Acta Limnologica Brasiliensia

Publication of the Brazilian Association of Limnology

Review Articles
Acta Limnologica Brasiliensia, 2024, vol. 36, e14
https://doi.org/10.1590/S2179-975X8723
ISSN 2179-975X on-line version

Status of studies about Brazilian bioindicator fishes, a review

Status dos estudos sobre os bioindicadores da ictiofauna brasileira, uma revisão

Caroline de Paula Batista[1], Agatha de Almeida Ferreira[2] and Guilherme José da Costa Silva[2]*

[1]Departamento de Ciências Biológicas, Universidade Santo Amaro – UNISA, R. Prof. Enéas de Siqueira Neto, 340, Jardim das Imbuias, CEP 04829-300, São Paulo, SP, Brasil

[2]Programa de Pós-graduação em Saúde Única, Universidade Santo Amaro – UNISA, R. Prof. Enéas de Siqueira Neto, 340, Jardim das Imbuias, CEP 04829-300, São Paulo, SP, Brasil

*e-mail: gjsilva@prof.unisa.br

Cite as: Batista, C.P., Ferreira, A.A. and Silva, G.J.C. Status of studies about Brazilian bioindicator fishes, a review. *Acta Limnologica Brasiliensia*, 2024, vol. 36, e14. https://doi.org/10.1590/S2179-975X8723

Abstract: Aim: The freshwater environment is indeed diverse and complex, and it faces numerous challenges due to human activities. One approach to evaluating these human interventions is through the use of bioindicators, with fish being one of the key groups studied in the aquatic environment. However, the existent studies report that only a limited number of Brazilian ichthyofauna species have been investigated as potential bioindicators. **Methods:** The data present here were organized through a bibliographic review that adopts an exploratory and descriptive approach, focusing on articles published between the years 2000 and 2022, utilizing terms such as "bioindicators," "Brazilian fish," and "aquatic ecosystem" in both Portuguese and English languages. **Results:** Despite Brazil having the most diverse ichthyofauna on the planet, the research has focused on only 45 species thus far. Among these, *Rhamdia quelen* (Quoy & Gaimard, 1824) emerged as the most frequently studied species. The analysis of gill and liver tissues was found to be the most common method employed in these studies, while other tissues received relatively little attention. Moreover, the distribution of studies on bioindicator species was uneven, with the Upper Paraná ecoregion having the highest number of species investigated. This suggests that research efforts in this field have not been uniformly distributed across Brazil. **Conclusions:** The patchy nature of studies on bioindicators of the Brazilian ichthyofauna highlights the need for greater incentives and support for research in this area. With Brazil's exceptional ichthyofauna diversity, there is ample potential to identify and utilize additional species as environmental indicators. By expanding the scope of studies and addressing the geographical imbalance, a more comprehensive understanding of the impacts of human activities on freshwater ecosystems in Brazil can be achieved. This knowledge is vital for effective conservation and management efforts to protect and sustain the country's valuable aquatic resources.

Keywords: Brazilian fish; aquatic ecosystem; ecoregions; degradation; biomarkers.

Resumo: Objetivo: O ambiente de água doce é amplamente diverso e complexo, e devido às atividades e intervenções antrópicas, enfrenta numerosos desafios. Uma das abordagens utilizada para avaliar essas intervenções humanas é através do uso de bioindicadores, sendo os peixes um dos principais grupos estudados no ambiente aquático. Entretanto, os trabalhos disponíveis relatam que apenas um número limitado de espécies da ictiofauna brasileira foi investigado como potenciais bioindicadores. **Métodos:** Os dados do presente trabalho foram organizados por meio de uma revisão bibliográfica que adota abordagem exploratória e descritiva, com foco em artigos publicados entre os anos de 2000 e 2022, utilizando termos como "bioindicadores", "peixes brasileiros" e "ecossistema aquático" tanto em língua portuguesa quanto inglesa. **Resultados:** Apesar de o Brasil ter a ictiofauna mais diversificada do planeta, a pesquisa se concentrou em apenas 45 espécies até o momento. Dentre estas, *Rhamdia quelen* (Quoy & Gaimard, 1824) emergiu como a espécie mais estudada. A análise dos tecidos branquiais e hepáticos foi considerada o método mais comum empregado nesses estudos, enquanto outros tecidos receberam relativamente pouca atenção. Além disso, a distribuição dos estudos sobre espécies bioindicadoras foi desigual, sendo a ecorregião do Alto Paraná a que apresentou o maior número de espécies investigadas. **Conclusões:** Isso sugere que os esforços de pesquisa na área da ictiofauna como bioindicador não têm sido distribuídos uniformemente pelo Brasil. A natureza fragmentada dos estudos sobre bioindicadores da ictiofauna brasileira destaca a necessidade de maiores incentivos e apoio à pesquisa nesta área. Com a excepcional diversidade da ictiofauna do Brasil, há amplo potencial para identificar e utilizar espécies adicionais como indicadores ambientais. Ao ampliar o escopo dos estudos e abordar o desequilíbrio geográfico, pode-se alcançar uma compreensão mais abrangente dos impactos das atividades humanas nos ecossistemas de água doce no Brasil. Este conhecimento é vital para esforços eficazes de conservação e gestão para proteger e sustentar os valiosos recursos aquáticos do país.

Palavras-chave: peixes brasileiros; ecossistema aquático; ecorregiões; degradação; biomarcadores.

1. Introduction

The complexity and diversity of the aquatic environment are easily observable. It encompasses a wide range of ecosystems such as rivers, lakes, lagoons, estuaries, and oceans (Rand et al., 1995). Furthermore, this environment is characterized by its openness and dynamism, consisting of various elements, both living (biotic) and non-living (abiotic). Consequently, it is continuously subjected to alterations and influences that impact its composition (Costa et al., 2008; Rand et al., 1995).

The constant changes occurring in the environment are primarily caused by various human activities. These activities encompass mining, urbanization, construction of dams and reservoirs, alterations in natural river courses, unregulated disposal of industrial and domestic waste, deforestation, pollution, unsustainable land use, introduction of non-native species, and the implementation of fish farming systems (Baptista et al., 2003; De Filippo, 2000; Goulart & Callisto, 2003; Langeani et al., 2007; Reis et al., 2016). Consequently, these actions bring about alterations in the physical, chemical, and biological characteristics of the environment, directly impacting the aquatic ecosystem and resulting in a loss of biodiversity (Clements, 2000) as well as a decline in water quality (Costa et al., 2008; Goulart & Callisto, 2003).

Water pollution and eutrophication are significant concerns in the degradation of aquatic ecosystems. The sources of pollution can be broadly categorized into three main areas. Firstly, agricultural activities contribute to pollution through the leaching process, where pesticides and fertilizers are transported by rainwater (Baptista et al., 2003; Cerejeira et al., 2003). Secondly, households discharge untreated wastewater, while industries release chemical and mining waste, as well as waste from slaughterhouses and farms (De Filippo, 2000). These multiple sources of pollution exacerbate the degradation of water quality and pose a threat to the health of aquatic ecosystems.

Pollution can manifest in various forms, including physical, chemical, and biological alterations within the aquatic environment (De Filippo, 2000). Physical pollution encompasses changes in temperature, brightness, turbidity, water velocity, and sedimentation, among others. Chemical pollution involves shifts in pH levels, dissolved salts, and other chemical constituents. Biological pollution refers to changes in the composition of the ecological community (De Filippo, 2000).

In contrast, eutrophication occurs when the aquatic ecosystem experiences an excess of nutrients, resulting in the rapid proliferation of algae and aquatic plants (De Filippo, 2000). This process, as described by Smith and Schindler (2009), can lead to noticeable changes in the taste, odor, and color of the water. Additionally, eutrophication can cause a decrease in dissolved oxygen levels and a decline in aquatic biodiversity, further exacerbating the negative impacts on the ecosystem (Smith & Schindler, 2009).

Organisms are commonly employed to determine and assess various degradation processes. According to Markert's (1994) definition, organisms (or parts thereof) are classified as bioindicators if they carry information that can evaluate the quality of an environment. In the context of the aquatic environment, fish (Chovanec et al., 2003; Freitas & Siqueira-Souza, 2009), crustaceans, aquatic plants, mammals, birds, algae, mollusks, and other organisms are considered bioindicators (Baptista et al., 2003; Lins et al., 2010; MacKenzie et al., 1995; Printes

& Callaghan, 2003; Vital et al., 2011). Organisms positioned at the top of the food chain are often utilized as bioindicators due to their consumption of organisms at lower trophic levels, leading to the accumulation and concentration of contaminating substances (Lins et al., 2010). Additionally, a bioindicator must possess the capability to thrive in a healthy environment and endure exposure to contaminants (Barbieri et al., 2022; Chovanec et al., 2003). The research approach for a bioindicator can be classified as toxicological (e.g. sensitivity to metals and pesticides) (Braga et al., 2015; Silva et al., 2015; Florêncio et al., 2014; Martinez & Cólus, 2002; Moraes et al., 2012), morphological (e.g. analyses of gonadal diameter, hepatosomatic index, condition factor)(Arias et al., 2007; Barrilli et al., 2015; Morado et al., 2017; Schulz & Martins-Junior, 2001) histopathological (e.g. tissue analyses)(Amadeo et al., 2013; Martinez & Cólus, 2002; Miranda et al., 2008; Sousa et al., 2013) or physiological (e.g. enzymatic activity and blood tests) (Arias et al., 2007; Miranda et al., 2008; Morado et al., 2018; Rodrigues & Castilhos, 2003; Tortelli et al., 2006). Fish have traditionally been widely used as bioindicators in aquatic ecosystems (Chovanec et al., 2003; Martinez & Cólus, 2002), and there are several reasons why they are widely used to determine the natural characteristics of aquatic habitats and to assess their condition (Chovanec et al., 2003). The fish community includes several species scattered between trophic levels, with some species at the top of the chain, capable of accumulating contaminating substances that indicate and interferm in the occurrence of environmental disturbances (Freitas & Siqueira-Souza, 2009; Martinez & Cólus, 2002).

Certain species exhibit greater sensitivity to chemical and physical alterations, including changes in pH and dissolved oxygen, which can be attributed to shifts in environmental quality (Chovanec et al., 2003; Freitas & Siqueira-Souza, 2009). In comparison to other groups, such as invertebrates, fish offer a greater capacity to provide insights into the environmental conditions within their habitat due to their ease of identification and capture (Freitas & Siqueira-Souza, 2009).

Despite Brazil being recognized as the country with the highest biodiversity worldwide (Calixto, 2003; Mittermeier et al., 2005), research focused on utilizing ichthyofauna as bioindicators is often limited in scope and encompasses only a limited number of species. Recognizing the necessity to consolidate groups with the capacity to assess and evaluate aquatic environmental conditions due to their extensive utilization, the objective of this study is to assemble a comprehensive collection of Brazilian fish species that possess the potential to serve as bioindicators, using an approach that refers to the focal species and their corresponding toxicological, morphological, histopathological and physiological analyzes in response to anthropogenic interventions.

2. Material and Methods

The present study is a bibliographic review that adopts an exploratory and descriptive approach to investigate the Brazilian ichthyofauna as potential bioindicators. The dataset was compiled by conducting a search on the Google Scholar and SciELO platforms, focusing on articles published between the years 2000 and 2022.

To gather relevant articles, search terms such as "bioindicators," "Brazilian fish," and "aquatic ecosystem" were utilized in both Portuguese and English languages. These terms were combined in various combinations using the AND/OR conjunctions, and the searches were conducted to include singular, plural, and variant forms of the terms.

Following the identification of articles containing the targeted search terms, a citation and reference check was conducted to supplement the progress and requirements of the present study.

The results were gathered in a table whose validated potential refers to rather the species were submitted or not to tests capable to determinate whether it is a bioindicator. If the species has validated potential, it means that it has been subjected to testes, whether morphological, physiological, toxicological or histological. To develop the map, the Brazilian freshwater ecoregion presented by Abell et al. (2008) were used. These freshwater ecoregions are based on the distribution and composition of freshwater fish species, incorporating key ecological and evolutionary patterns.

3. Results

The bibliographic survey conducted in this study identified a total of 45 species of Brazilian ichthyofauna that have been recognized as potential bioindicators. These findings are based on the analysis of 39 articles (refer to Table 1 for a comprehensive list of the identified species). It is important to note that unpublished works and studies mentioning variations in the composition

Table 1. Bioindicator species by freshwater ecoregion and their research approach.

Species	Popular Name	Ecoregions	Validated Potencial	Research approach	References
Astyanax bimaculatus (Linnaeus 1758)	Lambari	329	Yes	Physiological	Batista et al. (2014)
		328	Yes	Toxicological	Nunes & Jesus (2019)
Astyanax lacustris (Lütken 1875)	Tambiú	330	Yes	Toxicological and physiological	Disner et al. (2017)
		344	Yes	Toxicological, histological, physiological and morphological	Martinez & Cólus (2002)
Brachyplatystoma filamentosum (Lichtenstein 1819)	Piraíba	321	Yes	Toxicological	Queiroz et al. (2019)
Brachyplatystoma rousseauxii (Castelnau 1855)	Dourada	321	Yes	Toxicological	Braga et al. (2015)
		321	Yes	Toxicological	Moraes et al. (2012)
Brachyplatystoma vaillantii (Valenciennes 1840)	Piramutaba	323	Yes	Toxicological	Serrão et al. (2014)
Cathorops agassizii (Eigenmann & Eigenmann 1888)	Bagre gaivota	323	Yes	Toxicological	Serrão et al. (2014)
Curimata inornata (Vari 1989)	Branquinha	323	Yes	Toxicological	Serrão et al. (2014)
Eigenmannia virescens (Valenciennes 1836)	Peixe espada	314	Yes	Toxicological	Bücker et al. (2006)
Geophagus brasiliensis (Quoy & Gaimard 1824)	Acará-Topete	330	Yes	Toxicological, histological and physiological	Disner et al. (2017)
		329	Yes	Morphological	Morado et al. (2017)
		329	Yes	Physiological and morphological	Morado et al. (2018)
		329	Yes	Morphological and physiological	Arias et al. (2007)
Geophagus iporangensis (Haseman 1911)	Cará	344	Yes	Toxicological	Rodrigues & Smith (2022)
Geophagus proximus (Castelnau 1855)	Acaratinga	323	Yes	Toxicological	Serrão et al. (2014)
Hoplias malabaricus (Bloch 1794)	Traíra	344	Yes	Toxicological, physiological and histopathological	Miranda et al. (2008)
		328	Yes	Toxicological	Nunes & Jesus (2019)
Hoplosternum littorale (Hancock 1828)	Caborja	344	Yes	Toxicological	Rodrigues & Smith (2022)
Hyphessobrycon eques (Steindachner 1882)	Mato Grosso	328	Yes	Toxicological	Cruz et al. (2015)
		344	Yes	Toxicological	Silva et al. (2015)
		344	Yes	Toxicological	Florêncio et al. (2014)
Hypostomus affinis (Steindachner 1877)	Cascudo-areia	329	Yes	Morphological	Morado et al. (2017)
Hypostomus ancistroides (Ihering 1911)	Cascudo	344	Yes	Toxicological	Rodrigues & Smith (2022)
		344	Yes	Histopathological	Amadeo et al. (2013)
Hypostomus auroguttatus (Kner 1854)	Cascudo	329	Yes	Morphological	Morado et al. (2017)
Lithodoras dorsalis (Valenciennes 1840)	Bacu pedra	323	Yes	Toxicological	Serrão et al. (2014)
Megaleporinus obtusidens (Valenciennes 1837)	Piau-verdadeiro	334	Yes	Toxicological	Glusczak et al. (2011)
Mylossoma duriventre (Cuvier 1818)	Pacu Manteiga	324	Yes	Morphological	Stragliotto et al. (2018)
			No	Criteria proposed by Johnson et al. (1993)	Freitas & Siqueira-Souza (2009)
Peckoltia multispinis (Holly 1929)	Acari	330	Yes	Physiological	Klemz & Assis (2005)
Pellona castelnaeana (Valenciennes 1847)	Apapá		No	Criteria proposed by Johnson et al. (1993)	Freitas & Siqueira-Souza (2009)
Phalloceros caudimaculatus (Hensel 1868)	Guaru	328	Yes	Toxicological	Cruz et al. (2015)
Phalloceros harpagos (Lucinda 2008)	Barrigudinho	344	Yes	Morphological and physiological	Barrilli et al. (2015)
Piaractus mesopotamicus (Holmberg 1887)	Pacu	328	Yes	Toxicological	Cruz et al. (2015)
		344	Yes	Toxicological	Florêncio et al. (2014)

Table 1. Continued...

Species	Popular Name	Ecoregions	Validated Potencial	Research approach	References
Pimelodus maculatus (Lacepède 1803)	Mandi	329	Yes	Morphological and physiological	Morado et al. (2018)
		329	Yes	Morphological and physiological	Araújo et al. (2018)
Plagioscion squamosissimus (Heckel 1840)	Corvina	323	Yes	Toxicological	Serrão et al. (2014)
Poecilia reticulata (Peters 1859)	Barrigudinho	344	Yes	Morphological	Alves et al. (2016)
		328	Yes	Physiological	Stringuetti et al. (2008)
		344	Yes	Morphological and physiological	Barrilli et al. (2015)
Poecilia vivípara (Bloch & Schneider 1801)	Guaru	344	Yes	Morphological and toxicological	Silva et al. (2002)
Potamorhina altamazonica (Cope 1878)	Branquinha		No	Criteria proposed by Johnson et al. (1993)	Freitas & Siqueira-Souza (2009)
Prochilodus lineatus (Valenciennes 1837)	Grumatã	344	Yes	Toxicological	Martinez & Cólus (2002)
		344	Yes	Toxicological	Rodrigues & Smith (2022)
		344	Yes	Histological, physiological and toxicological	Winkaler et al. (2007)
		344	Yes	Toxicological	Modesto & Martinez (2010)
Prochilodus nigricans (Spix & Agassiz 1829)	Corimbatá		No	Criteria proposed by Johnson et al. (1993)	Freitas & Siqueira-Souza (2009)
Psalidodon fasciatus (Cuvier 1819)	Lambari	344	Yes	Histological and physiological	Martinez & Cólus (2002)
		334	Yes	Morphological	Schulz & Martins-Junior (2001)
Psalidodon paranae (Eigenmann 1914)	Lambari	344	Yes	Morphological and physiological	Barrilli et al. (2015)
Pterygoplichthys ambrosettii (Holmberg 1893)	Cascudo	344	Yes	Toxicological	Rodrigues & Smith (2022)
Pterygoplichthys pardalis (Castelnau 1855)	Acari	316	Yes	Toxicological	Silva et al. (2019)
			No	Criteria proposed by (Johnson et al., 1993)	Freitas & Siqueira-Souza (2009)
Pygocentrus nattereri (Kner 1858)	Piranha vermelha	322	Yes	Toxicological	Silva et al. (2005)
			No	Criteria proposed by Johnson et al. (1993)	Freitas & Siqueira-Souza (2009)
Rhamdia quelen (Quoy & Gaimard 1824)	Jundiá	332	Yes	Toxicological, physiological and histological	Miron et al. (2008)
		344	Yes	Toxicological	Rodrigues & Smith (2022)
		334	Yes	Toxicological	Menezes et al. (2011)
		333	Yes	Toxicological	Ferreira et al. (2010)
Schizodon intermedius (Garavello & Britski 1990)	Piava	344	Yes	Morphological	Martinez & Cólus (2002)
Schizodon nasutus (Kner 1858)	Timboré	344	Yes	Morphological	Martinez & Cólus (2002)
Sciades herzbergii (Bloch 1794)	Bagre branco	325	Yes	Histological	Sousa et al. (2013)
Serrasalmus aff. eigenmanni (Norman 1929)	Piranha branca	316	Yes	Toxicological	Dórea et al. (2004)
Serrasalmus rhombeus (Linnaeus 1766)	Piranha preta	316	Yes	Toxicological	Dórea et al. (2004)
		323	Yes	Histopathological and toxicological	Montes et al. (2020)
		323	Yes	Histopathological and toxicological	Borges et al. (2018)
			No	Criteria proposed by Johnson et al. (1993)	Freitas & Siqueira-Souza (2009)
Steindachnerina insculpta (Fernández-Yépez 1948)	Saguiru	344	Yes	Morphological	Martinez & Cólus (2002)
Triportheus angulatus (Spix & Agassiz 1829)	Sardinha		No	Criteria proposed by Johnson et al. (1993)	Freitas & Siqueira-Souza (2009)

of ichthyological communities as bioindicators were excluded from the bibliographic analysis.

The individual capacity of each species to serve as a bioindicator was prioritized in this study, as suggested by Viana et al. (2010). Gills and muscles were the most commonly studied animal tissues for bioindicator analysis.

Among the identified species, *Rhamdia quelen* (Quoy & Gaimard, 1824), *Hoplias malabaricus* (Bloch, 1794), *Geophagus brasiliensis* (Quoy & Gaimard, 1824), *Poecilia reticulata* (Peters, 1859) and the genus *Astyanax* were the most frequently cited as bioindicators (refer to Table 1). Some species listed in the table have not been yet validated but hold potential as bioindicators according to the criteria proposed by Johnson et al. (1993). These criteria include easy recognition, cosmopolitan distribution, numerical abundance, limited mobility, well-known ecological characteristics, and suitability for laboratory studies.

The distribution of bioindicator species shows a significant disparity (Figure 1). The Upper Paraná ecoregion stands out with 18 bioindicator species, while several other ecoregions lack substantial research indicating species with bioindicator potential.

4. Discussion

Scientific literature underscores the significance of national-level scientific research in fostering innovation and driving economic development. Nevertheless, recent studies reveal an uneven distribution of scientific development within Brazil, primarily favoring regions in the south and southeast (Melo et al., 2019). This concentration of scientific activities has resulted in regional disparities in development and underscores the association between resource allocation and the economic capacity of specific regions (Melo et al., 2019; Mowery & Sampat, 2009). The ramifications of this centralized approach to scientific development are potentially detrimental to various domains of scientific research, including the study of biodiversity and the distribution of ichthyofauna.

The Upper Paraná watershed is recognized for its rich diversity of scientifically validated

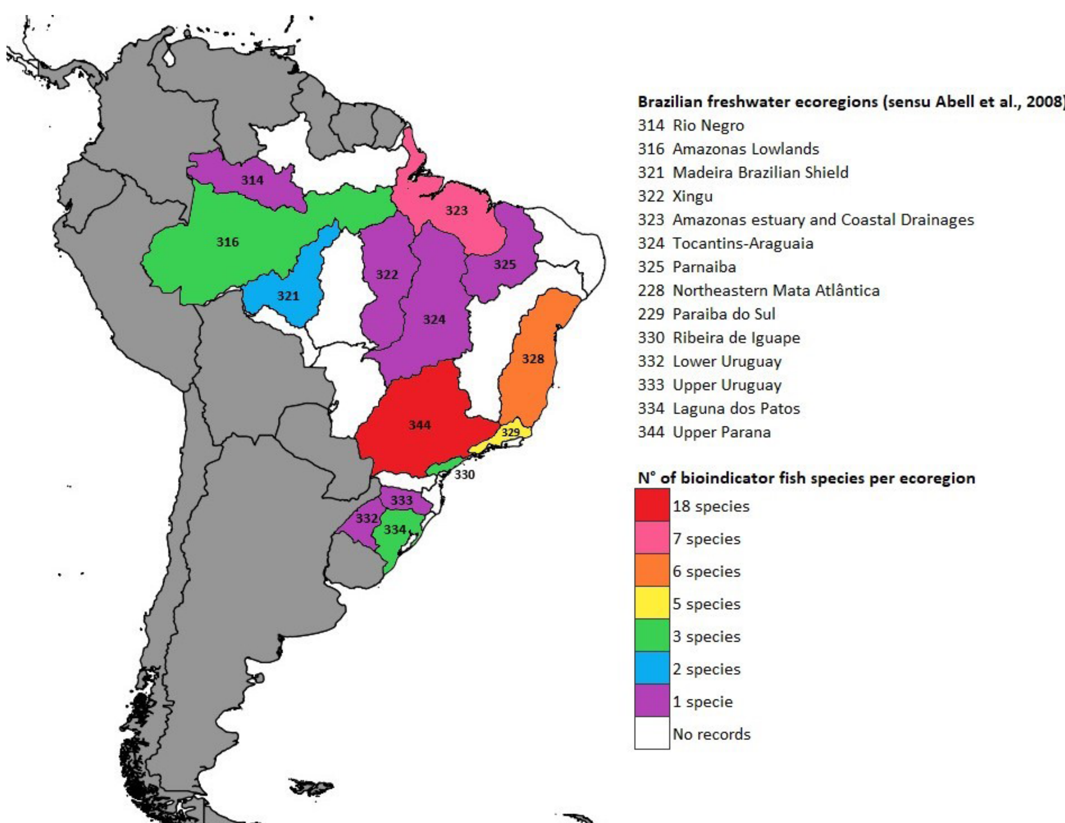

Figure 1. Reported distribution map of bioindicator species in Brazilian freshwater ecoregions. The map shows the distribution of species in South American freshwater ecoregions highlighted in color, marked by numbers, according to Abell et al. (2008). The uncolored and unnumbered regions did not show records of bioindicator species. The regions highlighted in gray are not part of the territory addressed in this work.

bioindicator species (Figure 1). However, this basin is facing substantial anthropic disturbances, making it one of the most impacted regions in the area (Agostinho et al., 2003; Castro & Arcifa, 1987). Despite extensive research conducted in Brazil, there still exists a significant number of species within this ecoregion that remain unknown or understudied (Agostinho & Júlio Júnior, 1999; Langeani et al., 2007). Molecular studies and identification efforts have highlighted this knowledge gap (Pereira et al., 2013), emphasizing the vulnerability of the ichthyofauna in the area. It is important to note that this situation may be even more critical in regions with higher biodiversity, where studies on fish as bioindicators are scarce or virtually non-existent.

Castro and Polaz (2020) highlight the limited translocation capacity of small species in aquatic environments, which leads to their local endemism as they do not migrate extensively between ecoregions during their life cycle. However, *Poecilia reticulata*, a small species (Lucinda, 2003), has been intentionally introduced for vector control and has achieved a widespread geographic distribution across various water bodies (Graça & Pavanelli, 2007). The broad distribution of *P. reticulata* presents significant potential for conducting comparative studies in degraded regions, especially when compared to locally distributed species. *P. reticulata* has the ability to indicate negative environmental disturbances in its habitat due to its high resilience to anthropogenic changes (Souza & Tozzo, 2013). However, it is important to consider that despite its bioindicator characteristics, these attributes may ultimately contribute to environmental issues for small aquatic communities (Souza & Tozzo, 2013; Widianarko et al., 2000).

Rhamdia quelen, a nocturnal species, displays a generalist feeding strategy, with a tendency towards omnivory. Small individuals primarily consume insects, while adults predominantly feed on fish (Casatti & Castro, 1998; Gomiero & Braga, 2008; C. C. G. F. Pereira et al., 2004). This species has a wide distribution (Albert et al., 2020) and is commonly found in fish farming, particularly in southern Brazil (Gomes et al., 2000; Marchioro & Baldisserotto, 1999). It exhibits remarkable resilience to environmental stressors, including temperature fluctuations and low salinity levels (Marchioro & Baldisserotto, 1999). Considering its morphological and physiological characteristics, *R. quelen* is regarded as a valuable bioindicator species (Chovanec et al., 2003; Johnson et al., 1993). However, taxonomic investigations have revealed that *R. quelen* represents a complex taxonomic scenario encompassing multiple species (Albert et al., 2020; Ríos et al., 2020; Scaranto et al., 2018; Silfvergrip, 1996). As different species may respond differently to the same environmental stimuli, studies employing *R. quelen* as a bioindicator must be conducted with care, preferably focusing on regional scopes, as observed in the studies included in this review (Table 1). Consequently, the ability to make comparisons between distant ecoregions, as is the case with *Poecilia reticulata*, may be compromised.

Several tissues have been tested for their bioindicator potential, but their use has proven to be limited, making comparisons between species and regions challenging (Table 1). Among the tissues, the branchial and hepatic tissues stand out as the most promising. Not only are they the most extensively studied, but they also possess characteristics that favor their use. The gills, being directly exposed to substances in the aquatic environment, are the first to experience the negative effects of pollution (Batista et al., 2014; Chovanec et al., 2003; Lins et al., 2010; Stagg & Shuttleworth, 1982). On the other hand, the liver receives a majority of circulating pollutants through the bloodstream, resulting in a higher accumulation of pollutants in liver tissue and making the organ more susceptible to damage (Batista et al., 2014; Chovanec et al., 2003; Lins et al., 2010). In addition to the average number of studies indicating the use of fish and their tissues as bioindicators, some authors have tested enzymes as biomarkers for individuals and environmental contamination (e.g., mercury and pesticides) (Batista et al., 2014; Braga et al., 2015; Menezes et al., 2011; Queiroz et al., 2019; Klemz & Assis, 2005; Moraes et al., 2012; Sinhorin et al., 2014; Tortelli et al., 2006).

In conclusion, this study highlights the incomplete nature of research on bioindicators of the Brazilian ichthyofauna, considering the vast number of species in existence. Currently, only a limited number of species have been studied, and research efforts are unevenly distributed. As a result, only a few species and a small number of tissues have been investigated. It is crucial to expand studies in this field to explore the bioindicator potential of species residing in other regions, such as the Amazon and the São Francisco region. Additionally, given the importance of ichthyofauna in assessing environmental quality, the scientific community should prioritize and conduct more studies focused on utilizing ichthyofauna as bioindicators.

References

Abell, R., Thieme, M.L., Revenga, C., Bryer, M., Kottelat, M., Bogutskaya, N., Coad, B., Mandrak, N., Balderas, S.C., Bussing, W., Stiassny, M.L.J., Skelton, P., Allen, G.R., Unmack, P., Naseka, A., Ng, R., Sindorf, N., Robertson, J., Armijo, E., Higgins, J.V., Heibel, T.J., Wikramanayake, E., Olson, D., López, H.L., Reis, R.E., Lundberg, J.G., Sabaj Pérez, M.H., & Petry, P., 2008. Freshwater ecoregions of the world: a new map of biogeographic units for freshwater biodiversity conservation. Bioscience 58(5), 403-414. http://doi.org/10.1641/B580507.

Agostinho, A.A., & Júlio Júnior, H.F., 1999. Peixes da Bacia do Alto Rio Paraná. In: Lowe-McConnell, R.H., ed. Estudos ecológicos de comunidades de peixes tropicais. São Paulo: Edusp, 374-400.

Agostinho, A.A., Gomes, L.C., Suzuki, H.I., & Júlio Júnior, H.F., 2003. Migratory fishes of the Upper Paraná River Basin, Brazil. In: Carosfeld, J., Harvey, B., Ross, C.V., & Baer A. eds. Migratory fishes of South America: biology, fisheries and conservation status. Ottowa: The World Bank, International Development Centre, 19-98.

Albert, J.S., Tagliacollo, V.A., & Dagosta, F., 2020. Diversification of neotropical freshwater fishes. Annu. Rev. Ecol. Evol. Syst. 51(1), 27-53. http://doi.org/10.1146/annurev-ecolsys-011620-031032.

Alves, G.H.Z., Tófoli, R.M., Ganassin, M.J.M., & Hahn, N.S., 2016. Diet of *Poecilia reticulata* Peters, 1959 in streams from Paraná River basin: influence of the urbanization. Acta Sci. Biol. Sci. 38(3), 313-318. http://doi.org/10.4025/actascibiolsci.v38i3.29881.

Amadeo, R.M., Godinho, J.P., Ghisi, N.C., & Oliveira, E.C., 2013. Histopatologias em tecido hepático do peixe cascudo *Hypostomus ancistroides* (Ihering, 1911) como indicadores de contaminação aquática no rio Pirapó. In: Anais do 17° Seminário de Iniciação Científica e Tecnologia da UTFPR. Curitiba: UTFPR.

Araújo, F.G., Morado, C.N., Parente, T.T.E., Paumgartten, F.J.R., & Gomes, I.D., 2018. Biomarkers and bioindicators of the environmental condition using a fish species (*Pimelodus maculatus* Lacepède, 1803) in a tropical reservoir in Southeastern Brazil. Braz. J. Biol. 78(2), 351-359. PMid:28832840. http://doi.org/10.1590/1519-6984.167209.

Arias, A.R.L., Buss, D.F., Alburquerque, C., Inácio, A.F., Freire, M.M., Egler, M., Mugnai, R., & Baptista, D.F., 2007. Utilização de bioindicadores na avaliação de impacto e no monitoramento da contaminação de rios e córregos por agrotóxicos. Cien. Saude Colet. 12(1), 61-72. PMid:17680059. http://doi.org/10.1590/S1413-81232007000100011.

Baptista, D.F., Buss, D.F., & Egler, M., 2003. Macroinvertebrados como bioindicadores de ecossistemas aquáticos contaminados por agrotóxicos. In: Peres, F., & Moreira, J., eds. É veneno ou é remédio? Agrotóxicos, saúde e ambiente. Rio de Janeiro: Fiocruz, 157-175.

Barbieri, E., Marinho, D., & Brusius, B.K., 2022. Bagre estuarino *Cathorops spixii* como bioindicador de metais pesados: um estudo de caso. In Cordeiro, C.A.M., Sampaio, D.S., & Holanda, F.C.A.F., eds. Engenharia de pesca: aspectos teóricos e práticos. São Paulo: Científica Digital, vol. 3, 105-116. http://doi.org/10.37885/211206960.

Barrilli, G.H.C., Rocha, O., Negreiros, N.F., & Verani, J.R., 2015. Influence of environmental quality of the tributaries of the Monjolinho River on the relative condition factor (Kn) of the local ichthyofauna. Biota Neotrop. 15(1), 1-9. http://doi.org/10.1590/1676-06032015010714.

Batista, M.T.O., Rodrigues Junior, E., Feijó-Oliveira, M., Ribeiro, A.C., Rodrigues, E., Suda, C.N.K., & Vani, G.S., 2014. Tissue levels of the antioxidant enzymes superoxide dismutase and catalase in fish *Astyanax bimaculatus* from the Una River Basin. Rev. Ambient. Água 9(4), 621-631. https://doi.org/10.4136/ambi-agua.1473.

Borges, A.C., Montes, C.S., Barbosa, L.A., Ferreira, M.A.P., Berrêdo, J.F., & Rocha, R.M., 2018. Integrated use of histological and ultrastructural biomarkers for assessing mercury pollution in piranhas (*Serrasalmus rhombeus*) from the Amazon mining region. Chemosphere 202, 788-796. PMid:29614470. http://doi.org/10.1016/j.chemosphere.2018.02.169.

Braga, C.P., Bittarello, A.C., Padilha, C.C.F., Leite, A.L., Moraes, P.M., Buzalaf, M.A.R., Zara, L.F., & Padilha, P.M., 2015. Mercury fractionation in dourada (*Brachyplatystoma rousseauxii*) of the Madeira River in Brazil using metalloproteomic strategies. Talanta 132, 239-244. PMid:25476304. http://doi.org/10.1016/j.talanta.2014.09.021.

Bücker, A., Carvalho, W., & Alves-Gomes, J.A., 2006. Avaliation of mutagenicity and gentotoxicity in *Eigenmannia virescens* (Teleostei: Gymnotiformes) exposed to benzene. Acta Amazon. 36(3), 357-364. http://doi.org/10.1590/S0044-59672006000300011.

Calixto, J.B., 2003. Biodiversidade como fonte de medicamentos. Cienc. Cult. 55(3), 37-39.

Casatti, L., & Castro, R.M.C., 1998. A fish community of the São Francisco River headwaters riffles, southeastern Brazil. Ichthyol. Explor. Freshwat. 9(3), 229-242.

Castro, R.M.C., & Arcifa, M.S., 1987. Comunidades de peixes de reservatórios no sul do Brasil. Rev. Bras. Biol. 47(4), 493-500.

Castro, R.M.C., & Polaz, C.N.M., 2020. Small-sized fish: the largest and most threatened portion of the megadiverse neotropical freshwater fish fauna. Br. Educ. Res. J. 20(1), 1-12. http://doi.org/10.1590/1676-0611-bn-2018-0683.

Cerejeira, M.J., Viana, P., Batista, S., Pereira, T., Silva, E., Valério, M.J., Silva, A., Ferreira, M., & Silva-Fernandes, A.M., 2003. Pesticides in Portuguese surface and ground waters. Water Res. 37(5), 1055-1063. PMid:12553980. http://doi.org/10.1016/S0043-1354(01)00462-6.

Chovanec, A., Hofer, R., & Schiemer, F., 2003. Fish as bioindicators. In: Markert, B.A.A., Breure, M., & Zechmeister, H.G., eds. Bioindicators and biomonitors. Amsterdam: Elsevier Science Ltd., 639-676.

Clements, W.H., 2000. Integrating effects of contaminants across levels of biological organization: an overview. J. Aquat. Ecosyst. Stress Recovery 7(2), 113-116. http://doi.org/10.1023/A:1009927612391.

Costa, C.R., Olivi, P., Botta, C.M.R., & Espindola, E.L.G., 2008. A toxicidade em ambientes aquáticos: discussão e métodos de avaliação. Quim. Nova 31(7), 1820-1830. http://doi.org/10.1590/S0100-40422008000700038.

Cruz, C., Silva, A.F., Shiogiri, N.S., Garlich, N., & Pitelli, R.A., 2015. Imazapyr herbicide efficacy on floating macrophyte control and ecotoxicology for non-target organisms. Planta Daninha 33(1), 103-108. http://doi.org/10.1590/S0100-83582015000100012.

De Filippo, R., 2000. Impactos ambientais sobre os ecossistemas aquáticos. Inf. Agropecu. 21(202), 45-53.

Disner, G.R., Calado, S.L.M., Silva Assis, H.C., & Cestari, M.M., 2017. Toxicity of naphthalene in the neotropical fish *Astyanax lacustris* (Characiformes: Characidae) and *Geophagus brasiliensis* (Perciformes: Cichlidae). Evidência 17(1), 7-22. http://doi.org/10.18593/eba.v17i1.12976.

Dórea, J.G., Barbosa, A.C., Souzade, J., Fadini, P., & Jardim, W.F., 2004. Piranhas (*Serrasalmus* spp.) as markers of mercury bioaccumulation in Amazonian ecosystems. Ecotoxicol. Environ. Saf. 59(1), 57-63. PMid:15261723. http://doi.org/10.1016/j.ecoenv.2003.07.012.

Ferreira, D., Motta, A.C., Kreutz, L.C., Toni, C., Loro, V.L., & Barcellos, L.J.G., 2010. Assessment of oxidative stress in *Rhamdia quelen* exposed to agrichemicals. Chemosphere 79(9), 914-921. PMid:20371099. http://doi.org/10.1016/j.chemosphere.2010.03.024.

Florêncio, T., Carraschi, S.P., Cruz, C., Silva, A.F., Marques, A.M., & Pitelli, R.A., 2014. Neotropical bioindicators of ecotoxicity and environmental risk of drugs with aquaculture interest. Bol. Inst. Pesca 40(4), 569-576. Retrieved in 2024, March 24, from https://institutodepesca.org/index.php/bip/article/view/1062

Freitas, C.E.C., & Siqueira-Souza, F.K., 2009. O uso de peixes como bioindicador ambiental em áreas de várzea da bacia amazônica. Agrogeoambiental 1(2), 39-45. http://doi.org/10.18406/2316-1817v1n2200975.

Glusczak, L., Loro, V.L., Pretto, A., Moraes, B.S., Raabe, A., Duarte, M.F., Fonseca, M.B., Menezes, C.C., & Valladão, D.M.S., 2011. Acute exposure to glyphosate herbicide affects oxidative parameters in piava (*Leporinus obtusidens*). Arch. Environ. Contam. Toxicol. 61(4), 624-630. PMid:21465245. http://doi.org/10.1007/s00244-011-9652-4.

Gomes, L.C., Golombieski, J.I., Gomes, A.R.C., & Baldisserotto, B., 2000. Biologia do jundiá *Rhamdia quelen* (Teleostei, Pimelodidae). Cienc. Rural 30(1), 179-185. http://doi.org/10.1590/S0103-84782000000100029.

Gomiero, L.M., & Braga, F.M.S., 2008. Feeding habits of the ichthyofauna in a protected area in the state of São Paulo, southeastern Brazil. Biota Neotrop. 8(1), 41-47. http://doi.org/10.1590/S1676-06032008000100004.

Goulart, M.D.C., & Callisto, M., 2003. Bioindicadores de qualidade de água como ferramenta em estudos de impacto ambiental. Rev FAPAM. 2(1), 1-9. Retrieved in 2024, March 24, from https://labs.icb.ufmg.br/benthos/index_arquivos/pdfs_pagina/Goulart%20&%20Callisto-Fapam.pdf

Graça, W.J., & Pavanelli, C.S., 2007. Peixes da planíce de inundação do alto rio Paraná e áreas adjacentes. Maringá: EDUEM.

Johnson, R.K., Wiederholm, T., & Rosenberg, D.M., 1993. Freshwater Biomonitoring Using Individual Organisms, Populations, and Species Assemblages of Benthic Macroinvertebrates. In: Rosenberg, D.M., & Resh, V.H., eds. Freshwater biomonitoring and benthic macroinvertebrates. New York: Springer, 40-158.

Klemz, C., & Assis, H.C.S., 2005. Efeitos do endosulfano na atividade da acetilcolinesterase de cascudo (*Ancistrus multispinnis*, fish, teleostei). Rev. Acad. Ciênc. Anim. 3(4), 51-58. http://doi.org/10.7213/cienciaanimal.v3i4.9231.

Langeani, F., Castro, R.M.C., Oyakawa, O.T., Shibatta, O.A., Pavanelli, C.S., & Casatti, L., 2007. Diversidade da ictiofauna do Alto Rio Paraná : composição atual e perspectivas futuras. Biota Neotrop. 7(3), 181-197. http://doi.org/10.1590/S1676-06032007000300020.

Lins, J.A.P.N., Kirschnik, P.G., Queiroz, V.S., & Cirio, S.M., 2010. Uso de peixes como biomarcadores para monitoramento ambiental aquático. Rev. Acad. 8(4), 469-484. http://doi.org/10.7213/cienciaanimal.v8i4.11018.

Lucinda, P.H.F. 2003. Family Poeciliidae. In: Reis, R.E., Kullander, S.O., & Ferraris Junior, C.J., eds. Check list of the freshwater fishes of South and Central America. Porto Alegre: EDIPUCRS, 555-581.

MacKenzie, K., Williams, H.H., Williams, B., Mcvicar, A.H., & Siddall, R., 1995. Parasites as indicators of water quality and the potential use of helminth transmission in marine pollution studies. Adv. Parasitol. 35, 85-144. PMid:7709856. http://doi.org/10.1016/S0065-308X(08)60070-6.

Marchioro, M.I., & Baldisserotto, B., 1999. Sobrevivência de alevinos de Jundiá (*Rhamdia quelen* Quoy & Gaimard, 1824) à variação de salinidade da água. Cienc. Rural 29(2), 315-318. http://doi.org/10.1590/S0103-84781999000200021.

Markert, B., 1994. Biomonitoring - Quo Vadis. Environ. Sci. Eur. 6(3), 145-149. http://doi.org/10.1007/BF02937693.

Martinez, C.B.R.R., & Cólus, I.M.S.S., 2002. Biomarcadores em peixes neotropicais para o monitoramento da poluição aquática na bacia do rio Tibagi. In: Medri, M.E., Bianchini, E., Shibatta, O.A., & Pimenta, J.A., eds. A bacia do rio Tibagi. Londrina: Eduel, 551-577.

Melo, J.N., Santana, J.R., & Silva, G.F., 2019. Ciência, tecnologia e inovação no Brasil: uma análise inter-regional por meio de indicadores. Rev. Bras. Gest. Desenvolv. Reg. 15(1), 76-90. https://doi.org/10.54399/rbgdr.v15i1.4321.

Menezes, C.C., Loro, V.L., Fonseca, M.B., Cattaneo, R., Pretto, A., Miron, D.S., & Santi, A., 2011. Oxidative parameters of *Rhamdia quelen* in response to commercial herbicide containing clomazone and recovery pattern. Pestic. Biochem. Physiol. 100(2), 145-150. http://doi.org/10.1016/j.pestbp.2011.03.002.

Miranda, A.L., Roche, H., Randi, M.A.F., Menezes, M.L., & Ribeiro, C.A.O., 2008. Bioaccumulation of chlorinated pesticides and PCBs in the tropical freshwater fish *Hoplias malabaricus*: histopathological, physiological, and immunological findings. Environ. Int. 34(7), 939-949. PMid:18400298. http://doi.org/10.1016/j.envint.2008.02.004.

Miron, D. dos S., Moraes, B., Becker, A.G., Crestani, M., Spanevello, R., Loro, V.L., & Baldisserotto, B., 2008. Ammonia and pH effects on some metabolic parameters and gill histology of silver catfish, *Rhamdia quelen* (Heptapteridae). Aquaculture 277(3-4), 192-196. http://doi.org/10.1016/j.aquaculture.2008.02.023.

Mittermeier, R.A., Da Fonseca, G.A.B., Rylands, A.B., & Brandon, K., 2005. Uma breve história da conservação da biodiversidade no Brasil. Megadiversidade 1(1), 14-21. http://doi.org/10.1590/S0011-52582006000100003.

Modesto, K.A., & Martinez, C.B.R., 2010. Roundup® causes oxidative stress in liver and inhibits acetylcholinesterase in muscle and brain of the fish *Prochilodus lineatus*. Chemosphere 78(3), 294-299. PMid:19910015. http://doi.org/10.1016/j.chemosphere.2009.10.047.

Montes, C.S., Ferreira, M.A.P., Giarrizzo, T., Amado, L.L., & Rocha, R.M., 2020. Evaluation of metal contamination effects in piranhas through biomonitoring and multi biomarkers approach. Heliyon 6(8), e04666. PMid:32904315. http://doi.org/10.1016/j.heliyon.2020.e04666.

Morado, C.N., Araújo, F.G., & Gomes, I.D., 2017. The use of biomarkers for assessing effects of pollutant stress on fish species from a tropical river in Southeastern Brazil. Acta Sci. Biol. Sci. 39(4), 431-439. http://doi.org/10.4025/actascibiolsci.v39i4.34293.

Morado, C.N., Parente, T.E.M., Araújo, F.G., Paumgarten, F.J.R., & Gomes, I.D., 2018. Induced CYP1A activity and DNA damage in fish from the middle Paraíba do Sul River Basin, southeastern Brazil. Acta Sci. Biol. Sci. 40(1), e1. http://doi.org/10.4025/actascibiolsci.v40i1.36666.

Moraes, P.M., Santos, F.A., Padilha, C.C.F., Vieira, J.C.S., Zara, L.F., De, M., & Padilha, P., 2012. A preliminary and qualitative metallomics study of mercury in the muscle of fish from Amazonas, Brazil. Biol. Trace Elem. Res. 150(1-3), 195-199. PMid:22956354. http://doi.org/10.1007/s12011-012-9502-x.

Mowery, D.C., & Sampat, B.N., 2009. Universities in national innovation systems. In: Fagerberg, J., & Mowery, D.C., eds. The Oxford handbook of Innovation. Oxford: Oxford University Press, 209-239. http://doi.org/10.1093/oxfordhb/9780199286805.003.0008.

Nunes, V.J., & Jesus, T.B., 2019. Determinação de metais pesados (Mn, Cd, Cr, Cu, Pb) em peixes das espécies *Astyanax bimaculatus*, *Hoplias malabarcius* e *Oreochromis niloticus* presente na Lagoa Salgada - Rio Subaé - Feira de Santana (Bahia). Rev. Bras. Meio Ambient. 5(1), 2-13.

Pereira, C.C.G.F., Smith, W.S., & Espíndola, E.L.G., 2004. Feeding habits of nine species of fish in Três Irmãos reservoir, São Paulo, Brazil. Univ Cienc. (spe 1), 33-38. Retrieved in 2024, March 24, from https://www.redalyc.org/articulo.oa?id=15409905

Pereira, L.H.G., Hanner, R., Foresti, F., & Oliveira, C., 2013. Can DNA barcoding accurately discriminate megadiverse Neotropical freshwater fish fauna? BMC Genet. 14, 20. PMid:23497346. http://doi.org/10.1186/1471-2156-14-20.

Printes, L.B., & Callaghan, A., 2003. Intraclonal variability in Daphnia acetylcholinesterase activity: the implications for its applicability as a biomarker. Environ. Toxicol. Chem. 22(9), 2042-2047. PMid:12959529. http://doi.org/10.1897/02-424.

Queiroz, J.V., Vieira, J.C.S., Oliveira, G., Braga, C.P., Bataglioli, I.C., Silva, J.M., Araújo, W.L.P., &

Padilha, P.M., 2019. Identification of biomarkers of mercury contamination in *Brachyplatystoma filamentosum* of the Madeira River, Brazil, using metalloproteomic strategies. Biol. Trace Elem. Res. 187(1), 291-300. PMid:29740802. http://doi.org/10.1007/s12011-018-1363-5.

Rand, G.M., Wells, P.G., & Mccarty, L.S., 1995. Introduction to aquatic toxicology. In: Rand, G.M., ed. Fundamentals of aquatic toxicology: effects, environmental fate, and risk assessment. Bristol: Taylor & Francis, 3-67, 2 ed.

Reis, R.E., Albert, J.S., Di Dario, F., Mincarone, M.M., Petry, P., & Rocha, L.A., 2016. Fish biodiversity and conservation in South America. J. Fish Biol. 89(1), 12-47. PMid:27312713. http://doi.org/10.1111/jfb.13016.

Ríos, N., Casanova, A., Hermida, M., Pardo, B.G., Martínez, P., Bouza, C., & García, G., 2020. Population genomics in *Rhamdia quelen* (Heptapteridae, siluriformes) reveals deep divergence and adaptation in the neotropical region. Genes 11(1), 1-27. PMid:31963477. http://doi.org/10.3390/genes11010109.

Rodrigues, A.P.C., & Castilhos, Z.C., 2003. Avaliação de risco ecológico em ecossistemas aquáticos contaminados por mercurio. Estudo de caso: Ilha das Enxadas, Baía de Guanabara, RJ. In: Anais da 11ª Jornada de Iniciação Científica. Rio de Janeiro: CETEM/MCTI. Retrieved in 2024, March 24, from http://mineralis.cetem.gov.br/handle/cetem/810

Rodrigues, K.F.S., & Smith, W.S., 2022. Assessment of potentially toxic metals in water, sediment, and the tissues of seven important fish species from neotropical brazilian river. Neotrop. Ichthyol. 20(4), 1-16. http://doi.org/10.1590/1982-0224-2021-0155.

Scaranto, B.M.S., Ribolli, J., & Zaniboni Filho, E., 2018. DNA barcoding reveals blend of silver catfish *Rhamdia* species from fish farms in Southern Brazil. Aquacult. Res. 49(5), 1907-1913. http://doi.org/10.1111/are.13646.

Schulz, U.H., & Martins-Junior, H., 2001. *Astyanax fasciatus* as bioindicator of water pollution of Rio dos Sinos, RS, Brazil. Braz. J. Biol. 61(4), 615-622. PMid:12071317. http://doi.org/10.1590/S1519-69842001000400010.

Serrão, C.R.G., Pontes, A.N., Dantas, K.G.F., Dantas Filho, H.A., Pereira Júnior, J.B., Nunes, P.O., Carvalho, F.I.M., & Palheta, D.C., 2014. Biomonitoring metallic elements in freshwater fish of Amazon. Rev. Virtual Quim. 6(6), 1661-1676. http://doi.org/10.5935/1984-6835.20140107.

Silfvergrip, A.M.C., 1996. A systematic revision of the neotropical catfish genus *Rhamdia* (Teleostei, Pimelodidae). Stockholm: Stockholm University.

Silva, A.F., Carraschi, S.P., Gírio, A.C.F., Nader Neto, A., Cruz, C., & Pitelli, R.A., 2015. Ecotoxicity of vinasse for fish tetra-serpae (*Hyphessobrycon eques*) and macrophyte duckweed (*Lemna minor*). Bol. Inst. Pesca 41(3), 557-565. Retrieved in 2024, March 24, from https://institutodepesca.org/index.php/bip/article/view/41_3_557-565

Silva, D.S., Lucotte, M., Roulet, M., Poirier, H., Mergler, D., Santos, E.O., & Crossa, M., 2005. Trophic structure and bioaccumulation of mercury in fish of three natural lakes of the Brazilian amazon. Water Air Soil Pollut. 165(1-4), 77-94. http://doi.org/10.1007/s11270-005-4811-8.

Silva, L.D., Rosa, E.V., Santos, S.C., & de Sabóia-Morais, S.M.T., 2002. Análise morfométrica do epitélio de revestimento branquial do guaru (*Poecilia vivipara*) exposto a frações do extrato da folha e casca do caule de pequi (*Caryocar brasiliensis*). Arq. Ciênc. Saúde UNIPAR 6(3), 101-106. Retrieved in 2024, March 24, from http://repositorio.bc.ufg.br/handle/ri/16620

Silva, S.F., Oliveira, D.C., Pereira, J.P.G., Castro, S.P., Costa, B.N.S., & Lima, M.O., 2019. Seasonal variation of mercury in commercial fishes of the Amazon Triple Frontier, Western Amazon Basin. Ecol. Indic. 106, 1-8. http://doi.org/10.1016/j.ecolind.2019.105549.

Sinhorin, V.D.G., Sinhorin, A.P., Teixeira, J.M. dos S., Miléski, K.M.L., Hansen, P.C., Moreira, P.S.A., Kawashita, N.H., Baviera, A.M., & Loro, V.L., 2014. Effects of the acute exposition to glyphosate-based herbicide on oxidative stress parameters and antioxidant responses in a hybrid Amazon fish surubim (*Pseudoplatystoma* sp.). Ecotoxicol. Environ. Saf. 106, 181-187. PMid:24840881. http://doi.org/10.1016/j.ecoenv.2014.04.040.

Smith, V.H., & Schindler, D.W., 2009. Eutrophication science: where do we go from here? Trends Ecol. Evol. 24(4), 201-207. PMid:19246117. http://doi.org/10.1016/j.tree.2008.11.009.

Sousa, D.B.P., Almeida, Z.S., & Carvalho-Neta, R.N.F., 2013. Biomarcadores histológicos em duas espécies de bagres estuarinos da Costa Maranhense, Brasil. Arq. Bras. Med. Vet. Zootec. 65(2), 369-376. http://doi.org/10.1590/S0102-09352013000200011.

Souza, F., & Tozzo, R.A., 2013. *Poecilia reticulata* Peters 1859 (Cyprinodontiformes, Poeciliidae) como possível bioindicador de ambientes degradados. Rev. Meio Ambient. Sustentabilidade 3(2), 162-175. https://doi.org/10.22292/mas.v3i2.164.

Stagg, R.M., & Shuttleworth, T.J., 1982. The accumulation of copper in *Platichthys flesus* L. and its effects on plasma electrolyte concentrations. J. Fish Biol. 20(4), 491-500. http://doi.org/10.1111/j.1095-8649.1982.tb03942.x.

Stragliotto, L.K.D., Paz, F.S., Paz, D.S., Tchaicka, L., Carvalho Neta, R.N.F., & Sousa, D.B.P., 2018.

Genotoxic biomarkers in fishes of the Chapada das Mesas National Park, Brazil. In: Suratman, M.N., ed. National parks: management and conservation. Rijeka: IntechOpen, 85-96. http://doi.org/10.5772/intechopen.72558.

Stringuetti, C., Guilhermino, L., & Silva, E.M., 2008. Cholinesterase activity in the head of wild *Poecilia reticulata* from Bahia, Brazil: biochemical characterization, effects of sample storage and normal range of activity. J. Braz. Soc. Ecotoxicol. 3(1), 57-63. http://doi.org/10.5132/jbse.2008.01.009.

Tortelli, V., Colares, E.P., Robaldo, R.B., Nery, L.E.M., Pinho, G.L.L., Bianchini, A., & Monserrat, J.M., 2006. Importance of cholinesterase kinetic parameters in environmental monitoring using estuarine fish. Chemosphere 65(4), 560-566. PMid:16643981. http://doi.org/10.1016/j.chemosphere.2006.02.047.

Viana, A.P., Lucena Frédou, F., Frédou, T., Torres, M.F., & Bordalo, A.O., 2010. Fish fauna as an indicator of environmental quality in an urbanised region of the Amazon estuary. J. Fish Biol. 76(3), 467-486. PMid:20666891. http://doi.org/10.1111/j.1095-8649.2009.02487.x.

Vital, J.F., Varella, A.M.B., Porto, D.B., & Malta, J.C. de O., 2011. Sazonalidade da fauna de metazoários de *Pygocentrus nattereri* (Kner, 1858) no lago Piranha (Amazonas, Brasil) e a avaliação de seu potencial como indicadora da saúde do ambiente. Biota Neotrop. 11(1), 199-204. http://doi.org/10.1590/S1676-06032011000100021.

Widianarko, B., van Gestel, C.A.M., Verweij, R.A., & Van Straalen, N.M., 2000. Associations between trace metals in sediment, water, and guppy, *Poecilia reticulata* (Peters), from urban streams of Semarang, Indonesia. Ecotoxicol. Environ. Saf. 46(1), 101-107. PMid:10806000. http://doi.org/10.1006/eesa.1999.1879.

Winkaler, E.U., Santos, T.R.M., Machado-Neto, J.G., & Martinez, C.B.R., 2007. Acute lethal and sublethal effects of neem leaf extract on the neotropical freshwater fish *Prochilodus lineatus.* Comp. Biochem. Physiol. C Toxicol. Pharmacol. 145(2), 236-244. PMid:17251062. http://doi.org/10.1016/j.cbpc.2006.12.009.

Received: 18 September 2023
Accepted: 25 March 2024

Associate Editor: Ronaldo Angelini.