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Article

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Abstract: The city of Macapá in the Brazilian Amazon faces critical aquatic pollution challenges due to inadequate sanitation infrastructure, leading to metal contamination in fish within its urban water bodies. This study evaluates concentrations of metals (Cu, Cd, Cr, Fe, Mn, Ni, Pb, Zn, Hg) in muscle tissues of fish from igarapés, floodplain lakes, and canals. Samples were collected from six sites to investigate the bioaccumulation of these metals and their potential human health risks. Using Atomic Absorption Spectrometry and Inductively Coupled Plasma Optical Emission Spectrometry for Hg, metal levels were analyzed in three carnivorous and seven omnivorous fish species. Cd concentrations in several species exceeded safety thresholds for human consumption, while the estimated daily intake (EDI) of Pb and Hg also surpassed reference doses. Risk assessment combining the risk quotient (RQ) for individual metals and the risk index (RI) for metal mixtures indicated considerable health risks associated with consuming fish from these contaminated waters. These findings reveal concerning exposure to contaminants, underscoring the need for environmental management and ongoing monitoring to protect public health in vulnerable urban areas.

Keywords: heavy metals; bioaccumulation; human health risk assessment; fish contamination; Brazilian Amazon; urban water pollution

1. Introduction

Macapá is the capital of the Brazilian state of Amapá, has an estimated population of 522,357 inhabitants, a territory of 6,563,849 km² [1] and, in the Basic Sanitation Ranking of the 100 largest Brazilian cities, occupies last place [2]. The Macapá urban area is located on the left bank of the Amazon River mouth, inserted in the estuarine coastal zone, and is subject to constant anthropogenic pressure on the use and conservation of soil, water resources, and climate [3,4]. Its complex urban design is characterized by dry land and flooded areas that interact and are linked, making it in many cases difficult to distinguish where one type of territory begins and where the other ends [5]. Igarapés, ressaca areas, and channels constitute the extensive network that makes up the system of urban water bodies in Macapá [6]. The floodplain areas called ressaca areas are under the strong urbanization processes characterized by the presence of wooden houses supported by stilts (called Palafitas in Portuguese), built over the waters [3,5]. Approximately 30% of the Macapá urban population lives in ressaca areas, and these areas are under increased socio-environmental vulnerability and a population growth rate of 20% every four years. In general, solid, and liquid domestic wastes generated in stilt houses are released directly into the water below them without any type of treatment [5]. Igarapés are small branches of rivers that generally have preserved riparian forests. These water bodies are used for fishing, leisure, and transport of people and various products. Channels are the water bodies that cover most of Macapá's urban area and flow directly into the Amazon River. All these aquatic environments are heavily impacted by human activities, the Amazon River inflows, and the Atlantic Ocean tide effect [3]. When considered together, these urban aquatic environments act as natural filters that receive, retain, and attenuate urban drainage [6].

Urban aquatic environments are among the ecosystems most affected by different human activities since cities generate large amounts of liquid and solid waste that flow into local water resources [7–9]. Particularly, urban Amazonian aquatic ecosystems are increasingly vulnerable to stress resulting from human activities [3,10], mainly because the sanitation infrastructure has not kept pace with population growth and the speed of urbanization [11]. Therefore, solid and liquid waste from industrial and domestic origins are the main drivers of pollution into these aquatic environments. Notably, these effluents carry potentially toxic organic and inorganic chemicals, including metals, directly into waters [12,13].

Contamination of aquatic environments by toxic metals is one of the most serious environmental problems worldwide, both for the conservation of fish species and for human health owing to the potential for bioaccumulation and biomagnification [3,14,15]. Freshwater fish are the main source of protein for Amazonian communities, and the artisanal fishing industry provides the livelihood for around 40% of families in fishing communities [16]. Despite they are still little studied, Rivero et al. [17] demonstrated that fishing households living in urban Amazonian areas are highly dependent on fish consumption and use fishing as a subsistence strategy to deal with food insecurity. Approximately 80% of fishing households living in urban centers eat fish almost every day [17]. However, studies conducted in different hydrographic basins from the Amapá State have demonstrated the bioaccumulation of toxic metals in the muscle tissue of several fish species and that there are risks to human health resulting from their consumption [18–22]. Thus, the high consumption of fish contaminated by toxic metals from Amazonian rivers can represent serious risks to human health for local vulnerable populations [17,21,23].

The most vulnerable population in the urban area of Macapá fishes and consumes fish caught in urban water bodies daily. Considering that small-scale urban fishing is practically not studied, despite its enormous relevance for reducing poverty and developing policies to combat food insecurity [17]. Our objective was to quantify the concentrations of metals (Cu, Cd, Cr, Fe, Mn, Ni, Pb, Zn, and Hg) in muscle tissue samples from various fish species collected across three distinct aquatic environments (igarapés, ressaca areas, and channels) within the urban area of Macapá. Furthermore, the study aimed to evaluate the bioaccumulated risks for human health associated with both the individual and combined exposure to these metals through fish consumption.

2. Materials and Methods

2.1. Sampling Sites

For fish collection, we selected 6 sampling sites located in the urban area of Macapá. All sampling sites belong to the Igarapé da Fortaleza sub-basin, which is part of the Amazon River Basin. Three sampling sites are located in channels, two in igarapes, and one in a ressaca area (Figure 1).

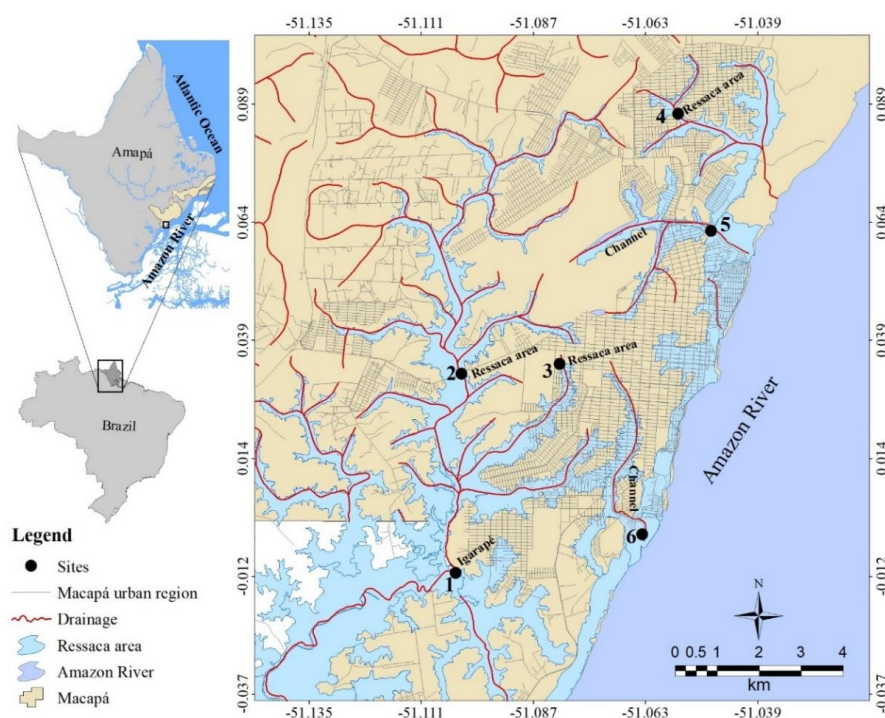


Figure 1. The six sampling sites located in different urban aquatic environments in Macapá, State of Amapá, Brazil.

The sampling sites were selected based on strong human influence, particularly the release of untreated domestic sewage and solid waste, which negatively impacts the quality of all waters in the Amazon River. Indeed, the Amazon River has become the main recipient of industrial effluents, often inadequately treated, from the urban regions of Amapá State [24]. Sampling was carried out between March and June 2019 during the daytime.

2.2. Fish Sampling

All fish samples were collected using gill nets with mesh sizes ranging from 1.5 to 8.0 cm between adjacent nodes and cast nets. After capture, biometric data, total weight (g) and standard length (mm), were obtained using an ichthyometer and a field scale, respectively. In the field, the fish were euthanized by cervical transection, individually labeled, and transported in ice boxes to the laboratory. In the laboratory, taxonomic identification of fish samples was performed using specialized literature [25,26]. Specimens were thoroughly rinsed with running water to eliminate surface impurities before tissue dissection. Approximately 5 mg of muscle tissue samples for metal analysis were obtained between the dorsal fin and the end of the caudal peduncle. In the laboratory, they were kept at -20°C for a maximum period of 30 days. This project was approved by the Ethics Committee on Animal Use at UNIFAP (017/2019).

2.3. Preparation of Fish Muscle Samples and Determination of Metals

The preparation of fish muscle tissue samples was performed according to the protocol described by Viana et al. [27]. Briefly, muscle samples were dehydrated at 40 °C for 3 h and then macerated and sieved. Aliquots of 0.5 g were transferred to digestion tubes containing 10 mL of a sulfonitric mixture (HNO₃/H₂SO₄ - 1:1 v/v) and 0.1% (w/v) V₂O₅ and kept at rest for 2 h. Blank samples were prepared according to Olmedo et al. [28]. The samples were analyzed in duplicate using an Atomic Absorption Spectrometer (Shimadzu, model AA7000, Japan), with flame atomization, to quantify Cd, Pb, total Cr, Ni, Fe, Mn, Cu, and Zn [29]. To quantify Hg present in the samples, we used a hydride generator coupled with Inductively Coupled Plasma Optical Emission Spectrometry. Each metal was measured according to its calibration curves, confirming linearity, a key validation parameter. The operating conditions of the instrument were as follows: power, 1000 W; 15 L min⁻¹, argon gas flow; 1.5 L min⁻¹, auxiliary gas flow; 10 s, replication time; 15 s, stabilization time; 10 s, cleaning time; and 253 to 652 nm, wavelength reading for Hg [27]. Detection limits (µg g⁻¹) were as follows: Cu = 0.06, Cd = 0.01, Cr = 0.01, Fe = 0.05, Mn = 0.03, Ni = 0.04, Pb = 0.06, and Zn = 0.08 and Hg = 0.10. All analytical standards used were purchased from Merck KGaA, Darmstadt, Germany. Each metal was quantified according to its calibration curve, and the following detection limits (µg g⁻¹) were obtained:

2.4. Risk Assessment for Human Health from Fish Consumption and Estimation of Daily Intake (EDI)

We performed risk assessments for each metal individually and also for mixtures of metals present in fish muscle tissue samples. For individual risk assessment of each metal, we use the risk quotient (RQ) approach. The QRs were calculated by the ratios between the concentrations of each metal present in the fish muscle tissue samples and the maximum limits (MLs) established by the Brazilian legislation for human consumption [30,31]. RQ values < 1 indicate no risk to human health, while RQ values > 1 indicate risks of adverse effects [32,33]. For risk assessment of metal mixtures, we use the risk index (RI) approach. The RIs were obtained by summing the RQ values obtained for each metal. The higher the RI value, the greater the risk of damage to human health resulting from fish consumption [21].

To refine risk assessment for human health, we included EDI calculated by the ratio between the concentration of each bioaccumulated metal in the muscle of fish samples and the average daily fish consumption by adult individuals as a function of average body weight. The IDE calculation allows a more realistic risk estimation since it is based on the concentrations of metals found in food and the best available data on food intake for a specific population [34]. EDI calculation was performed according to the protocol described by Viana et al. [21], as:

$$EDI = BC \times Df/BW$$

where EDI is µg kgbw⁻¹ day⁻¹, BC is the mean metal concentration bioaccumulated in fish muscle tissue (µg g⁻¹), and Df is the daily fish consumption rate (416.39 g person⁻¹ day⁻¹) for the Brazilian Amazon population [35,36]. BW is the average human body weight (60 kg) [35]. The EDI values obtained were compared with reference doses (RfDs) established for each metal. We used the RfDs established by Agência Nacional de Vigilância Sanitária do Brasil, Nota Técnica 8/2019 (ANVISA) [37] for all metals, except Pb. In this case, the RfD was established by FAO/WHO [38]. The RfD represents the maximum amount of exposure to each metal that humans can be exposed to without adverse health effects [20,39].

3. Results

Nine native fish species were collected from different urban aquatic environments. The non-native species *Oreochromis niloticus* (Linnaeus 1758) was collected from the sampling sites located in the ressaca area (sampling site 3). Three species of carnivorous fish (*Acestrorhynchus altus* (Menezes 1969), *Pygocentrus nattereri* (Kner 1858), and *Serrasalmus spilopleura* (Kner 1858) and 7 species of omnivorous fish (*Astyanax lacustris* (Lutken 1875), *Acaronia nassa* (Heckel 1840), *Cichlasoma*

amazonarum (Kullander 1983), *Krobia guianensis* (Regan 1905), *Leporinus friderici* (Bloch 1794), *Myloplus rubripinnis* (Müller and Troschel 1844), and *O. niloticus* were collected (Table 1). The majority of fish samples were collected at the sampling site located in the ressaca area (57 specimens), followed by sampling sites located in canals (19 specimens) and in igarapés (17 specimens, all of the same species). The weight of the fish samples collected ranged from 6.00 to 512.57 g and the size from 4.5 to 23.28 cm (Table 1).

Table 1. Sampled fish species, length (cm) and weight (g) (Mean \pm SD), feeding habits, and habitats of different urban aquatic environments in Macapá, Amapá, Brazil.

Fish species	Igarapé		Ressaca areas		Channels		Standard length (cm)	Total weight (g)	Feeding habits	Habitats
	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6				
<i>A. altus</i>	0	5	0	0	0	0	11.02 \pm 0.72	18.18 \pm 3.41	Carnivore	Benthopelagic
<i>P. nattereri</i>	0	5	0	0	0	0	8.84 \pm 1.66	37.56 \pm 20.76	Carnivore	Pelagic
<i>S. spilopleura</i>	0	0	0	0	0	4	7.25 \pm 0.31	12.80 \pm 2.20	Carnivore	Benthopelagic
<i>A. lacustris</i>	17	0	0	0	5	0	8.50 \pm 0.85	20.01 \pm 6.75	Omnivore	Benthopelagic
<i>A. nassa</i>	0	0	0	3	0	0	4.50 \pm 1.13	6.00 \pm 4.24	Omnivore	Benthopelagic
<i>C. amazonarum</i>	0	0	7	0	0	0	10.10 \pm 0.88	61.62 \pm 27.58	Omnivore	Benthopelagic
<i>K. guianensis</i>	0	0	20	0	0	0	11.16 \pm 0.99	63.80 \pm 40.54	Omnivore	Benthopelagic
<i>L. friderici</i>	0	0	0	0	0	9	9.02 \pm 2.67	23.87 \pm 14.82	Omnivore	Benthopelagic
<i>M. rubripinnis</i>	0	10	0	0	0	0	9.55 \pm 1.66	42.21 \pm 15.40	Omnivore	Benthopelagic
<i>O. niloticus</i>	0	0	7	0	0	0	23.28 \pm 2.46	512.57 \pm 166.44	Omnivore	Benthopelagic
Total	17	20	34	3	5	14				

3.1. Metal Concentrations in Fish Species and Their Compliance with Legal Limits

We observed relatively similar concentrations of the metals analyzed in both carnivorous and omnivorous fish species collected in the different types of urban aquatic environments of Macapá. Concentrations of Pb, Cr, Ni, Hg, Cu, and Zn were lower than the ML established by Brazilian legislation [30,31,37] and were thus considered safe for human consumption (Figure 2B–I). Brazilian legislation does not establish ML for Fe. However, Cd showed concentrations above the ML [30], making all fish species sampled unfit for human consumption, regardless of eating habits, size, weight, foraging behavior or type of urban aquatic environment (Figure 2A). Cd presented an average concentration of ~ 0.06 ($\mu\text{g g}^{-1}$) (Figure 2A). The fish species that presented higher Cd concentrations in their muscle tissue were *A. nassa* ($0.09 \mu\text{g g}^{-1}$), followed by *A. altus* ($0.07 \mu\text{g g}^{-1}$), *L. friderici* ($0.07 \mu\text{g g}^{-1}$), *S. spilopleura* ($0.07 \mu\text{g g}^{-1}$), *P. nattereri* ($0.07 \mu\text{g g}^{-1}$), *C. amazonarum* ($0.06 \mu\text{g g}^{-1}$), *K. guianensis* ($0.06 \mu\text{g g}^{-1}$), *A. lacustris* ($0.06 \mu\text{g g}^{-1}$), *M. rubripinnis* ($0.06 \mu\text{g g}^{-1}$) and *O. niloticus* ($0.05 \mu\text{g g}^{-1}$) (Figure 2A). The species with higher Pb concentrations in their muscle tissue were *M. rubripinnis* with ~ 0.28 ($\mu\text{g g}^{-1}$), followed by *O. niloticus* with ~ 0.24 ($\mu\text{g g}^{-1}$) (Figure 2B). *A. nassa* presented the smallest concentrations of Cr, Ni, Fe, Hg, Mn, Cu, and Zn in muscle tissue samples, while *L. friderici* had higher concentrations of Fe, Hg and Mn (Figure 2).

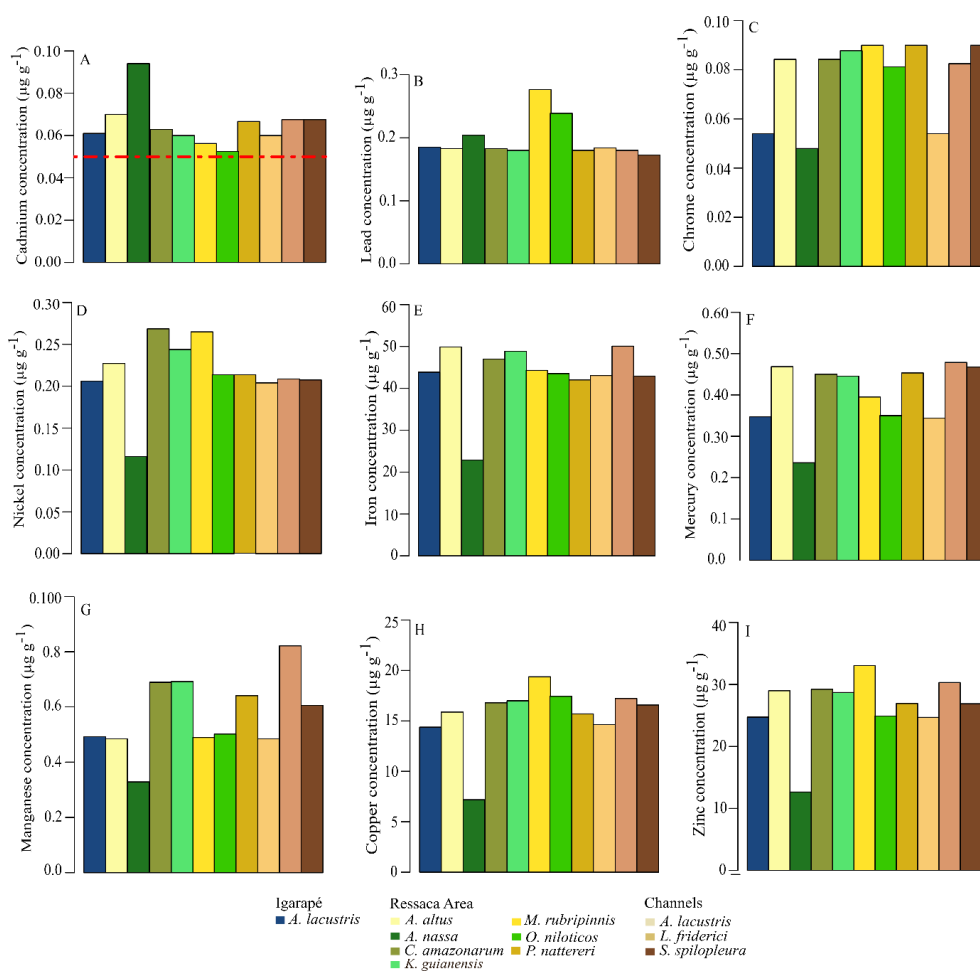


Figure 2. Metal concentrations ($\mu\text{g g}^{-1}$) present in fish muscle samples collected in different urban aquatic environments in Macapá. The red dotted line represents the maximum limit established for Cd by Brazilian legislation [30].

3.3. Human Health Risk Assessment from Fish Consumption

In all fish species sampled, Cd was the only metal that presented risks to human health ($\text{RQs} > 1$). The highest risk was observed for *A. nassa* samples collected at sampling site 4 (ressaca area). Pb, Cr, Ni, Hg, Cu, and Zn did not individually pose risks to human health associated with fish consumption ($\text{RQs} < 1$) for all species sampled from different aquatic environments (Table. 2).

Table 2. Risk assessment for human health related to fish consumption sampled in different aquatic environments located within the Macapá urban area. RQs above the red dotted line represent risk to human health ($\text{RQs} > 1$).

Fish species	Sites	Risk assessment to human health						
		Cd	Pb	Cr	Ni	Hg	Cu	Zn
<i>A. lacustris</i>	Igarapé	1.22	0.61	0.54	0.04	0.69	0.48	0.49
<i>A. altus</i>	Ressaca areas	1.37	0.60	0.84	0.04	0.47	0.53	0.58
<i>A. nassa</i>	Ressaca areas	1.88	0.68	0.48	0.02	0.47	0.24	0.25
<i>C. amazonarum</i>	Ressaca areas	1.26	0.62	0.84	0.05	0.91	0.56	0.58

<i>K. guianensis</i>	Ressaca areas	1.25	0.60	0.88	0.05	0.89	0.56	0.57
<i>M. rubripinnis</i>	Ressaca areas	1.12	0.92	0.90	0.05	0.79	0.64	0.66
<i>O. niloticus</i>	Ressaca areas	1.05	0.79	0.81	0.04	0.71	0.58	0.50
<i>P. nattereri</i>	Ressaca areas	1.33	0.60	0.90	0.04	0.45	0.52	0.54
<i>A. lacustris</i>	Channels	1.20	0.61	0.54	0.04	0.69	0.49	0.49
<i>L. friderici</i>	Channels	1.35	0.60	0.82	0.04	0.96	0.57	0.60
<i>S. spilopleura</i>	Channels	1.35	0.57	0.90	0.04	0.47	0.55	0.54

Bold: Cd risks to human health (RQs > 1).

All fish species collected had RI values > 1, indicating a potential risk to human health related to the consumption of these fish (Figure 3).

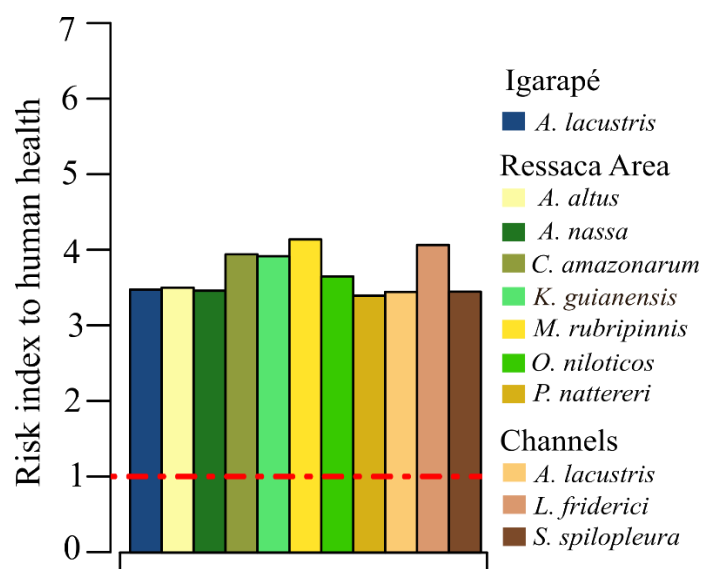


Figure 3. Risk indexes (RIs) determined for the protection of human health in relation to the consumption of different fish species contaminated by mixtures of metals and collected in different aquatic environments from Macapá urban area. RIs above the red dotted line pose a risk to human health (IRs > 1).

3.4. Estimation of Daily Intake (EDI)

For all evaluated fish species, except for *S. spilopleura*, the EDI values for Pb exceeded the RfD established [37,38]. The EDI values obtained for Cd, Cr, Ni, Fe, Mn, and Cu showed lower values than the established RfD [37,38]. However, Hg presented EDI values higher than the RfD established in Brazil [37] or all fish species evaluated, regardless of the sampled sites. This indicates that Hg poses risks to human health from the daily consumption of fish (Table 3).

Table 3. Average daily intake (EDI) ($\mu\text{g kg}^{-1}\text{bw day}^{-1}$) of metals through consumption of fish muscle tissue from different species and feeding behavior collected in different urban aquatic environments in Macapá, Amapá, Brazil, and the oral reference dose (RfD) for each metal.

Fish species	Sites	Element daily intake (EDI)								
		Cd	Pb	Cr	Ni	Fe	Hg	Mn	Cu	Zn
<i>A. lacustris</i>	Igarapé	0.42	1.2	0.37	1.43	304.34	2.41	3.41	99.75	171.59
			8							
<i>A. altus</i>	Ressaca areas	0.47	1.2	0.58	1.58	346.72	3.25	3.36	111.07	201.17
			6							
<i>A. nassa</i>	Ressaca areas	0.65	1.4	0.33	0.80	158.80	1.64	2.28	49.86	87.75
			1							
<i>C. amazonaru m</i>	Ressaca areas	0.44	1.2	0.58	1.87	329.23	3.17	4.78	116.48	202.67
			9							
<i>K. guianensis</i>	Ressaca areas	0.43	1.2	0.61	1.70	339.20	3.09	4.80	117.90	200.12
			5							
<i>M. rubripinnis</i>	Ressaca areas	0.39	1.9	9.22	1.84	307.36	2.74	3.37	134.44	229.37
			2							
<i>O. niloticus</i>	Ressaca areas	0.36	1.6	0.56	1.48	301.30	2.48	3.48	120.93	172.91
			5							
<i>P. nattereri</i>	Ressaca areas	0.46	1.2	0.62	1.48	291.54	3.15	4.44	108.93	186.86
			5							
<i>A. lacustris</i>	Channels	0.41	1.2	0.37	1.41	298.72	2.39	3.36	101.47	171.37
			7							
<i>L. friderici</i>	Channels	0.47	1.2	0.57	1.45	347.55	3.32	5.70	119.45	210.41
			5							
<i>S. spilopleura</i>	Channels	0.47	1.2	0.62	1.44	297.96	3.24	4.20	114.98	186.63
			0							
RfD		0.83	1.2	45.00	1000.0	3470.0	0.57	2300.0	6935.0	23,500.0
		a	b	a	0 ^a	0 ^a	a	0 ^a	0 ^a	0 ^a

Reference dose (RfD): ANVISA [37]^a and FAO/WHO [38]^b; bold: Hg concentrations above RfD from ANVISA [37].

4. Discussion

In general, carnivorous fish are considered to have higher concentrations of metals in their organs and tissues because they are at the top of food chains. However, several studies have observed greater metal bioaccumulation in omnivorous fish [14]. Viana et al. [21] observed that both the distribution and concentrations of Cr, Ni, Fe, Hg, Mn, Cu, and Zn were similar in all fish species collected in the lower stretch of the Araguari River (Brazilian State of Amapá), regardless of eating habits. Naka et al. [40] pointed out that the increase in Cd in urban Amazonian aquatic environments is mainly related to the irregular disposal of household/urban waste and the burning of fossil fuels used by boats. According to Rico et al. [41], about 90% of wastewater from urban areas located in the Amazon region is discharged without adequate treatment, and it is directly released into the Amazon River or its small tributaries. This wastewater contains several types of toxic chemicals, including different metals [41]. Thus, the bioaccumulation of Cd in muscle tissue from the collected fish samples seems to be related mainly to wastewaters and solid wastes that directly impact urban waterbodies.

Similarly, studies conducted in urban rivers of Bangladesh, such as those by Islam et al. [42], have reported significant metal contamination in fish and water, primarily due to the discharge of untreated industrial effluents and domestic sewage. Likewise, in urban rivers of India, elevated concentrations of metals such as Pb and Cd have been linked to the disposal of industrial wastewater and agricultural runoff [43,44]. These investigations identify Pb and Cd as the main toxic agents, posing substantial health risks to communities that rely on fish as their primary source of protein. This evidence demonstrates that metal contamination is not an issue unique to Macapá but rather a widespread problem affecting urban aquatic ecosystems globally.

In Macapá, fish is commonly consumed as an essential and easily accessible source of protein since urban aquatic environments are located close to human habitations, or even below them, as in the case of the inhabited areas of ressacas. Cd levels can vary between species, within species and by location [45]; however, based on the descriptive analysis of the collected data (Figure 2A), no noteworthy variation in Cd concentrations was observed across species, within species, or by location. Diet is the main source of exposure to Cd for the non-smoking population [46], and daily ingestion of fish containing high levels of Cd can cause severe chronic human health problems, including anemia, insomnia, kidney and liver damage, cancers, and osteoporosis, among others [47,48].

However, even though individual concentrations of the analyzed metals do not pose risks to human health, it is important to emphasize that chronic exposure to metal mixtures can cause oxidative stress, cytotoxicity, immunotoxicity, hepatotoxicity, nephrotoxicity, neurotoxicity, and the development of different types of cancer [49,50]. Consequently, for risk assessment of metal mixtures contained in each fish species sampled, we calculated RIs. The RIs are based on the concentration addition (CA) model [51], commonly used for risk assessment of toxic metal mixtures. The CA model is based on dilution theory and assumes that each constituent of a mixture can be replaced by an effective concentration of another constituent, maintaining the final effect of the mixture [50]. According to Martin et al. [52] the CA model can be safely used as the standard concept for anticipating the combined effects of chemicals. Particularly in the case of mixtures of metal ions the frequency of synergistic effects is very low and, when they occurred, the concentrations of the metal ions were very high [53].

Throughout the Amazon region, fish is the main source of protein and subsistence for riverine and indigenous communities [11,54], and also for vulnerable urban populations [17]. In this region, the average per capita consumption of fish is 135 kg/person/year, which is considered to be higher than the world average [20]. Thus, risk assessment of metal mixtures in fish muscle tissue is particularly important in the Macapá urban area because many families consume contaminated fish on a daily basis [17], putting them at serious risk. In addition, metals, such as Cd, Pb, Hg, and Cr, are also harmful to aquatic biota, even when present in aquatic environments in low concentrations, owing to their high toxicity and bioaccumulation potentials [27], which can compromise biodiversity and regional fisheries resources.

The RfD is the maximum amount considered safe for exposure by all sources. When a single source exceeds its value, it is possible to verify a serious situation because the population can be exposed to Hg by other sources, such as water, air, and foods other than fish. Hg is a very toxic element, even at low concentrations, and it can induce severe damage to human health, including neurological, mutagenic, carcinogenic, and hepatic effects, among others [21]. Families residing in areas of urban aquatic environments in Macapá consume these contaminated fish by the exigencies of their socioeconomic situation, which does not allow for greater diversification of protein sources. Therefore, contamination of freshwater fish by Hg in the Amazon region threatens food safety and has become a serious public health problem [16,55].

Contamination of water and fish by Hg in the Amazon region is associated with small-scale artisanal gold mining, often carried out illegally, as Hg is used to extract gold from rocks through the amalgamation process [23,55]. The different urban aquatic environments in Macapá are contaminated with Hg, likely originating from long distances, mainly from the tidal effect of the Amazon River or

atmospheric deposition of particulates [18,55]. With the effect of the tide, contaminants are distributed to other water bodies, as in the case of all urban aquatic environments studied here. Viana et al. [21] found high EDI values for Hg in eleven Amazonian fish species from the Araguari River, ranging from 2.34 to 2.62 $\mu\text{g kg}^{-1}\text{bw day}^{-1}$. Costa et al. [20] reported a high risk of Hg present in the muscle tissue of the Amazonian fish species *Plagioscion squamosissimus* from sampling done in the Araguari River middle and lower sections. Hacon et al. [18] observed high concentrations of Hg in several Amazonian fish species, highlighting the risks of consuming contaminated fish, especially for riverine and indigenous communities. Viana et al. [56] also found Hg contamination in different organs of an endemic fish species from the Amazon Basin, *Colomesus asellus*, sampled in the Pedrinhas Channel, which is located on the banks of the Amazon River in the Macapá urban area.

5. Conclusions

Metal concentrations and their distribution profiles were similar among different fish species, regardless of their feeding behavior, and the type of aquatic environment where they were collected. The RIs obtained for all fish species sampled indicate that the mixture of metals Cd, Hg, Pb, Cr, Ni, Fe, Mn, and Cu present in muscle tissues presented risks related to their consumption. Furthermore, for Pb and Hg, EDI values higher than the RfD were found for all fish species. Together, our results indicate that all populations consuming fish caught in aquatic environments from the Macapá urban area are at risk and may develop serious chronic health problems resulting from long-term exposure to metals. Therefore, the urban aquatic environments of Macapá require pollution recovery projects to guarantee the maintenance and conservation of native species of Amazonian fish, as well as food security.

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