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Original Article

Gill and hepatic histological alterations in *Sciades herzbergii* resulting from trace element contamination in the Port of São Luiz, Brazil

Alterações histológicas branquiais e hepáticas em *Sciades herzbergii* resultantes da contaminação por elementos traços no Porto de São Luís, Brasil

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Abstract

The objective of this study was to evaluate, through changes in the gills and livers of *Sciades herzbergii*, the environmental contamination to which estuarine organisms are exposed in two areas in São Marcos Bay - MA. Two collection areas located in São Marcos Bay were selected for this study: A1, an area close to the Port Complex, and A2, an area on Caranguejos Island (included in the Environmental Protection Area of Baixada Maranhense). Collections were carried out during rainy and dry periods. Sediments (for trace element analyses), surface water (for physico-chemical analyses), and specimens of *S. herzbergii* (for biometric measurements and identification of branchial and hepatic histopathology) were collected. Physico-chemical parameters (pH, dissolved oxygen, temperature and salinity) were within limits established by Brazilian legislation. Arsenic (in A1) and nickel (in A1 and A2) were above the legal standards in both periods. The highest percentage of histological alterations in the gills (aneurysms, lamellar fusion and detachment of the epithelium) occurred in the port area, in the rainy (93%) and dry (74%) periods. Liver alterations (melanomacrophage centers and necrosis) occurred only in specimens from the same area, in the rainy (41%) and dry (36%) periods. The highest histological indices of gill and liver changes were recorded in A1. This result was further supported by the total HI value of the lesions, which was higher in the port area compared to A2 (less impacted area), suggesting that the environmental conditions in that location are less favorable for the well-being of these organisms. Permanent environmental monitoring of the area is necessary to control environmental impacts efficiently.

Keywords: estuarine catfish, biological response, branchial lesions, liver lesions.

Resumo

O objetivo deste estudo foi avaliar, por meio de alterações nas brânquias e fígados de *Sciades herzbergii*, a contaminação ambiental a que os organismos estuarinos estão expostos em duas áreas da Baía de São Marcos - MA. Para este estudo foram selecionadas duas áreas de coleta localizadas na Baía de São Marcos: A1, área próxima ao Complexo Portuário, e A2, área na Ilha dos Caranguejos (incluída na Área de Proteção Ambiental da Baixada Maranhense). As coletas foram realizadas nos períodos chuvoso e seco. Foram coletados sedimentos (para análises de elementos traço), águas superficiais (para análises físico-químicas) e espécimes de *S. herzbergii* (para medidas biométricas e identificação de histopatologia branquial e hepática). Os parâmetros físico-químicos (pH, oxigênio dissolvido, temperatura e salinidade) estiveram dentro dos limites estabelecidos pela legislação brasileira. Arsênio (em A1) e níquel (em A1 e A2) estiveram acima dos padrões legais em ambos os períodos. A maior porcentagem de alterações histológicas nas brânquias (aneurismas, fusão lamelar e descolamento do epitélio) ocorreu na área portuária, nos períodos chuvoso (93%) e seco (74%). As alterações hepáticas (centros de melanomacrófagos e necrose) ocorreram apenas nos espécimes dessa mesma área, nos períodos chuvoso (41%) e seco (36%). Os maiores índices histológicos de alterações branquiais e hepáticas foram registrados em A1. Esse resultado foi ainda corroborado pelo valor de IH total das lesões, que foi maior na área portuária em comparação com A2 (área menos impactada), sugerindo que as condições ambientais naquele local são menos favoráveis ao bem-estar desses organismos. O monitoramento ambiental permanente da área é necessário para controlar os impactos ambientais de forma eficiente.

Palavras-chave: bagre estuarino, resposta biológica, lesões branquiais, lesões hepáticas.

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1. Introduction

Increased levels of pollutants and the degradation of estuaries have raised great concerns about environmental resources. Organisms that inhabit estuaries can be subject to a wide range of toxic contaminants, which are associated with sediments and particulate matter suspended in the water (Righi et al., 2022). The effects of different pollutants on fishing resources are propagated through other ecosystem components, causing changes in population characteristics and dynamics (reproduction, migration, restoration, and mortality), the structure and function of communities (changes in species diversity, changes in the predator-prey relationship), and ecosystem function (changes in respiration and photosynthesis processes, and nutrient flow) (Silva et al., 2013).

The Port of Itaqui, which is part of the Port Complex of São Luís is one of the most important public ports for cargo handling in Brazil and Latin America. The main cargoes transported were grains, various minerals, fuels and chemicals (EMAP, 2021). However, in recent years, chemical contamination of industrial waste has become a growing threat to the health of aquatic organisms (Carvalho Neta et al., 2014). Previous studies (Jesus et al., 2020; Oliveira et al., 2019) carried out in locations along the São Luís Port Complex, in São Marcos Bay, report that this region already suffers from the impacts caused by chemical contaminants from of anthropic activities. The increase and variety of pollutants in the aquatic environment, can lead to several deleterious changes in local organisms, especially fish (Dalzochio et al., 2016).

Considering that the survival of aquatic organisms in an area is intrinsically associated with the impact of the contaminants present (Zuhara and Isaifan, 2018), it is essential to conduct studies to identify the presence of pollutants in the aquatic environment, especially their previous effects on estuarine organisms, which can be achieved through biological monitoring.

Biomonitoring, recognized worldwide, uses organisms to assess the quality of aquatic environments and serves as a bioindicator of environmental pollution (Okay et al., 2016). Among the fishing resources found on the coast of Maranhão, *Sciades herzbergii* (Bloch, 1794), an estuarine catfish, has great commercial relevance in artisanal fishing in the state and has been successfully used in biomarker studies (Carvalho Neta et al., 2017; Soares et al., 2020; Viana et al., 2021).

Biomarkers and bioindicators are the two main elements of the hierarchy of biomonitoring processes (Sumudumali et al., 2021). In environmental monitoring, the sublethal effects of contaminants on organisms can be detected using biomarkers (Dalzochio et al., 2016). These, in turn, reflect changes at the cellular, biochemical, molecular, and physiological levels and can be measured in cells, body fluids, tissues, and organs, in addition to indicating the presence and/or effects of toxic substances (Lionetto et al., 2019).

Determining histological changes in the gills and liver after exposure to chemicals is an important approach to assessing the quality of the environment, especially the resident organisms (Jabeen et al., 2018). The liver is an organ involved in the metabolism and detoxification of the organism, is an important part of the innate immune system, and is responsible for producing substances necessary for immune and inflammatory responses (Wang et al., 2017). The gills indicate the environmental quality of the aquatic environment because of their direct interaction with contaminants (such as metals and oil or its subproducts such as polycyclic aromatic hydrocarbons - PAHs) in the water and because they are the first structures of the organism in contact with these substances (Barišić et al., 2015; Santos-Filho et al., 2014).

Thus, the aim of this study was to evaluate the environmental contamination to which estuarine organisms are exposed in two areas in São Marcos Bay, MA, by investigating gill and liver alterations (injuries) in *S. herzbergii*.

2. Material and Methods

2.1. Study area

The two collection sites selected for this study are in two areas in São Marcos Bay, Maranhão, Brazil. The São Luís Port Complex (2°34'17"S, 44°22'40"W), which is composed of a set of public and private ports handling various types of cargo, and is the largest in the north and northeast of Brazil is in this area (Sant'Ana-Júnior, 2017). Previous studies have indicated the presence of chemical contaminants such as heavy metals (Oliveira et al., 2019), toxic trace elements, and polycyclic aromatic hydrocarbons (PAHs) (Pinheiro-Sousa et al., 2021). Thus, we considered this area, called A1 in this study, to be an impacted location. Caranguejos Island (2°49"48" S, 44°28"34" W), one of the largest continuous extensions of mangroves in Maranhão and part of the Environmental Protection Area of Baixada Maranhense (Carvalho Neta et al., 2017) is located 30 km from the port area. Caranguejos Island was a low-impact site called A2, in this study.

2.2. Sampling and biometric data

The capture of fish was authorized by the Ethics Committee of Maranhão State University (number 064/2017-2018 CRMV-MA). In these areas (A1 and A2) four collections were carried out, two in March (rainy period) and two in September (dry period) 2018. The fish were collected in their natural habitats using gillnets. Then they were all anesthetized in 5% benzocaine hydrochloride for 15 minutes. The biometric measurements: total length in centimeters and total weight and gonad weight in grams were registered for each specimen. The condition factor (K) was calculated according to a specific methodology (Vazzoler, 1996). The gonadosomatic index (GSI) was evaluated using the formula: gonad mass/body mass x 100. Then, all fish were dissected to remove the gills and livers, for further histological processing at the Laboratory of Biomarkers in Aquatic Organisms (LABOAq), at the State University of Maranhão (UEMA).

2.3. Physico-chemical parameters of water

Water temperature, salinity, pH, conductivity, and dissolved oxygen were measured in duplicate during each sampling period using an AK88 multiparameter analyzer.

2.4. Analysis of metals in sediments

Sediment was collected in both areas with a collector pipe launched three times to compose samples of approximately 500 g. After collection, the samples were placed in labeled sterile plastic bags. They were then stored in thermal boxes with ice and transported to the laboratory for further processing, where they were stored at 4°C.

The sediment samples were granulometrically standardized in 200 mesh (74 µm), dried in ovens at 40 °C and macerated. A portion of 1.0 g was transferred to the teflon tube of the digester, thus proceeding with acid digestion with nitric acid (HNO_3) and hydrogen peroxide (H_2O_2) by method 3051 USEPA (EPA, 2007). After being digested, the solutions were filtered and their volume was completed. Final solutions were transferred to falcon tubes and stored at 4°C. Subsequently, they were analyzed by inductively coupled plasma optical emission spectrometry (ICP-OES Optima 8300; Perkin Elmer, Waltham, MA, USA) for the determination of the following metals: arsenic (As), cadmium (Cd), copper (Cu), chromium (Cr), nickel (Ni) and zinc (Zn). The limits of quantification (LOQs) were determined using the formula 3 times the standard deviation of the reagent blank. The results were expressed in mg kg $^{-1}$ for the HCl and HNO_3 extracts, and the values obtained were as follows: Cd, 0.10; Cr, 0.20; Ni, 0.10; Cu, 0.20; Zn, 0.01; and As, 0.1.

To ensure analytical quality, reagents with a high degree of purity (PA, Merck) and certified reference samples (Sediment: SS2 SSP-SCIENCE) were used. The solutions were prepared using ultrapure water (Milli-Q Plus, Millipore). All glassware used was previously decontaminated in 5% HNO_3 solution (v/v, Merck) for 24 hours and rinsed with ultrapure water. The blank sample was prepared by adding the acid solution without a sample. The average recovery rates for each metal analyzed were between 80% and 120%.

2.5. Histological analyzes

Samples of the gills (first branchial arches) and liver (middle region) for the histological study were placed in Bouin's fixative solution, dehydrated in ethanol, and embedded in Paraplast Plus resin. Sections (5 µm thick) were stained with hematoxylin and eosin. Four tissue sections from each fish were examined by light microscopy. The slides were analyzed using an optical microscope at 4x, 10x, and 40x magnification.

Histopathological alterations were classified according to the criteria established by Bernet et al. (1999), in which each histological change in the investigated organ was categorized into one of five reaction patterns (Rp): circulatory disturbances (Rp1), regressive changes (Rp2), progressive changes (Rp3), inflammation (Rp4), and tumor (Rp5). An importance factor (w) was assigned to each alteration, varying from 1 to 3, where 1 = minimal pathological importance (easily reversible lesions), 2 = moderate pathological importance (reversible lesions in most cases), and 3 = severe pathological importance (generally irreversible injuries).

Based on these criteria, histological indices (HI) were calculated. The index for each reaction pattern of an organ (IH Rp) was assigned, from which the organ index (IH of the gills and IH of the liver) was obtained. By totaling each organism's gill and liver indices, it was possible to obtain the total index (total HI), which represents a measure of the general state of health based on the level of histological lesions (Bernet et al., 1999).

2.6. Statistical analysis

The results were presented as percentages or means and standard deviations. All data were subjected to Shapiro–Wilk and Kolmogorov–Smirnov normality tests. The Mann-Whitney and Student's t-tests were used to verify significant differences between the study locations during the data collection periods. All statistical analyses were performed using Statistica software (version 12.0; StatSoft, Tulsa, OK, USA). In all the cases, the significance level was set at 95% ($\alpha = 0.05$).

3. Results

3.1. Physico-chemical parameters of water

The physicochemical parameters of the water in each of the two fish collection areas (A1 e A2), related to the two sample periods (wet and dry) respectively, were: pH (7.15 ± 0.49 - 7.55 ± 0.21), dissolved oxygen (5.15 ± 0.07 - 6.2 ± 0.14 mg L^{-1}), temperature (28.55 ± 0.92 - 28.95 ± 0.35 °C), and salinity (18.85 ± 1.48 - 16.75 ± 0.64 psu). The data did not show a significant difference ($p > 0.05$) between collection sites or between periods.

3.2. Analysis of metals in sediment

The results of the analysis of metals in the sediments (Table 1) showed that the concentrations of arsenic found in A1 (most impacted), exceeded the limits established by Brazilian environmental legislation (CONAMA 454, 2012). Nickel levels were above Brazilian legal standards for both collection periods and areas. In A1, despite meeting the legislation, the other concentrations of metals were slightly higher in the first collection period compared to the second.

3.2.1. Biometric analysis

The biometric parameters (Table 2) showed that, although the male and female individuals from the port area (A1) had greater length, females and males collected from the less impacted area (A2) were heavier ($p < 0.05$). This result is consistent with the values obtained for the condition factor and GSI for individuals collected on Caranguejos Island (A2), which are higher than those in relation to the port area (A1) ($p < 0.05$).

3.3. Histological analysis

The histological changes observed in the gills and livers of *S. herzbergii* are shown in Figure 1. The results (Figure 2) showed that the highest percentage of histological changes in the gills occurred in the port area at both periods ($P < 0.05$). Aneurysms, fusion of lamellae and epithelium detachment were the most frequent injuries, accounting for 93% and 74% of injuries in the rainy and dry periods,

Table 1. Trace element concentrations in the sediment of the São Marcos Bay.

Heavy metals (mg kg $^{-1}$)	Rainy period		Dry period		LOQ[a]	CONAMA 454/2012[b] (mg kg^{-1})	
	A1	A2	A1	A2		L1	L2
Arsenic	112.9	56.7	119	53.6	0.1	19	70
Cadmium	<0.10	<0.10	<0.10	<0.10	0.10	1.2	7.2
Copper	8.20	6.29	21.99	6.32	0.20	34	270
Chromium	25.93	23.54	30.72	25.09	0.20	81	370
Nickel	122.59	108.22	127.92	104.49	0.10	20.9	51.6
Zinc	29.60	26.62	41.50	22.04	0.01	150	410

A1 = Port Region; A2 = Caranguejos Island. [a]LOQ limits of quantification. [b]Limits established by the National Council for the Environment (CONAMA) in Resolution No. 454 of 2012 for sediments in the waterbed of level 1 (saline water) and level 2 (brackish water).

Table 2. Biometric parameters of *S. herzbergii* collected from the in two areas of São Marcos Bay.

Sampling area	Gender	Total length (cm)	Total weight (g)	Weight of gonads (g)	Condition factor	GSI
A1	M	22.79 ± 7.38*	153.28 ± 93.55*	0.18 ± 0.35*	0.82 ± 0.27*	0.14 ± 0.30*
	F	21.68 ± 6.64	152.47 ± 81.75*	1.0 ± 1.0*	0.86 ± 0.26*	0.57 ± 0.42*
A2	M	18.0 ± 1.85*	180.30 ± 19.11*	1.30 ± 0.46*	1.23 ± 0.03*	0.74 ± 0.26*
	F	20.70 ± 3.75	212.10 ± 44.69*	2.30 ± 0.76*	1.28 ± 0.13*	1.09 ± 0.19*

A1 = Port Region; A2 = Caranguejos Island. *Indicates statistical difference ($p < 0.05$) in biometric data of individuals of the same gender between locations (A1 and A2).

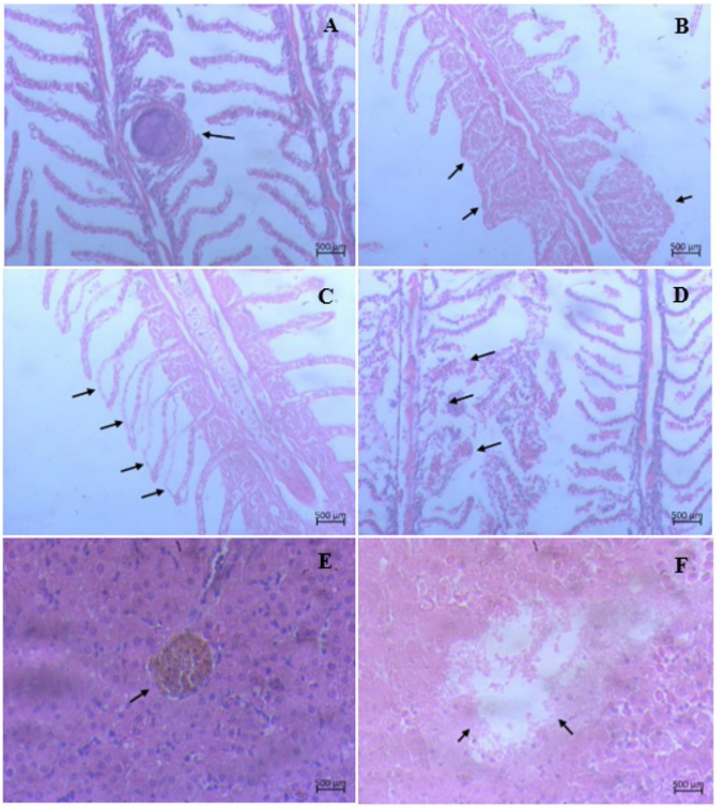

Figure 1. Histological changes observed in the gills and livers of *S. herzbergii*. (A) gill – aneurysm (arrow); (B) gill – lamellar fusion (arrow); (C) gill – detachment of the epithelium (arrow); (D) gill – necrosis (arrow); (E) liver – melanomacrophage center (arrow); (F) liver – necrosis (arrow).

Table 3. Histological indices of gills and livers of *S. herzbergii* captured in two areas in São Marcos Bay.

Histological indices	Gender	Rainy period		Dry period	
		A1	A2	A1	A2
IH gills Rp1	M	13.5 ± 2.12^{a}	3.0 ± 0^{a}	NF	6.0 ± 0
	F	$1.0 \pm 5.13^{a,b}$	3.0 ± 0^{a}	10.0 ± 0^{b}	NF
IH gills Rp2	M	10.57 ± 3.20^{a}	2.0 ± 0^{a}	11.33 ± 17.69^{a}	2.0 ± 0^{a}
	F	9.25 ± 1.89^{a}	2.0 ± 0^{a}	5.5 ± 6.35	NF
IH liver Rp1		NF	NF	NF	NF
IH liver Rp2	M	7.80 ± 4.54	NF	7.0 ± 1.73	NF
	F	6.0 ± 0	NF	6.0 ± 0	NF
IH liver Rp4	M	1.5 ± 0.70	NF	2.0 ± 0	NF
	F	3.0 ± 2.58	NF	2.0 ± 0	NF
IH gills	M	11.22 ± 3.15^{a}	2.33 ± 0^{a}	11.66 ± 17.57^{a}	4.0 ± 2.82^{a}
	F	$12.7 \pm 4.96^{a,b}$	2.33 ± 0^{a}	6.4 ± 5.85^{b}	NF
IH liver	M	6.0 ± 4.83	NF	5.75 ± 2.87	NF
	F	3.66 ± 2.59	NF	4.0 ± 2.82	NF
IH total	M	$8.93 \pm 4.66^{a,b}$	2.33 ± 0^{a}	$9.71 \pm 14.76^{a,b}$	4.0 ± 2.82^{a}
	F	$8.42 \pm 6.06^{a,b}$	2.33 ± 0^{a}	5.71 ± 5.05^{b}	NF

A1 = Port Region; A2 = Caranguejos Island; a = Indicates statistical difference ($p < 0.05$) in histological indices between sites (A1 and A2) and within the same seasonal period (rainy and dry periods); b = Indicates a statistical difference between seasonal periods; NF = Not found.

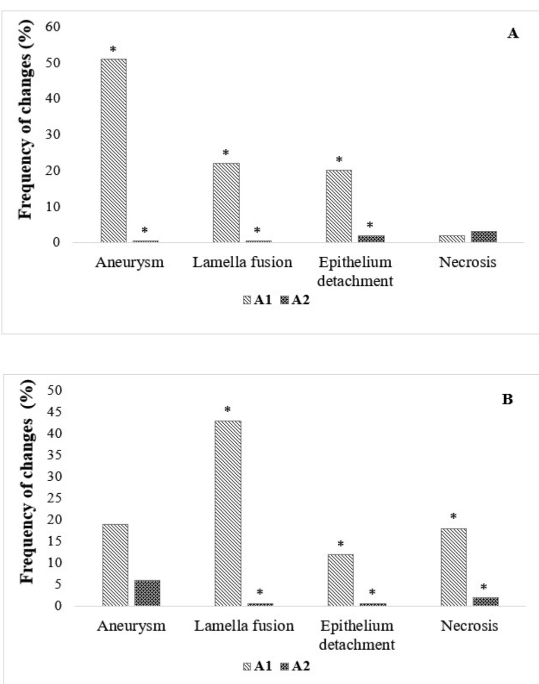

Figure 2. Frequency of histological alterations in the gills of *S. herzbergii* in two areas in São Marcos Bay, Maranhão, Brazil, in the rainy period (A) and dry period (B). *Indicates a statistical difference ($p < 0.05$). A1 = Port region; A2 = Caranguejos Island.

respectively. This result shows a greater capacity for altered biological responsiveness in the gill tissue of A1 fish.

As for liver alterations, melanomacrophage centers and necrosis were the lesions identified, representing 41% and 36% of lesions in the rainy and dry periods, respectively. Such lesions only occurred in specimens from the port region during the two seasonal periods ($p > 0.05$). This data indicates that the liver tissue of A1 fish is more sensitive to local stressors.

The average histological indices (IHs) of gill and liver alterations are presented in Table 3. Gill IH values were higher in A1 for males during the dry period ($p > 0.05$), and for females during the rainy period ($p < 0.05$). This index was composed of alterations classified as circulatory disorders (Rp1) and regressive changes (Rp2); other types of histopathologies did not occur.

Liver IHs for individuals from the port region showed similar values considering both seasonal periods ($p > 0.05$), but were lower compared to gill IHs. The liver IH was composed of regressive changes (Rp2) and inflammation (Rp4). There were no records of liver histopathologies in individuals from A2. It is worth noting that the highest values for the total histological index (total IH) were observed in the port area.

4. Discussion

The physical-chemical parameters of the water analyzed at the sampled points in São Marcos Bay were in compliance with the Brazilian environmental legislation (CONAMA 357 – Brasil, 2005). The data indicated that arsenic and nickel were the two metals that exceeded the maximum limits allowed by CONAMA Resolution No. 454/2012 (Brasil, 2012). Therefore, it is important to emphasize that the presence of these elements, in addition to their contributions to environmental contamination, can affect human health. Souza and Baggio (2020) found that heavy metals are important environmental contaminants that tend to accumulate in bottom sediments and can be assimilated by organisms because they are in direct contact with them. Arsenic, depending on its form in the environment, has carcinogenic characteristics, and a large part of its intake occurs through contaminated food from the marine environment, where environmental characteristics may favor its absorption (Silva et al., 2021). At low concentrations, nickel acts by regulating the fat content in tissues and the formation of red blood cells. However, it is toxic at high concentrations, causing diseases (Nazir et al., 2015), which serves as a warning, considering that this element was also found in the less impacted area. In a study conducted on the sediments of the Ravi River (Pakistan), high contamination levels of arsenic, chromium, nickel, and zinc, caused by the discharge of industrial effluents, were found (Jabeen et al., 2018). In another study, despite being at acceptable levels, the levels of As, Cu, Cr, Ni, Cd, Pb, and Zn in samples of mangrove sediments were higher in the area influenced by the industrial port than in the sediments collected in the estuary of the Paciencia River, both on São Luís Island, Brazil (Oliveira et al., 2019).

Data showed variation in biometric measurements (condition factor and GSI) of *S. herzbergii* between sites and collection periods. Where individuals from the port region (A1) had the lowest values for these parameters. Studies have reported that this differentiation may be related to factors such as variations in food availability, competition, energy expenditure for survival, and differences in environmental quality conditions (Froese, 2006; Rotta and Yamamoto, 2021).

The data from the present study are similar to those obtained by Castro et al. (2018) for *S. herzbergii* where the length of the individuals analyzed in the dry period was greater in the port region, while the specimens from the control area (Igarapé do Puca, located in the municipality of Alcântara) were heavier. In the present study, the highest body weight was observed in females on Caranguejos Island, which is an area protected by state legislation. However, the smallest individuals occurred in the port area, which may indicate that exposure to contaminants impacts the growth of fish, as reported in previous studies (Oliveira et al., 2019; Soares et al., 2020). Montes et al. (2023) found that the lowest biometric values (of weight and length) of specimens of *S. herzbergii* were recorded in catfish (N=176) from São Marcos Bay in a comparative study with catfish (N=176) from the Caeté Estuary, Pará. These authors add that this reduction in the size of fish in the São Marcos area may be associated with the high levels of turbidity found, in addition to the presence of contaminants.

Noleto et al. (2022) when analyzing muscle samples from 68 specimens of *S. herzbergii* collected in São José Bay (São José de Ribamar), identified concentrations of trace elements (lead, zinc, iron and magnesium) above the limits recommended by Brazilian legislation for fish meat, indicating that the analyzed fish are suffering some level of environmental contamination. Pinheiro-Sousa et al. (2021) identified trace elements and polycyclic aromatic hydrocarbons (PAHs) in sediments in the same region as the present study.

The presence of contaminants in the aquatic environment can influence the health of organisms present there, causing various damages to tissues (Noleto et al., 2022; Freitas et al., 2022). Next, we will highlight the morphological changes found in gill and liver tissues of *S. herzbergii*.

The gill is a physiologically diverse organ whose primary function is breathing. When the physiology of this organ is affected, there is an impact on the health of the fish (Gjessing et al., 2019). In this study, aneurysms, lamellar fusion, epithelial detachment, and necrosis were of alterations observed in the branchial tissue of *S. herzbergii*, with the first two being the most frequent, regardless of the period. According to Bernet et al. (1999), aneurysms are well-delineated dilations of blood vessels, while lamellar fusion and epithelial detachment are one of the changes that occur in tissue structure. In addition, changes in the shape and arrangement of cells and necrosis correspond to the morphological state of cells or tissues after the irreversible loss of cellular function.

Similar lesions were also registered by other studies for this same species in two areas in the region of the Complexo Estuarino de São Marcos - MA (Castro et al., 2018; Viana et al., 2021) and in gills of *Oreochromis niloticus* (Linnaeus, 1758) from the Laguna da Jansen (area with a history of contamination by domestic effluents), São Luís, Brazil (Pereira et al., 2014). Freitas et al. (2022) found other types of branchial lesions (hyperplasia, lamellar disorganization, proliferation of mucous cells and dilation of venous sinuses and congestion) in *Hoplias malabaricus* in two stretches of the Mearim River in the Baixada Maranhense region. Morphological changes in gills and impairment of their functions are considered indicative of cumulative chemical or physical changes in the immediate vicinity of the organism's habitat, given that they are structures with a large surface area and interact extensively with water (Jerome et al., 2017).

Melanomacrophage centers and necrosis were the liver lesions found only in fish from the port region. The first is characterized by aggregates of macrophages, which play an important role in the immune response of fish (Qualhato et al., 2018). According to Camargo and Martinez (2007), the accumulation of melanomacrophage centers is associated with the detoxification of compounds. Regarding hepatic necrosis, which is an irreversible lesion, Rabitto et al. (2005) state that a large part of this type of alteration can cause organ failure, harming health and impacting the survival of the population of organisms.

These two categories of lesions were also found in the sentinel species *Arius thalassinus* (Rüppell 1837) and *Pelates quadrilineatus* (Bloch, 1790) collected in Kuwait Bay, a region with records of several pollutants, such as polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and heavy metals (Al-Zaidan et al., 2015). In a toxicity study of the species *Poecilia reticulata* (Peters, 1859), the results showed a greater number of melanomacrophage centers after 21 days of exposure to iron oxide nanoparticles, indicating an inflammatory and immunological process as a cellular response (Qualhato et al., 2018).

Detection of pathological changes in the liver suggests toxic responses resulting from the absorption of xenobiotics present in their natural environment (Feist et al., 2015). This is because the liver of teleost fish performs vital functions, such as the biotransformation of xenobiotic substances, the elimination of harmful metals, metabolism of sex hormones and participates in the digestion and storage of substances (Adeogun at al., 2016).

The histological indices (HIs) quantified individually for gills and livers varied among the areas, indicating greater damage to the fish in A1 during both periods. This result was further supported by the total HI value of the lesions, which was higher in the port area compared to A2 (less impacted area), suggesting that the environmental conditions in that location are less favorable for the well-being of these organisms. Santos et al. (2023), when analyzing *Centropomus undecimalis* and *Gobionellus stomatus*, considered good pollution sentinels in estuarine systems along the coast of the state of Pernambuco (Northeast Brazil), reported higher indices than those reported in the present study. Soares et al. (2020) obtained similar results to the present study, observing a significantly higher total histological index for catfish analyzed in the potentially impacted location (Porto Grande, São Marcos Bay - MA).

The reaction patterns identified for the gill lesions were circulatory disturbances (imbalances in blood and interstitial fluid) and regressive changes (capable of reducing organ function). For the liver lesions, regressive changes and inflammation (an inflammatory process related to other reaction patterns) were observed, according to Bernet et al. (1999). Soares et al. (2020) observed histological alterations of regressive patterns (in gills and livers) and progressive patterns (in gills) when analyzing specimens of *S. herzbergii* in two distinct areas of São Marcos Bay. Feist et al. (2015), while examining livers and gonads of deep-water fish in the northeastern region of the Bay of Biscay, reported evidence of histopathologies (inflammatory and degenerative lesions) potentially associated with exposure to algal toxins. Qualhato et al. (2018) found high histopathological indices associated with circulatory disturbance and inflammatory responses in *Poecilia reticulata* after an acute toxicity test using iron oxide nanoparticles.

The classification of the lesions ranged from minimal pathological importance to high (severe). The first is reversible when the exposure to irritants ends. The second is considered irreversible (such as necrosis) as it can lead to partial or total loss of organ function. Severe liver changes (steatosis, necrosis, and infiltration) and moderate to severe gill alterations were found by Santos et al. (2023) when examining the species *C. undecimalis* and *G. stomatus* in an estuarine region with a history of mercury pollution and residues from the sugarcane industry. Viana et al. (2021) reported mild, moderate, and severe changes in gills and livers of *S. herzbergii* and *Bagre bagre* from the Santo Antonio River basin and the estuarine complex of Curupu Bay, Maranhão.

The toxicity resulting from continuous water pollution causes a variety of effects and harm to aquatic life forms, which can lead to the death of these organisms (Singh et al., 2023). The emergence of lesions, such as those found in this study, can be attributed to adaptive or defense mechanisms of fish. Modifications in the structure of the gills can be an adaptive measure to reduce the transepithelial transport of contaminant substances (Poleksić and Mitrović-Tutundžić, 1994) or a measure to address issues in osmoregulation and ionic balance (Powell et al., 2005). Lesions in the liver tissue can be attributed to the absorption of contaminants through available food resources in the environment (Ogbeide et al., 2019) and the dynamics in metabolic activity during the detoxification process of these substances (van der Oost et al., 2003).

5. Conclusions

The analysis of branchial and hepatic histological alterations in *S. herzbergii* led to the conclusion that such organisms from the port zone showed a greater compromised biological response. Which may be associated with adverse conditions in their habitat, as most of the lesions, higher histological indices, and lower biometric data were recorded for fish in this region.

The histological data also showed that the organs contained reversible and irreversible damage, which indicates the sensitivity and susceptibility of the specimens to factors that generate environmental stress that may be inducing the appearance or severity of these damages.

Therefore, it can be inferred that the quality of the aquatic environment directly influences the health and, consequently, the development and survival of resident estuarine species such as *S. herzbergii*. Permanent environmental monitoring of the area is necessary to control environmental impacts efficiently.

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