0.0315 $\mu g \cdot g^{-1}$ and mollusks 0.0057 $\mu g \cdot g^{-1}$. Despite these low concentrations, mercury remains hazardous to health, even in small amounts, due to its capacity for bioaccumulation. This underscores the need for public policies on regular monitoring and public awareness campaigns, particularly targeting vulnerable populations, to inform them about which species are safe to consume. Such initiatives align with the objectives of the Minamata Convention, which Brazil has ratified, and aim to protect public health through mercury phase-out programs and control strategies, especially in areas with a history of contamination.

In conclusion, this review advocates for global partnerships and stricter regulations on mercury management, particularly in bays like Sepetiba, in which the local biota serves as a crucial source of protein for the population. Ensuring the implementation of the Minamata Convention by 2030 remains a key priority to minimize the risks posed by mercury exposure.

CONFLICT OF INTEREST

Nothing to declare.

DATA AVAILABILITY STATEMENT

The data will be available upon request.

AUTHORS' CONTRIBUTION

Conceptualization: Macedo, L. and Mársico, E. T.; **Formal Analysis:** Macedo, L.; **Supervision:** Mársico, E. T.; **Data curation:** Macedo, L.; **Writing – original draft:** Macedo, L.; **Writing – review & editing:** Mársico, E. T.; **Final approval:** Mársico, E. T.

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