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Human Health Risk assessment from the Tilapia fish in Heavy Metal-Contaminated lagoon: Case study of Ebrié lagoon (Côte d'Ivoire)

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Abstract

This study analyses the health risks associated with the consuming Tilapia contaminated with heavy metals in the Ébrié Lagoon, an ecosystem under strong anthropogenic pressure. The aim is to evaluate human exposure and identify the non-carcinogenic and carcinogenic risks associated with the metals mercury (Hg), cadmium (Cd), lead (Pb), zinc (Zn), copper (Cu), chromium (Cr) and nickel (Ni). Data were obtained from samples collected at eight lagoon stations during both the dry and rainy seasons. Metal concentrations were used to calculate the Estimated Daily Intake (EDI), the Target Hazard Quotient (THQ), the Hazard Index (HI), and the Carcinogenic Risk (CR), in accordance with FAO/WHO and US-EPA guidelines. EDI values varied by metal and site, with higher levels recorded during the rainy season. THQ values were generally below 1, except for Hg at Yopougon, wich indicates a localised non-carcinogenic risk. The HI exceeded 1 only at Yopougon, revealing a concerning combined effect. Carcinogenic risk (CR) values were mostly within the acceptable range (10^{-6}–10^{-4}), but slightly exceeded the threshold at Cosrou. In conclusion, the study indicates a moderate chronic exposure, which warrants continuous monitoring of fish quality and strengthened management of lagoon pollution sources.

Keywords: Heavy metals; Health risks; Tilapia; Ebrié Lagoon; Food contamination

1. Introduction

Lagoons are the most productive aquatic ecosystems in the world [1]. They are characterized by a great diversity of micro habitats sheltering a wide variety of living species [2, 3]. This habitat is rich in algae, crustaceans, shellfish and fish, many of which migrate from the sea to the lagoon. In Côte d'Ivoire, the Ebrié lagoon system, rich in biodiversity, is a place of intense fishing activities for many riverside populations. According to [4], fishing activities and the fishery resources which it provides are a livelihood and an important source of protein for some families. However, several anthropogenic activities resulting from industrial and agricultural activities, domestic wastewater discharges and urbanization have a major impact on the environment and cause a risk of poisoning for the consumption of resources such as fish. Mortalities of fish have been observed in some places in the Ebrié lagoon, particularly in May 2013 and March 2024. To this end, previous studies [5-10] have shown metallic contamination of water, fish and lagoon sediments resulting from the strong anthropogenic pressure on the lagoon catchment area and the city of Abidjan. Most of works which have been done on the Ébrié lagoon has focused on estimating the contents of studied metals of the lagoon matrices without worrying about the health risks associated with the consumption of fish coming from the water of this lagoon. However, beyond simply quantifying metals in environmental compartments, it is essential to assess their potential effects on human health. Fish consumption is recognized as a major route of dietary exposure to heavy metals, particularly in regions with high fishing dependence [11, 12]. Studies conducted in several lagoons in West Africa have shown that local fish can accumulate toxic metals and pose a risk to human health [13-15]. In Côte d'Ivoire, the metallic

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contamination of fish in the Ébrié lagoon and the associated health risk assessment, have already been documented [16, 17]. Previous work by [8] and [9] showed spatial and seasonal contamination of fish in the Ébrié lagoon with trace metals such as Hg, Cd, Zn, Cu, Cr, Ni and Pb. Based on these data, this article adopts a toxicological approach to assess the health risks associated with the consumption of these fish and to compare the estimated exposure levels to international benchmarks established by the WHO, FAO and US-EPA.

2. Materials and methods

2.1. Study site and sampling

The study is based on data from previous work carried out in the Ébrié lagoon, Côte d'Ivoire [8, 9]. Sampling was carried out during the dry season (February 2017) and the rainy season (July 2017) at eight stations: Cosrou, Biétri, Port, Youpougon, Banco, Cocody, Marcory and Koumassi (Table 1). These plants are mostly bordered by precarious neighborhoods, industrial units, or receive domestic and industrial effluents as well as household waste, which can contribute to the contamination of lagoon matrices.

Table 1 Geographic coordinates of sampling points

Sampling sites	**Coordinates**	
	N	**W**
Bietri	05°16'47''	03°59'39''
Port	05°17'06''	04°00'54''
Yopougon	05°17'53''	04°03'39''
Banco	05°19'45''	04°02'01''
Cocody	05°19'31''	04°00'45''
Marcory	05°19'09''	03°59'24''
Koumassi	05°17'32''	03°56'19''
Cosrou	05°18'57''	04°40'14''

2.2. Metals studied

The analyses focused on the flesh of the fish *Tilapia sp.*, a species widely consumed by local populations and representative of the lagoon's catches. Hg has been quantified by thermal decomposition atomic absorption spectrometry (AMA 254) [18]. The other trace metals (Pb, Cd, Cu, Cr, Ni and Zn) were determined after wet acid digestion and measured by ICP-OES (SPECTROBLUE)® approximately 200 mg of dried matter was digested with HNO_3 and superpure® H_2O_2 under controlled heating before filtration and adjustment to 50 ml.

2.3. Data used

The metal concentrations for each station and for each season are presented in Tables 2 and 3. These concentrations were extracted from previous studies [8, 9] and serve as a basis for the assessment of the health risks associated with fish consumption in this article.

Table 2 Mean concentrations (± standard deviation) of heavy metals (µg/kg dry weight) in the flesh of *Tilapia sp*. Taken from the different bays of the Ebrié lagoon during the rainy season

Sites	**Hg (µg/ Kg dry weight)**	**Cd (µg/ Kg dry weight)**	**Zn (µg/ Kg dry weight)**	**Cu(µg/ Kg dry weight)**	**Cr (µg/ Kg dry weight)**	**Ni(µg/ Kg dry weight)**	**Pb (µg/Kg dry weight)**
Cosrou	475,10±6,42	0,33±0,04	1456±6,00	35,48±0,07	7,43±0,02	124,97±0,50	2,86±0,02
Bietri	191,82±8,87	0,34±0,00	985±1,89	45,95±0,07	6,84±0,60	0,60±0,17	1,91±0,41
Port	610,90±9,12	0,22±0,03	1744±4,00	56,60±0,60	5,59±0,50	0,68±0,10	1,55±0,16

Yopougon	343,03±12,63	0,65±0,05	1526±5,13	30,25±0,25	6,99±0,04	0,20±0,02	0,87±0,04
Banco	668,02±15,59	0,34±0,04	2594±0,00	51,46±0,46	6,95±0,94	1,04±0,04	1,60±0,01
Cocody	740,75±12,01	0,43±0,03	1453±3,00	37,47±1,00	6,75±0,56	0,14±0,01	0,46±0,02
Marcory	259,82±4,49	0,26±0,01	2227±13,00	138,28±1,00	6,58±0,62	4,46±0,10	11,81±0,72
Koumassi	388,90±26,47	0,19±0,01	1454±3,61	69,39±0,39	5,53±0,03	0,59±0,10	3,57±0,07

Table 3 Mean concentrations (± standard deviation) of trace metals (µg/kg dry weight) in the flesh of Tilapia sp. collected from the different bays of the Ebrié lagoon during the dry season

Sites	**Hg (µg/ Kg dry weight)**	**Cd (µg/ Kg dry weight)**	**Zn (µg/ Kg dry weight)**	**Cu (µg/ Kg dry weight)**	**C r(µg/ Kg dry weight)**	**Ni (µg/ Kg dry weight)**	**Pb (µg/Kg dry weight)**
Cosrou	205,83±4,46	0,24±0,00	672±2,32	35,26±0,65	4,20±0,70	17,90±0,26	2,58±0,01
Bietri	106,33±2,86	0,53±0,03	889±1,00	47,72±0,72	3,97±0,36	0,59±0,10	1,04±0,04
Port	357,51±4,94	0,26±0,02	928±2,52	52,17±1,00	4,47±0,59	4,62±0,05	2,85±0,10
Yopougon	1110,30±0,76	0,34±0,03	1004±4,58	57,42±0,45	5,12±0,12	5,69±0,53	2,51±0,04
Banco	522,93±20,43	0,86±0,02	1007±3,00	49,27±1,00	9,13±0,38	11,83±0,03	1,40±0,36
Cocody	590,39±9,73	0,25±0,00	848±1,00	43,89±1,00	5,68±0,22	1,33±0,07	0,57±0,00
Marcory	333,41±6,13	0,26±0,00	894±2,00	48,81±0,79	6,14±0,24	2,45±0,05	1,12±0,04
Koumassi	231,47±1,04	0,38±0,00	1063±4,04	37,81±0,21	5,76±0,15	2,49±0,16	5,49±0,03

2.4. Data analysis

2.4.1. Estimated Daily Intake (EDI)

The daily intake of heavy metals from the consumption of *Tilapia sp*., caught in the Ebrié lagoon during the sampling period, is estimated from the following formula described by [19] for the non-carcinogenic risk:

$$\boldsymbol{EDI = \frac{C \times IR \times Cf}{Pw} \times 10^{-3}} \qquad (1)$$

With:

EDI: Estimated daily intake in $mg.kg^{-1}.day^{-1}$; C: Concentration of heavy metals in fish muscle (mg/kg dry weight); RI: Fish intake rate (44g/person/day) [20]; Cf: conversion factor (0.208) from fresh to dry weight of fish [21]; Pw: Average weight of an adult person (60.7 kg) [22].

2.4.2. Hazard Quotient (THQ)

The level of non-carcinogenic risk for each metal from the consumption *of Tilapia sp.* was assessed using the following formula [23]:

$$\boldsymbol{THQ = \frac{DJE}{RfD}} \qquad (2)$$

With

DJE: Daily exposure dose in mg/kg/day; RfD: Oral reference dose with 0.00016 mg/kg/day for mercury (Hg), 0.001 mg/kg/day for cadmium (Cd), 0.004 mg/kg/day for lead (Pb), 1.5 $mg.kg^{-1}.day^{-1}$ for chromium (Cr), 0.3 mg/kg/day for zinc (Zn), 0.04 mg/kg/day for copper (Cu) and 0.02 mg/kg/day for nickel (Ni) [24].

If THQ < 1, eating the fish is safe. On the other hand, there is a health hazard if THQ > 1.

2.4.3. Hazard index (HI)

The combined effect of heavy metals in fish flesh has been estimated using the following formula [25]:

$$\mathbf{IH} = \sum_{\mathbf{i=1}}^{\mathbf{n}} \mathbf{THQi} \qquad (3)$$

With

n: total number of heavy metals THQi: Target hazard quotient of a metal under consideration.

If IH< 1, the combined effect of the metals considered is safe for the consumer,

if IH > 1, the consumption of fish has a considerable non-carcinogenic effect on health.

2.4.4. Carcinogenic risk (CR)

The carcinogenic health risk associated with the consumption of *Tilapia sp*. is evaluated using the following formula:

$$\boldsymbol{CR = EDIXSF} \quad \mathbf{(4)}$$

With

CR: Carcinogenic risk; EDI: Estimated Daily Intake; SF: Carcinogenic slope factor (Table 4). The estimated duration of exposure (ED) for carcinogenic risks is 62 years. The acceptable risk level for carcinogenic effects is between 10^{-4} and 10^{-6} [26].

Table 4 The SF values used for this study

Metal	**Slope factor (SF) $(\mathbf{mg/kg/day})^{-1}$**	**Reference**
CD	6.1	[26]
Cr (VI)	0.5	[26]
Ni	0.91	[26]
Pb	0.0085	[27]

3. Results

3.1. Estimated Daily Intake (EDI)

Estimated daily intake (EDI) values of metals' trace in consumers of *Tilapia sp.* of the Ebrié lagoon revealed significant spatial and seasonal variations. Overall, the highest EDI was observed during the rainy season. Values range from 0.16×10^{-4} mg/kg/day to 1.67×10^{-4} mg/kg/day for Hg, from 1.51×10^{-8} mg/kg/day to 1.30×10^{-7} mg/kg/day for Cd, from 1.01×10^{-4} mg/kg/day to 3.91×10^{-4} mg/kg/day for Zn, from 4.56×10^{-6} mg/kg/day to 2.08×10^{-5} mg/kg/day for Cu, from 1.01×10^{-7} mg/kg/day to 1.38×10^{-6} mg/kg/day for Cr, from 2.11×10^{-8} mg/kg/day to 1.70×10^{-4} mg/kg/day for Ni, and from 6.94×10^{-8} mg/kg/day to 1.78×10^{-6} mg/kg/day for Pb (Table 5). Among the studied metals, zinc (Zn) and copper (Cu) have the highest EDI values, consistent with their natural abundance and their presence in many domestic and industrial discharges. In contrast, the most toxic heavy metals such as mercury (Hg), cadmium (Cd) and lead (Pb) show lower absolute EDIs, but their high inherent toxicity warrants special attention. The stations of Cocody, Banco and Marcory are distinguished by higher EDIs for the majority of metals, reflecting their exposure to multiple sources of pollution such as domestic effluents, urban landfills and industrial areas. Conversely, the stations of Biétri and Cosrou have the lowest values, reflecting less anthropogenic pressure.

Table 5 Estimated daily intakes (EDI, mg/kg/day) of trace metals for consumers of Tilapia sp. in the Ébrié lagoon. (IR = 44 g/day; Pw = 60.7 kg; Cf = 0.208)

Seasons	Sites	(Hg)	Cd	Zn	Cu	Cr	Ni	Pb
Dry season	**Cosrou**	0.31×10^{-4}	3.57×10^{-8}	1.01×10^{-4}	5.32×10^{-6}	6.33×10^{-7}	2.70×10^{-6}	3.89×10^{-7}
	Biétri	0.16×10^{-4}	7.95×10^{-8}	1.34×10^{-4}	7.20×10^{-6}	5.99×10^{-7}	8.90×10^{-8}	1.57×10^{-7}
	Port	0.54×10^{-4}	3.92×10^{-8}	1.40×10^{-4}	7.87×10^{-6}	6.74×10^{-7}	6.97×10^{-7}	4.30×10^{-7}
	Yopougon	1.67×10^{-4}	5.11×10^{-8}	1.51×10^{-4}	8.66×10^{-6}	7.72×10^{-7}	8.58×10^{-7}	3.78×10^{-7}
	Banco	0.08×10^{-4}	1.30×10^{-7}	1.52×10^{-4}	7.43×10^{-6}	1.38×10^{-6}	3.02×10^{-8}	2.11×10^{-7}
	Cocody	0.89×10^{-4}	3.78×10^{-8}	1.28×10^{-4}	6.62×10^{-6}	8.56×10^{-7}	2.01×10^{-7}	8.59×10^{-8}
	Marcory	0.50×10^{-4}	3.95×10^{-8}	1.35×10^{-4}	7.36×10^{-6}	9.26×10^{-7}	3.69×10^{-7}	1.69×10^{-7}
	Koumassi	0.35×10^{-4}	5.71×10^{-8}	1.60×10^{-4}	5.70×10^{-6}	8.68×10^{-7}	3.75×10^{-7}	8.28×10^{-7}
Rainy season	**Cosrou**	0.72×10^{-4}	4.97×10^{-8}	1.20×10^{-4}	5.35×10^{-6}	1.12×10^{-6}	1.70×10^{-4}	3.92×10^{-7}
	Biétri	0.29×10^{-4}	5.58×10^{-8}	1.49×10^{-4}	6.93×10^{-6}	1.03×10^{-6}	9.05×10^{-8}	2.88×10^{-7}
	Port	0.92×10^{-4}	3.29×10^{-8}	2.63×10^{-4}	8.53×10^{-6}	8.43×10^{-7}	1.03×10^{-7}	2.34×10^{-7}
	Yopougon	0.52×10^{-4}	9.95×10^{-8}	2.30×10^{-4}	4.56×10^{-6}	1.05×10^{-6}	1.05×10^{-6}	1.31×10^{-6}
	Banco	1.01×10^{-4}	5.58×10^{-8}	3.91×10^{-4}	7.76×10^{-6}	1.04×10^{-6}	1.57×10^{-7}	2.41×10^{-7}
	Cocody	1.12×10^{-4}	6.33×10^{-8}	2.19×10^{-4}	5.65×10^{-6}	1.01×10^{-7}	2.11×10^{-8}	6.94×10^{-8}
	Marcory	0.39×10^{-4}	3.92×10^{-8}	3.36×10^{-4}	2.08×10^{-5}	9.92×10^{-7}	6.72×10^{-7}	1.78×10^{-6}
	Koumassi	0.59×10^{-4}	1.51×10^{-8}	2.19×10^{-4}	1.05×10^{-5}	8.33×10^{-7}	8.90×10^{-8}	5.38×10^{-7}

3.2. Non-cancer risks (THQ, HI)

3.2.1. Hazard Quotient (THQ)

The calculated THQ values for heavy metals (Hg, Cd, Zn, Cu, Cr, Ni and Pb) are presented in Table 6 for both seasons of study. The calculated hazard quotients (HRQs) for each metal reveal marked disparities between stations and seasons. The values vary from 0.10 to 1.4 for Hg, from 1.51×10^{-5} to 1.30×10^{-4} for Cd, from 3.37×10^{-4} to 1.30×10^{-3} for Zn, from 1.14×10^{-4} to 5.21×10^{-4} for Cu, from 3.99×10^{-7} to 9.18×10^{-7} for Cr, from 2.11×10^{-8} to 1.70×10^{-4} for Ni and from 7.20×10^{-6} at 4.45×10^{-4} for the Pb. Generally, the hazard quotients related to the consumption of *Tilapia sp*. caught in the rainy season at sampling stations are higher than those in the dry season. However, the HQ of the metals considered in this study are less than 1 with a descending order as follows:

THQ(Hg)>THQ(Zn)>THQ(Cu)>THQ(Pb)>THQ(Cd)>THQ(Ni)>THQ(Cr) with the exception of THQ (Hg) related to the consumption of fish from the commune of Yopougon during the dry season. The ingestion of Hg via fish consumption during this period carries a real health risk with a THQ equal to 1.04.

Table 6 THQ values of trace metals in the flesh of Tilapia sp. from the Ébrié lagoon during the rainy and dry seasons

Seasons	Sites	Hg	Cd	Zn	Cu	Cr	Ni	Pb
Dry season	Cosrou	0.19	3.57×10^{-5}	3.37×10^{-4}	1.33×10^{-4}	4.22×10^{-7}	1.35×10^{-4}	9.72×10^{-5}
	Biétri	0.1	7.95×10^{-5}	4.46×10^{-4}	1.80×10^{-4}	3.99×10^{-7}	4.45×10^{-6}	3.93×10^{-5}
	Port	0.34	3.92×10^{-5}	4.67×10^{-4}	1.97×10^{-4}	4.49×10^{-7}	3.49×10^{-6}	1.07×10^{-4}
	Yopougon	1.04	5.11×10^{-5}	5.03×10^{-4}	2.16×10^{-4}	5.15×10^{-7}	4.29×10^{-5}	9.46×10^{-5}
	Banco	0.49	1.30×10^{-4}	5.07×10^{-4}	1.86×10^{-4}	9.18×10^{-7}	1.51×10^{-6}	5.28×10^{-5}
	Cocody	0.56	3.78×10^{-5}	4.27×10^{-4}	1.65×10^{-4}	5.71×10^{-7}	1.00×10^{-6}	2.15×10^{-5}

	Marcory	0.31	3.95x10^{-5}	4.50x10^{-4}	1.84x10^{-4}	6.17x10^{-7}	1.85x10^{-5}	4.22x10^{-5}
	Koumassi	0.22	5.71x10^{-5}	5.33x10^{-4}	1.43x10^{-4}	5.79x10^{-7}	1.88x10^{-5}	2.06x10^{-4}
Rainy season	Cosrou	0.45	4.97x10^{-5}	4.00x10^{-4}	1.34x10^{-4}	7.47x10^{-7}	1.70x10^{-4}	9.80x10^{-5}
	Biétri	0.18	5.58x10^{-5}	4.97x10^{-4}	1.73x10^{-4}	6.87x10^{-7}	9.05x10^{-8}	7.20x10^{-6}
	Port	0.56	3.29x10^{-5}	8.77x10^{-4}	2.13x10^{-4}	5.62x10^{-7}	1.03x10^{-7}	5.84x10^{-5}
	Yopougon	0.32	9.95x10^{-5}	7.66x10^{-4}	1.14x10^{-4}	7.03x10^{-7}	1.05x10^{-6}	3.28x10^{-5}
	Banco	0.63	5.58x10^{-5}	1.30x10^{-3}	1.94x10^{-4}	6.99x10^{-7}	1.57x10^{-7}	6.03x10^{-5}
	Cocody	0.7	6.33x10^{-5}	7.30x10^{-4}	1.42x10^{-4}	6.78x10^{-7}	2.11x10^{-8}	1.73x10^{-5}
	Marcory	0.24	3.92x10^{-5}	1.12x10^{-3}	5.21x10^{-4}	6.61x10^{-7}	6.72x10^{-7}	4.45x10^{-4}
	Koumassi	0.37	1.51x10^{-5}	7.30x10^{-4}	2.62x10^{-4}	5.56x10^{-7}	8.90x10^{-8}	1.35x10^{-4}

3.2.2. Overall risk (HI)

The hazard index (HI), representing the sum of the potential effects of all heavy metals, remains below 1 at the majority of stations, suggesting that the consumption of *Tilapia sp.* of the Ébrié lagoon does not pose an immediate non-carcinogenic risk to the general population. This index ranges from 0.10 to 1.04 in the dry season and from 0.18 to 0.70 for the rainy season at all stations (Table 7). The health effects related to the combined effect of metals are real during the dry season for the consumption of fish from the Yopougon station with a hazard index (HI) of 1.04 indicating a cumulative exposure of potential concern, particularly for riparian populations whose fish is a main source of potential protein (HI> 1). The analysis of HI by sampling site shows that the consumption of fish from the Banco, Yopougon, Port and Cocody stations produces greater health risks than that of fish from the Marcory, Koumassi, Cosrou and Biétry stations.

Table 7 HI values of trace metals in the flesh of Tilapia sp. from the Ébrié lagoon during the rainy and dry seasons

Sites	**Dry season**	**Rainy Season**
Cosrou	0.19	0.45
Bietri	0.10	0.18
Port	0.34	0.56
Yopougon	1.04	0.32
Banco	0.49	0.63
Cocody	0.56	0.70
Marcory	0.31	0.24
Koumassi	0.22	0.37

3.3. Carcinogenic Hazards (CR)

The calculated individual carcinogenic risk values (CR) for cadmium (Cd), chromium (Cr), nickel (Ni) and lead (Pb) are presented in Table 8. They vary according to the sites and the seasons, reflecting differences in contamination and exposure. Overall, the CR values are in the range of 10^{-6} to 10^{-4}, which is considered by the US EPA (2022) to be an area of tolerable risk to human health. However, localized peaks have been observed, particularly in Cosrou during the rainy season, where the sum of the carcinogenic risks ($\Sigma CR = 1.55\times10^{-4}$) slightly exceeds the upper tolerance threshold (10^{-4}), suggesting an unacceptable potential carcinogenic risk for regular consumers of fish from this area. The other stations, such as Marcory and Banco, also have relatively high values (ΣCR between 1.1×10^{-6} and 1.56×10^{-6}), indicating a non-negligible exposure but remaining within the acceptable (tolerable) range. On the other hand, Biétri, Cocody and Koumassi have the lowest levels (ΣCR between 0.46×10^{-6} and 0.94×10^{-6}), reflecting less contamination of fish in these areas. Seasonality plays a significant role. Indeed, CR values are systematically higher in the rainy season than in the dry season. Overall, the results indicate that, although the overall carcinogenic risks remain moderate, some areas (Cosrou, Marcory, Banco) have worrying levels that deserve continuous monitoring and awareness of the local populations about the frequent consumption of lagoon fish.

Table 8 Carcinogenic risks (CR $\times 10^{-6}$) associated with the consumption of Tilapia sp. from the Ébrié lagoon in the dry season

Seasons	Stations	Cd	Cr	Ni	Pb	Total risk (ΣCR)x10^{-6}	Nature of risk
Dry season	Cosrou	0.22	0.32	2.46	0.00	2.99	Tolerable
	Bietri	0.48	0.30	0.08	0.00	0.87	Negligible
	Port	0.24	0.34	0.63	0.00	1.21	Tolerable
	Yopougon	0.31	0.39	0.78	0.00	1.48	Tolerable
	Banco	0.79	0.69	0.03	0.00	1.51	Tolerable
	Cocody	0.23	0.43	0.18	0.00	0.84	Negligible
	Marcory	0.24	0.46	0.34	0.00	1.04	Tolerable
	Koumassi	0.35	0.43	0.34	0.01	1.13	Tolerable
Rainy season	Cosrou	0.30	0.56	154.70	0.00	155.57	Unacceptable
	Bietri	0.34	0.52	0.08	0.00	0.94	Negligible
	Port	0.20	0.42	0.09	0.00	0.72	Negligible
	Yopougon	0.61	0.52	0.96	0.01	2.1	Tolerable
	Banco	0.34	0.52	0.14	0.00	1.01	Tolerable
	Cocody	0.39	0.05	0.02	0.00	0.46	Negligible
	Marcory	0.24	0.50	0.61	0.02	1.36	Tolerable
	Koumassi	0.09	0.42	0.08	0.00	0.59	Negligible

4. Discussion

4.1. Daily intake assessment (EDI) and regional comparison

The estimated daily intake (EDI) of heavy metals via the consumption of *Tilapia sp*. was calculated by considering an individual with an average weight of 60.7 kg with a fish consumption of 44g/person/day [20, 22]. Compared to the tolerable reference values established by [11] and [28], the calculated EDIs for most metals remain below the permissible limits, indicating a non-immediate risk of exposure to consumers. However, the levels observed for Hg, particularly in Cocody and Banco, are close to critical values, suggesting a potential chronic risk in the event of regular consumption of fish from these areas, which is all the more important for children. Our results gave higher EDI in the rainy season than in the dry season, reflecting a more marked contamination of fish flesh during this period. Studies [29], [30] and [31] consistently show that heavy metal concentrations in aquatic environments are higher during the rainy season than during the dry season. This phenomenon is generally attributed to several mechanisms, such as increased runoff and urban and industrial discharges, which can be accentuated by stormwater runoff. These phenomena contribute to the elevation of heavy metal levels in water and sediment during precipitation, as well as to the resuspension of sediments containing heavy metals. These are then released into the water column, where they can be bioaccumulated by aquatic organisms, such as fish. The estimated daily intake (EDI) values obtained in this study are lower than those reported by [32] which recorded EDI values of 7.97×10^{-5} mg/kg/day for Hg, 2.90×10^{-5} mg/kg/day for Cd and 7.97×10^{-5} mg/kg/day for Pb in *Coptodon Zillii*and *Coptodon Guineesis* in sectors IV and V of the Ebrié lagoon (Côte d'Ivoire). Our values are also lower than the values obtained by [33] (Cd=0.02 mg/kg/day; Pb=0.46 mg/kg/day; Cu=0.57 mg/kg/day; Zn=12.31 mg/kg/day; Cr=0.03 mg/kg/day; Ni=0.03 mg/kg/day) in fish (*Chrysichthys nigrodigitatus*) from two lagoons in southwestern Nigeria. The EDIs observed in the Ébrié lagoon are in the same orders of magnitude as those reported elsewhere, particularly for mercury, confirming a comparable health risk in similar socio-environmental contexts (rapid urbanization, untreated effluents, industrial activity) (Table 9). Our results therefore indicate a significant exposure of local consumers. The highest values are for mercury (Hg) and zinc (Zn), especially in Yopougon and Banco, areas under strong anthropogenic pressures. Although the majority of EDIs remain below FAO/WHO thresholds, some occasionally exceed tolerable values, indicating a potential long-term risk. These results are consistent with those observed in other Ivorian lagoons: Grand-Lahou [34], Aby [17] and Fresco [16], where similar levels of Hg, Zn and Cu have been reported. At the regional scale, similar trends have been reported in the Keta Lagoon in Ghana [35], confirming diffuse contamination in African aquatic ecosystems. Internationally, comparable EDIs have been observed in Bangladesh [36] and China [37], as well as in the Ecuadorian Amazon [38, 39]. These similarities reflect the widespread global anthropogenic pressures related to domestic and industrial discharges. They emphasize the need for surveillance and prevention programmes, especially for vulnerable groups such as children and pregnant women. Chronic exposure, even at low doses, to metals such as Hg, Cd and Pb can cause nephrotoxic, neurotoxic and developmental disruptive effects, particularly in children and pregnant women [40]. Thus, although the average EDI calculated values are generally below tolerable thresholds, their cumulative nature and the high frequency of fish consumption in the Ivorian coastal areas justify continuous monitoring and the implementation of management measures to reduce metal contamination in the lagoon.

Table 9 Comparison of EDIs (mg/kg/day) and dominant metals reported in various studies

Study area	**Species(ies) studied**	**Dominant metals**	**EDI range (mg/kg/day)**	**Key risk identified**	**Reference**
Ébrié Lagoon (Ivory Coast)	Tilapia sp.	Hg, Zn	3.4×10^{-5} – 1.7×10^{-4}	Chronic Potential Risk (Hg)	This study
Grand-Lahou Lagoon (Ivory Coast)	Miscellaneous lagoon fishes	Hg, Pb	5.0×10^{-5} – 1.2×10^{-4}	Moderate neurotoxic risk (Hg)	[34]
Aby Lagoon (Ivory Coast)	Tilapia sp., Chrysichthys sp.	Cu, Zn, Cd	2.0×10^{-6} – 1.5×10^{-4}	Low to moderate chronic risk	[17]
Keta Lagoon (Ghana)	Varied fish	Hg, Pb	4.0×10^{-5} – 1.0×10^{-4}	Carcinogenic risk in children	[35]
Bangladesh (Asia)	Dried fish	Cd, Pb	2.0×10^{-6} – 1.2×10^{-4}	Potential carcinogenic risk	[36]
China (Bohai Sea)	Marine Fish	Cu, Zn	5.0×10^{-6} – 1.0×10^{-4}	Chronic dietary risk	[37]
Amazon (Ecuador–Peru)	River Fish	Hg, Pb	3.0×10^{-5} – 2.0×10^{-4}	Increased neurological risk	[38, 39]

4.2. Non-cancer risk assessment (HQ and HI)

The non-cancer risk assessment aims to determine whether exposure to heavy metals through the consumption of *Tilapia sp.* of the Ébrié lagoon could lead to adverse effects on human health in the long term. The values of the non-cancer risk index (THQ) for trace metals in the flesh of *Tilapia sp.* from the Ébrié lagoon vary according to the resorts and the seasons. Mercury (Hg) generally has the highest THQ. In some stations such as Yopougon, the THQ of Hg exceeds 1, suggesting a potential non-carcinogenic risk, especially for vulnerable populations (children, pregnant women). These observations are consistent with other West African lagoons (Table 10): Grand-Lahou [34] and Aby [17] reported THQ > 1 for Hg and Pb. In Ghana, the Keta Lagoon also exposes children to THQ above US-EPA thresholds [35]. Internationally, high THQ is reported in Asia: Bangladesh [36] for Cd, Pb and Hg, and China [37] for Cu and Zn. In Latin America, in the Ecuadorian and Peruvian Amazon, cumulative HI exceeds 1.2–3.8 depending on the species and site [38, 39]. The combination of exposure to several metals can lead to additive or synergistic effects, affecting the nervous system and the kidneys [11, 41]. Even when unit concentrations remain low, the sum of the THQ (HI > 1) reflects a significant overall risk. These results underline the need for regular monitoring, awareness of reasoned consumption and improved treatment of urban and industrial waste. In the long term, a national network for monitoring metal contaminants would help to better manage public health risks in Côte d'Ivoire.

Table 10 Comparison of THQ and HI for trace metals in fish

Study area	Species(ies) studied	Dominant metals	THQ max observed	HI (somme THQ)	Key Risk	Reference
Ébrié Lagoon (Ivory Coast)	Tilapia sp.	Hg, Pb	Hg:>1	HI: 1.2–1.5	Potential non-cancer risk	This study
Grand-Lahou Lagoon (Ivory Coast)	Miscellaneous lagoon fishes	Hg, Pb	>1	-	Chronic risk (Hg, Pb)	[34]
Aby Lagoon (Ivory Coast)	Tilapia sp., Chrysichthyssp.	Hg, Zn, Cu	Hg: 1.23	-	Local chronic risk	[17]
Keta Lagoon (Ghana)	Varied fish	Hg, Pb	3× US-EPA threshold (children)	-	High non-cancer risk in children	[35]
Bangladesh (Asia)	Dried fish	Cd, Pb, Hg	>1	-	Potential chronic risk	[36]
China (Bohai Sea)	Marine Fish	Cu, Zn	>1	-	Non-cancer risk for food	[37]
Amazon (Ecuador–Peru)	River Fish	Hg, Pb	-	1.2–3.8	High non-cancer risk	[38, 39]

4.3. Carcinogenic Risks (CR) from eating fish

The carcinogenic risk calculated values (CR) for Cd, Cr, Ni and Pb show that certain areas of the Ébrié lagoon present a potential risk for regular consumers of *Tilapias sp*. fish, particularly at the Banco, Marcory and Cocody sites. Although most CRs remain below the 10^{-4} tolerance threshold set by the US-EPA, several stations meet or exceed 10^{-5}, suggesting long-term exposure. These results are consistent with observations in other West African lagoons (Table 11): moderate CR for Cr and Cd in Grand-Lahou [34], levels close to 10^{-4} for Ni and Cr in Aby Lagoon [17] and exceedances for children in Keta (Ghana) related to Cd and Pb [35]. Internationally, similar CRs have been found in Zhejiang (China) for Cr and Ni up to 2.3×10^{-4} [37], in Bangladesh for Cd $>10^{-4}$ [36] and in the Amazon for Hg and Pb up to 10^{-3} [38], [39]. These data confirm that the consumption of fish which are contaminated by metal is a global problem, particularly in tropical areas with high anthropogenic pressure. Even when unit RCs are below critical thresholds, cumulative exposure and high frequency of fish consumption may increase the overall risk, highlighting the need for integrated monitoring and targeted mitigation measures [41].

Table 11 Comparison of carcinogenic (CR) risks for trace metals in fish

Study area	Species(s)	Dominant metals	CR observed	US-EPA threshold	Key Risk	Reference
Ébrié Lagoon (Côte d’Ivoire)	Tilapia sp.	Cd, Cr, Ni, Pb	10^{-5}–10^{-4}	10^{-4}	Potential carcinogenic risk	This study
Grand-Lahou (Côte d’Ivoire)	Miscellaneous fish	Cr, Cd	10^{-5}–10^{-4}	10^{-4}	Moderate carcinogenic risk	[34]
Aby Lagoon (Côte d’Ivoire)	Tilapia sp., Chrysichthys sp.	Ni, Cr	$\approx10^{-4}$	10^{-4}	Latent carcinogenic risk	[17]
Keta Lagoon (Ghana)	Varied fish	Cd, Pb	$>10^{-4}$ (children)	10^{-4}	High risk in children	[35]
Bangladesh	Dried fish	Cd	$>10^{-4}$	10^{-4}	Exposure of concern	[36]

China (Zhejiang)	Marine Fish	Cr, Ni	$\leq 2.3 \times 10^{-4}$	10^{-4}	Chronic exposure	[37]
Amazon (Ecuador–Peru)	River Fish	Hg, Pb	10^{-5}–10^{-3}	10^{-4}	High carcinogenic risk	[38, 39]

5. Conclusion

This study highlights that the consumption of Tilapia from the Ébrié lagoon exposes the riparian populations to variable levels of heavy metals, reflecting the influence of urban, industrial and domestic activities on the quality of the lagoon ecosystem. The analyses show that, despite generally low estimated daily intakes (EDI), some sites present non-carcinogenic (THQ, HI) and carcinogenic (CR) risks requiring special attention, in particular Yopougon and Cosrou. The high concentrations observed for certain metals, as well as the occasional exceedances of safety thresholds, reflect chronic exposure that can affect the long-term health of populations that regularly consume local fish. In this context, the protection of public health requires strengthening measures to manage metal discharges, systematic monitoring of bioaccumulators such as fish, and raising awareness among the population about safer consumption practices. Finally, this study highlights the importance of integrating health risk assessments into the environmental management strategies of the Ébrié lagoon, in order to guarantee the sustainability of fisheries resources and preserve the food security of local communities.

Compliance with ethical standards

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Disclosure of conflict of interest

No conflict of interest to be disclosed.

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