

1 **“Evaluation of trace metal element levels in water, sediment and two fish species (*Clarias gariepinus* and *Oreochromis***
2 ***niloticus*) in ten fish farms in the Moungo Department, Littoral region, Cameroon”**

3
4 **Abstract**

5 This study evaluated trace metal element (TME) concentrations in water, sediments, and muscle tissues of *Clarias gariepinus* and *Oreochromis*
6 *niloticus* collected from ten aquaculture farms in the Moungo Department, Littoral Region, Cameroon. Sampling was conducted during the rainy
7 season, and analyses were performed using energy-dispersive X-ray fluorescence spectrometry (Shimadzu EDX-7000). The main elements
8 detected were Fe, Cu, Zn, Ca, K, P, S, Si, and Ti. No regulated heavy metals (Pb, Cd, Hg) were detected above the analytical limits of detection.
9 Total arsenic, which is not regulated in fish flesh under European Union legislation, was also below detection limits. High concentrations of Fe
10 (20.94–65.94 mg/L) and Cu (30.83–34.72 mg/L) were measured in rearing water, exceeding WHO guideline values for drinking water. These
11 levels likely reflect local geochemical conditions, with possible additional inputs from agricultural practices or metal equipment used in farming
12 systems. Sediments were identified as the main accumulation compartment, particularly for Fe and Si, indicating a predominantly geological
13 origin. Fish exhibited site-specific bioaccumulation patterns, especially for Fe and Ca, but levels of priority toxic metals remained low.
14 These findings do not indicate regulatory concern but highlight the need for regular monitoring to detect potential changes in contamination
15 levels in the context of expanding aquaculture systems.

16 **Keywords:** *Clarias gariepinus*, *Oreochromis niloticus*, metals, sediments, water.

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18 **INTRODUCTION**

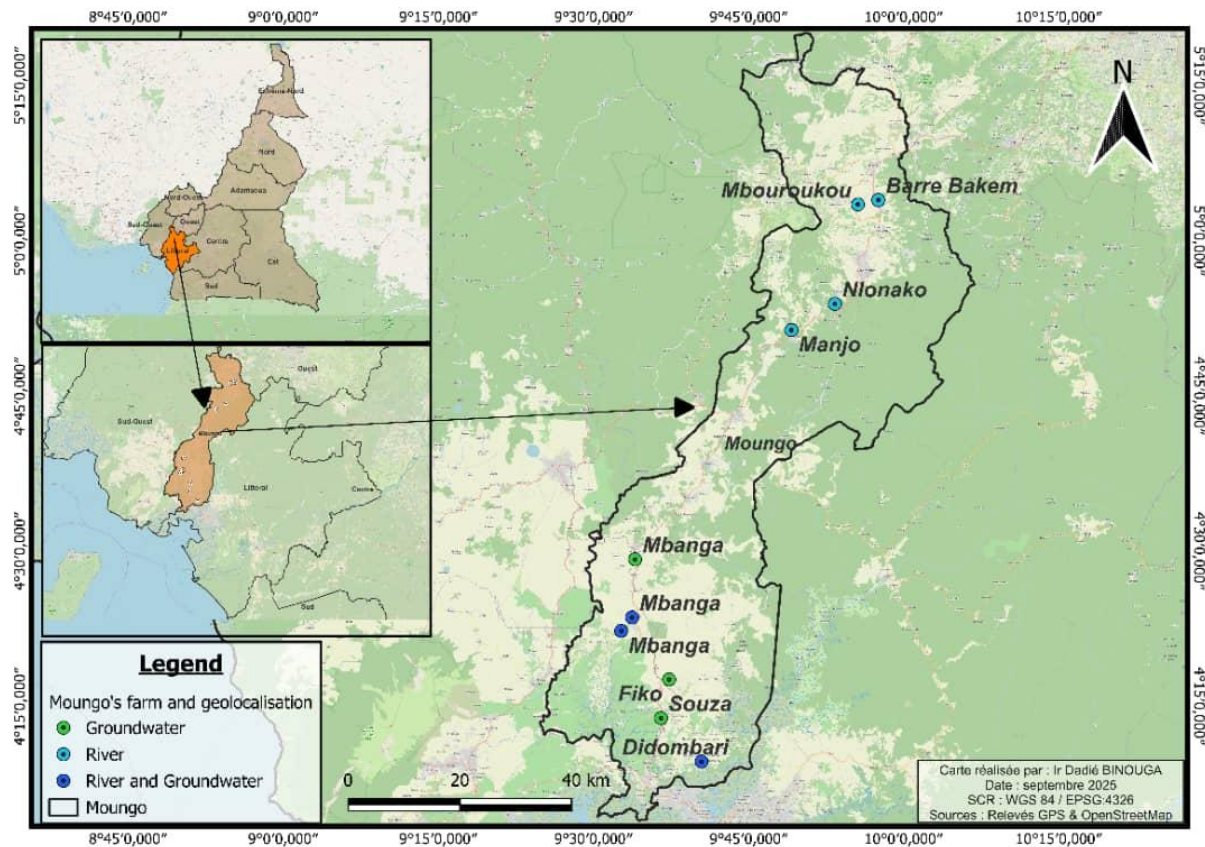
19 Aquaculture is one of the fastest-growing food industries worldwide and plays a key role in ensuring the food and nutritional security of
20 populations, especially in developing countries (FAO, 2022). According to FAO, the year 2022 saw global aquaculture production reach peaks,
21 accounting for more than 50% of the overall production of marine and freshwater animals. In addition, continental aquaculture is taking an
22 increasingly important place in the supply of animal protein (FAO, 2022b). Its development aims to reduce the growing gap between the demand
23 for seafood and the limits of traditional fishing, which remains at a constant level. According to the FAO, aquaculture will be the world's leading
24 source of fish supply by 2030. In this context, it appears as a strategic sector for food and nutritional security in sub-Saharan Africa, especially in
25 Cameroon, where the production of *Clarias gariepinus* and *Oreochromis niloticus* is predominant (FAO, 2022a, 2022b). According to Temegne
26 and Momo (2019), in Cameroon, fish constitutes nearly 40% of the protein supply of animal origin and covers 9.5% of the population's overall
27 nutritional needs. In Cameroon, each person consumes an average of 11 kg of fish per year, offering a protein intake of 22g for every 100g of fish
28 per individual (Kenfack *et al.*, 2019; Temegne and Momo, 2019). The Cameroonian population greatly values fish because of its availability and
29 cost, which positions it at the top of meat (Kenfack *et al.*, 2019; Pouokamet *et al.*, 2017). In 2017, the country's fish production amounted to only
30 181,678 tons per year, estimated at a value of 114.3 billion FCFA. In addition, less than 1000 tons per year came from fish farming activities,
31 representing less than 0.1% of GDP (Kenfack *et al.*, 2019; Temegne and Momo, 2019). However, the intensification of aquaculture practices,
32 associated with sometimes inadequate management of inputs and discharges, can cause a collection of trace metals (TME) in aquatic
33 environments (Onyena & Udensi, 2019). Contaminations, intensified by bioaccumulation and bioamplification, pose a threat to consumer health
34 (Alloway, 2013; FAO & WHO, 2011). In Cameroon, water pollution by heavy metals represents an environmental problem of primary
35 importance, especially in regions where industrial, mining and agricultural activity is intense. Studies on metal accumulation include the analysis
36 of muscles, since they constitute the part consumed by human beings (Şirin *et al.*, 2024). Metal concentrations in water may increase due to
37 agricultural practices (Han & Gu, 2023), wastewater discharges (Soleimani *et al.*, 2023), mining (Lakra *et al.*, 2019; Mishra *et al.*, 2008), acid
38 drainage of mines (Lebepe *et al.*, 2020) and industrial activities (Adegbola *et al.*, 2021). Heavy metals that are persistent in aquatic environments
39 have the potential to accumulate in living species, leading to physiological and reproductive changes in fish. They can also pose a threat to the
40 biological diversity and food security of riparian communities (Ali *et al.*, 2019; Oumarou *et al.*, 2021; FAO, 2022). Despite the notable expansion

41 of fish farming in the Littoral region, particularly in the department of Mongo, little research has focused on the evaluation of the TMEs present
42 in the waters, sediments and fish of these farms (Troell *et al.*, 2014). The purpose of this research is to evaluate the levels of metallic trace
43 elements (TME) in aquaculture waters, sediments and tissues of *C. gariepinus* and *O. niloticus* from ten fish farms located in the department of
44 Mongo, in order to provide an inventory and guide sustainable management practices (FAO, 2022a). These results will make it possible to
45 establish an assessment of local pollution and to provide crucial data for the sustainable management of these resources and health quality.

46 **MATERIALS AND METHODS**

47 **Sampling Sites**

48 The study was carried out in the department of Mongo, located in the Littoral region of Cameroon. The samples were taken from July 22 to 27,
49 2025 corresponding to the great rainy season in ten agro-fish farms selected through the information provided by the Ministry of Livestock,
50 Fisheries and Animal Industries (MINEPIA) in order to ensure the representativeness of local fish farming activity (Figure 1).The Mounjo
51 department, located in the Littoral Region, is a major agricultural basin on the Cameroonian coast, contributing disproportionately to regional
52 maize production and supporting important food and agro-industrial sectors (MINADER — AGRISTAT, 2023). Its favorable agro-ecological
53 position (volcanic soils around Mount Nlonako) and the combined presence of small farms and agro-industrial enterprises explain its central role
54 in food security and rural development in the Littoral.



55

56 **Figure 1.** Map of Cameroun showing the location of the 10 aquaculture and agriculture integrated farms sampled in the Littoral region.

57 The exact location of the ten agro-fish farms was achieved thanks to geolocation through the map coordinates.

58

59 **Table 1.** Coordinates and location of sampling sites.

Farm number	Geographical coordinates	Littoral region/Moungodepartment : Specific Area	Watersources
1	5°03'55.8"N 9°57'31.9"E	Barre Bakem	River (Mont Manengoumba)
2	5°03'30.4"N 9°55'33.5"E	Mbouroukou	River (Mont Manengoumba)
3	4°22'16.8"N 9°32'40.7"E	Mbanga	River and Groundwater
4	4°51'21.3"N 9°49'08.1"E	Manjo	River (Mont Manengoumba)
5	4°53'53.6"N 9°53'20.3"E	Nlonako	River (Mont Manengoumba)
6	4°29'11.7"N 9°34'01.0"E	Mbanga	Groundwater
7	4°23'34.9"N 9°33'43.2"E	Mbanga	River and Groundwater
8	4°13'50.9"N 9°36'31.2"E	Souza	Groundwater
9	4°17'35.2"N 9°37'18.6"E	Fiko	Groundwater
10	4°09'39.1"N 9°40'26.2"E	Didombari	River and Groundwater

60

61 Sampling procedure

62 Samples of livestock water, sediments and fish were taken for each farm. Water samples were collected at a depth of approximately 30 cm (to
63 avoid suspended particles), in bottles that have been previously rinsed with HNO₃ because HNO₃ eliminates metal traces adsorbed on the walls
64 and prevents contamination of the sample. The samples were kept at 4°C until their analysis. The sediments were collected at five points (four
65 corners and the center), the surface layer of sediment (around 0-5cm) was collected. For earthen ponds, a shovel was used, while for liner ponds,
66 the collection was done by hand. After taking the five points, the whole was mixed homogeneously and a quantity of 500g was taken. The

67 samples were then placed in bags (with a pre-wash with HNO₃) sealed and labeled and then put in the cooler before being transported and put in
68 the freezer at -18° before preparation in the laboratory. Regarding the fish, two species were sampled according to availability on each farm:
69 tilapia (*Oreochromis niloticus*) and African catfish (*Clarias gariepinus*). Five individuals were captured by species and by farms. For a total of 5
70 fish per farm and 50 fish for the entire study. The fish were weighed (average weight per fish about 0.3kg or 1.5 kg per batch of samples) before
71 being stored in coolers and then frozen at -18° before preparation in the laboratory. We sampled the *Oreochromis niloticus* in farms 1 and 4, while
72 the *Clarias gariepinus* was taken from farms 2,3,5,6,7,8,9 and 10.

73 **Sample preparation and analysis**

74 The samples were analyzed at the Laboratory of Analysis of Radiological Contaminants and Heavy Metals in Fishery Products. The water
75 samples were filtered (filter 0.45 µm) before analysis. The sediment samples were dried in the oven between 40 °C and 60 °C for a period of 24
76 to 48 hours, then mixed to obtain a fine powder. For each sample, five individuals of similar size, weight and shape were grouped together to
77 prepare a composite specimen to minimize individual variations in the determined TMEs. The fish were filleted then the muscle dried in the oven
78 (Memmert UN55). The fish meat samples were dried in the oven at 60 °C to constant weight in accordance with the AOAC Official Method
79 983.18 (AOAC, 2005). Then ground (stainless steel bench ground grinder) and homogenized to have a powder ready for analysis.

80 In this study, different categories of chemical elements were taken into account. The major elements (P, K, S) have been included as essential
81 macronutrients commonly found in the water and tissues of fish. Essential trace metals (Fe, Cu, Zn, Mn and Cr) were also analyzed, as they play
82 a key physiological role, but can become toxic at high concentrations. In addition, common toxic heavy metals (Pb, Cd, Hg and As) were
83 examined for their persistent nature, their tendency to bioaccumulation and their widely documented health hazards. For the sake of simplicity,
84 the term « metals » is generally used throughout the article to collectively refer to these groups of elements. The analysis of metallic trace
85 elements (TME) present in water, sediments and fish tissues was carried out using an EDXRF spectrometer (energy dispersion X fluorescence
86 spectrometer), the SHIMADZU EDX-7000. This device allows a qualitative and quantitative analysis of the chemical elements without

87 destroying the sample. The device has been calibrated according to the manufacturer's instructions. Certified reference materials (MRCs) were
88 used to verify. The results were expressed in ppm or mg/L for water, and in mg/kg dry weight for fish sediments and muscle.

89 The analytical limits of quantification (LQ) were 0.5 mg/kg dry weight for Fe, Cu, Pb, Cd and As, and 0.2 mg/kg for Ag in solid matrices
90 (sediment and fish tissue), with corresponding values of 0.05 and 0.02 mg/L in water. For Hg, the LQ was 5 mg/kg dry weight (1.25 mg/kg wet
91 weight), which is above the EU regulatory threshold for non-predatory fish (0.50 mg/kg wet weight). Therefore, Hg measurements by EDXRF
92 are qualitative only and do not allow a reliable compliance assessment.

93 **Method of analysis**

94 For analysis, 5 grams of each sample of sediment, water and fish, (previously dried and crushed for sediment and fish), were transferred to
95 adapted cups and sealed with a Mylar film. These samples were then placed in the EDXRF SHIMADZU EDX-7000 spectrometer (previously
96 calibrated using appropriate standards). Each sample was analyzed 60 times. The results processed using the PCEDX Navi/Pro software, making
97 it possible to obtain the concentrations of the elements in the form of ppm. Certified reference materials (CMRs) have been regularly analyzed to
98 ensure the **accuracy and** of the results.

99 **Bioaccumulation Factor (BAF)**

100 The bioaccumulation factor (BAF) corresponds to the ratio of the concentration of metals in an organ to that present in water or sediments (Arnot
101 & Gobas, 2006). It measures the total bioaccumulation, i.e. the contribution of all exposure pathways (water + food + sediments).

$$BAF = \frac{C_{organism} \text{ (concentration in fish mg/kg)}}{C_{environment} \text{ (sediment or water concentration } (\frac{mg}{kg} \text{ or } \frac{g}{l}) \text{)}}$$

102 **Statistical analysis of data**

103 The data was entered into an Excel sheet, encoded, verified, and then exported to the GraphPad V8.03 software for Windows (GraphPad PRISM,
104 California, USA). The data were presented as mean $\pm$ standard deviation (DS) in tables and figures. The one-factor orderly analysis of variance
105 (ANOVA) and the post-hoc Duncan test were used to make comparisons of the means between the groups. The Levene variance equality test was
106 used to verify the conditions of use of the ANOVA test. The statistical significance threshold has been set at $p < 0.05$. The data are presented as a
107 standard average deviation (DS). The one-factor orderly analysis of variance (ANOVA) and the Duncan post-hoc test were used to make
108 comparisons between groups. Bars with different letters are statistically significant at the threshold of $p < 0.05$.

109 The interpretation of analytical results for regulatory comparison requires converting concentrations measured on a dry weight (d.w.) basis to a
110 fresh weight (w.w.) basis, as regulatory thresholds for fish flesh are expressed on a fresh weight basis (European Commission, 2023). Based on
111 published proximate composition data for fish muscle, the average water content in most freshwater fish is between 70 % and 80 % (Huss, 1995).
112 In this study, a conversion factor of 0.25 was used, corresponding to 75 % water content. The equivalent LQ on a fresh weight basis was
113 calculated using the following equation:

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$$LQ_{fw} = LQ_{dw} \times (1 - \text{water content})$$

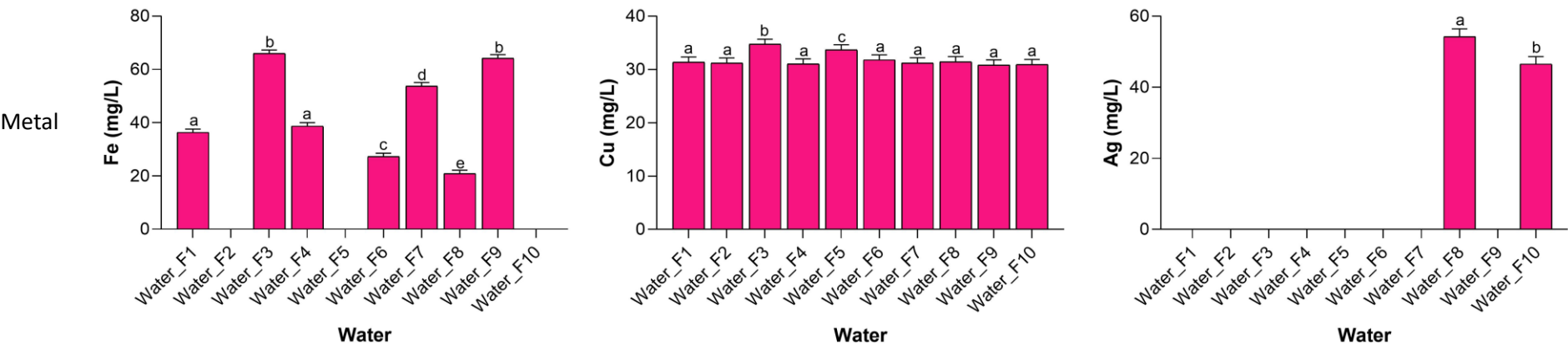
115 For example, a dry weight LQ of 0.5 mg/kg corresponds to approximately 0.125 mg/kg fresh weight (0.5×0.25). This conversion allows direct
116 comparison between analytical capabilities and regulatory thresholds. For Hg, however, the LQ of 5 mg/kg d.w. corresponds to 1.25 mg/kg w.w.,
117 which exceeds the EU limit for non-predatory fish (0.50 mg/kg w.w.), meaning that EDXRF results for Hg are qualitative only and do not allow
118 reliable compliance assessment.

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120 **Results:**

121 The results show the variation in average TME contents in fish farming waters, sediments and fish, taking into account both species:
122 *Oreochromisniloticus* and *Clarias gariepinus*.

123 **Change in average ETM levels in livestock water:**



124 Number of farms

125

126 **Figure 2.** Variation of heavy metals according to water samples

127 At the level of Table 2, the farms show significant variations in terms of iron (Fe) and copper (Cu). Fe concentrations showed marked spatial
128 variability, with peaks at F3 (65.94 mg/L) and F9 (64.17 mg/L), while the lowest level is noted at F8 (20.94 mg/L). The Cu, on the other hand,
129 has a more uniform distribution, ranging from 30.83 to 34.72 mg/L, with peaks noted at F3 and F5 farms.

130

131 **Table 2.** Concentrations of metals in the breeding water of the aquaculture farms studied (average $\pm$ standard deviation)

	Water									
Metals	Water_F1	Water_F2	Water_F3	Water_F4	Water_F5	Water_F6	Water_F7	Water_F8	Water_F9	Water_F10
Fe (mg/L)	36.32 ± 1.25 ^a	-	65.94 ± 1.33 ^b	38.73 ± 1.23 ^a	-	27.30 ± 1.21 ^c	53.72 ± 1.35 ^d	20.94 ± 1.17 ^e	64.17 ± 1.34 ^b	-
Cu (mg/L)	31.36 ± 0.96 ^a	32.2 ± 0.96 ^a	34.72 ± 0.95 ^b	31.04 ± 0.94 ^a	33.69 ± 0.95 ^b	31.78 ± 0.96 ^a	31.21 ± 0.99 ^a	31.45 ± 0.94 ^a	30.83 ± 0.96 ^c	30.93 ± 0.95 ^c

132 The values of the same line bearing the letters a, b etc. in exponent show a significant difference between the metals (p < 0.05) compared to the
133 farms studied.

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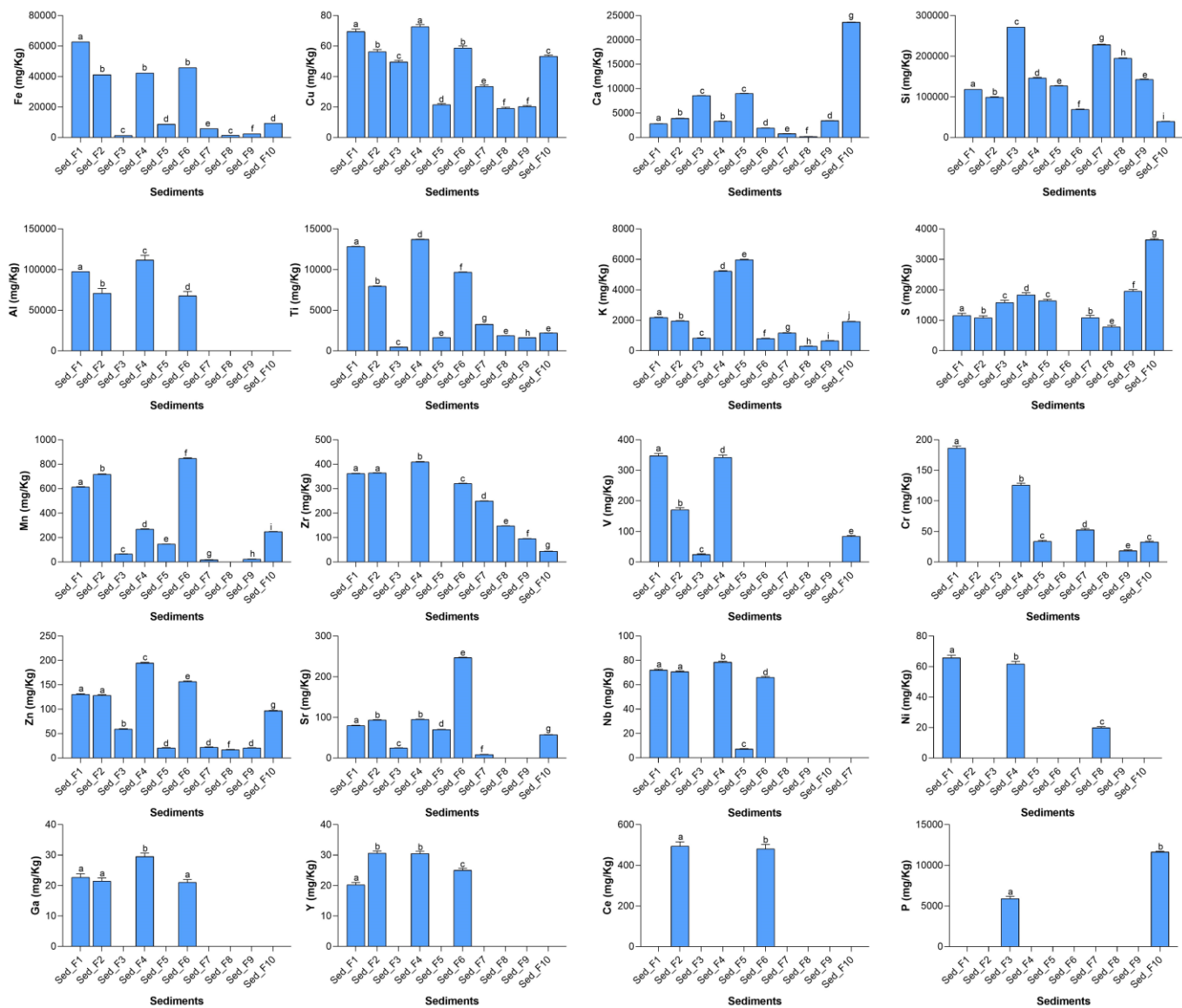
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148 **Variation of average TME levels in sediments:**

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150 Figure 3 shows the variation of metals in the sediment

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152 **Figure 3.** Variation of heavy metals across sediment samples

153 The analysis of the metal concentrations in the sediments of the ten aquatic farms examined shows great spatial variability (Table 3). A
 154 significant concentration of iron (Fe) is observed at F1 (62.83 mg/kg) and F6 (45.79 mg/kg), while it is considerably lower in the sediments of F3
 155 (1.34 mg/kg) and F8 (1.48 mg/kg). Silicon (Si) is the most present element, having reached a maximum concentration at F3 (271.34 mg/kg), then
 156 at F7 (227.97 mg/kg). Calcium (Ca) reaches its maximum level at F10 (23.63 mg/kg), as opposed to rather low values observed at F7 (0.78
 157 mg/kg) and F8 (0.20 mg/kg). The concentration of zinc (Zn) oscillates between 0.02 mg/kg (F5, F7, F8, F9) and 0.19 mg/kg (F4). Manganese
 158 (Mn) also has marked variations, reaching a peak at F6 (0.85 mg/kg), unlike a minimum concentration at F7 and F9 (0.02 mg/kg). Rather low
 159 concentrations, usually below 1 mg/kg, are often observed for other metals such as titanium (Ti), sulfur (S), vanadium (V), chromium (Cr) and
 160 strontium (Sr).

161 **Table 3.** Concentrations of metals in the sediment at the level of the aquaculture farms studied (mean $\pm$ standard deviation)

Metals ($\times 10^3$)	Sediment									
	Sediment_F1	Sediment_F2	Sediment_F3	Sediment_F4	Sediment_F5	Sediment_F6	Sediment_F7	Sediment_F8	Sediment_F9	Sediment_F10
Fe (mg/Kg)	62.83 $\pm$ 0.04 ^a	41.18 $\pm$ 0.03 ^b	1.34 $\pm$ 0.00 ^c	43.32 $\pm$ 0.03 ^b	8.71 $\pm$ 0.00 ^d	45.79 $\pm$ 0.03 ^b	5.82 $\pm$ 0.00 ^e	1.48 $\pm$ 0.00 ^c	2.41 $\pm$ 0.00 ^f	9.25 $\pm$ 0.00 ^d
Cu (mg/Kg)	0.07 $\pm$ 0.00 ^a	0.06 $\pm$ 0.00 ^b	0.05 $\pm$ 0.00 ^c	0.07 $\pm$ 0.00 ^a	0.02 $\pm$ 0.00 ^d	0.06 $\pm$ 0.00 ^b	0.03 $\pm$ 0.00 ^e	0.01 $\pm$ 0.00 ^f	0.02 $\pm$ 0.00 ^f	0.05 $\pm$ 0.00 ^c
Ca (mg/Kg)	2.8 $\pm$ 0.02 ^a	3.9 $\pm$ 0.03 ^b	8.6 $\pm$ 0.03 ^c	3.34 $\pm$ 0.02 ^b	9.02 $\pm$ 0.03 ^c	1.93 $\pm$ 0.02 ^d	0.78 $\pm$ 0.00 ^e	0.2 $\pm$ 0.00 ^f	3.44 $\pm$ 0.02 ^d	23.63 $\pm$ 0.04 ^g
Si (mg/Kg)	118.38 $\pm$ 1.3 ^a	99.06 $\pm$ 1.14 ^b	271.34 $\pm$ 0.13 ^c	146.62 $\pm$ 1.43 ^d	126.85 $\pm$ 0.83 ^e	69.1 $\pm$ 0.89 ^f	227.97 $\pm$ 1.31 ^g	194.71 $\pm$ 1.03 ^h	142.98 $\pm$ 0.86 ^e	39.5 $\pm$ 0.42 ⁱ
Al (mg/Kg)	97.6 $\pm$ 5.9 ^a	70.98 $\pm$ 5.89 ^b	-	111.75 $\pm$ 5.8 ^c	-	67.71 $\pm$ 5.35 ^d	-	-	-	-
Zn (mg/Kg)	0.13 $\pm$ 0.002 ^a	0.13 $\pm$ 0.00 ^a	0.06 $\pm$ 0.00 ^b	0.19 $\pm$ 0.00 ^c	0.02 $\pm$ 0.00 ^d	0.16 $\pm$ 0.00 ^e	0.02 $\pm$ 0.00 ^d	0.02 $\pm$ 0.00 ^f	0.02 $\pm$ 0.00 ^d	0.09 $\pm$ 0.00 ^g
Ti (mg/Kg)	12.8 $\pm$ 0.03 ^a	7.96 $\pm$ 0.02 ^b	0.47 $\pm$ 0.00 ^c	13.71 $\pm$ 0.03 ^d	1.64 $\pm$ 0.00 ^e	9.69 $\pm$ 0.02 ^f	3.26 $\pm$ 0.01 ^g	1.87 $\pm$ 0.00 ^e	1.63 $\pm$ 0.00 ^h	2.21 $\pm$ 0.00 ^e
K (mg/Kg)	2.18 $\pm$ 0.02 ^a	1.96 $\pm$ 0.02 ^b	0.83 $\pm$ 0.02 ^c	5.22 $\pm$ 0.04 ^d	5.98 $\pm$ 0.03 ^e	0.8 $\pm$ 0.02 ^f	1.16 $\pm$ 0.02 ^g	0.3 $\pm$ 0.01 ^h	0.66 $\pm$ 0.01 ⁱ	1.92 $\pm$ 0.01 ^j
S (mg/Kg)	1.15 $\pm$ 0.07 ^a	1.08 $\pm$ 0.06 ^b	1.58 $\pm$ 0.07 ^c	1.83 $\pm$ 0.07 ^d	1.64 $\pm$ 0.05 ^c	-	1.08 $\pm$ 0.08 ^b	0.78 $\pm$ 0.05 ^e	1.96 $\pm$ 0.05 ^f	3.64 $\pm$ 0.03 ^g
Mn (mg/Kg)	0.6 $\pm$ 0.00 ^a	0.72 $\pm$ 0.03 ^b	0.06 $\pm$ 0.00 ^c	0.27 $\pm$ 0.00 ^d	0.15 $\pm$ 0.00 ^e	0.85 $\pm$ 0.00 ^f	0.02 $\pm$ 0.00 ^g	-	0.02 $\pm$ 0.00 ^h	0.25 $\pm$ 0.00 ⁱ
Zr (mg/Kg)	0.36 $\pm$ 0.00 ^a	0.36 $\pm$ 0.00 ^a	-	0.41 $\pm$ 0.00 ^b	-	0.32 $\pm$ 0.00 ^c	0.25 $\pm$ 0.00 ^d	0.15 $\pm$ 0.00 ^e	0.09 $\pm$ 0.00 ^f	0.04 $\pm$ 0.00 ^g
V (mg/Kg)	0.34 $\pm$ 0.00 ^a	0.17 $\pm$ 0.06 ^b	0.02 $\pm$ 0.00 ^b	0.34 $\pm$ 0.00 ^c	-	-	-	-	-	0.08 $\pm$ 0.00 ^e
Cr (mg/Kg)	0.19 $\pm$ 0.00 ^a	-	-	0.12 $\pm$ 0.00 ^b	0.03 $\pm$ 0.00 ^c	-	0.05 $\pm$ 0.00 ^d	-	0.02 $\pm$ 0.00 ^e	0.03 $\pm$ 0.00 ^c

Sr (mg/Kg)	0.08±0.00 ^a	0.09±0.00 ^b	0.02±0.00 ^c	0.09±0.00 ^b	0.07±0.00 ^d	0.25±0.00 ^e	0.02±0.00 ^f	-	-	0.06±0.00 ^g
Nb (mg/Kg)	0.07±0.00 ^a	0.07±0.00 ^a	-	0.08±0.00 ^b	0.00±0.00 ^c	0.07±0.00 ^d	-	-	-	-

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Variation in average concentrations of trace metal elements in fish:

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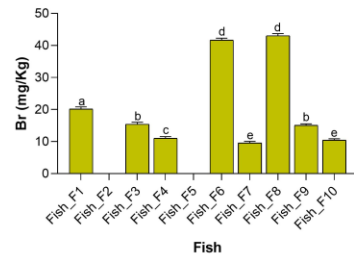
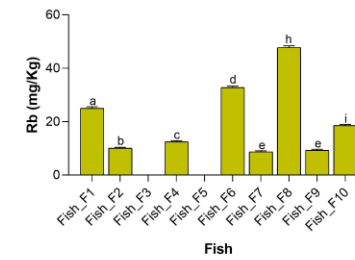
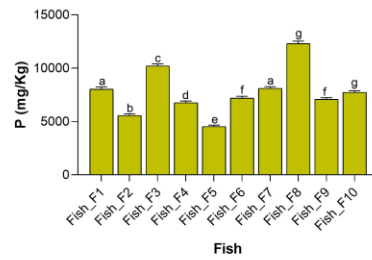
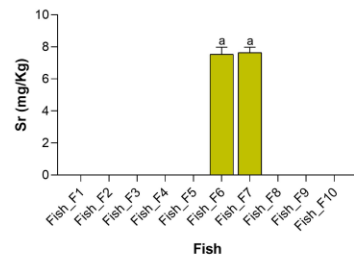
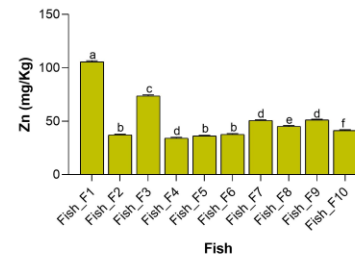
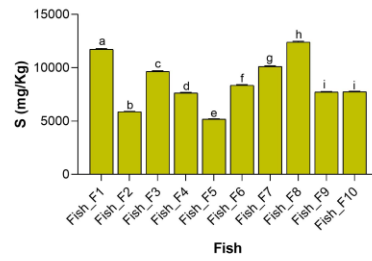
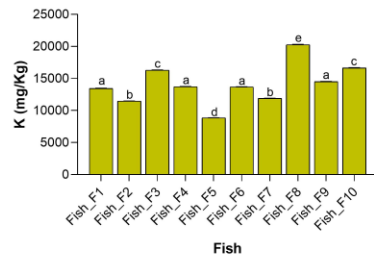
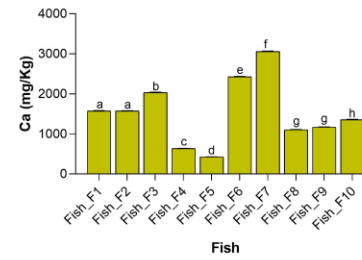
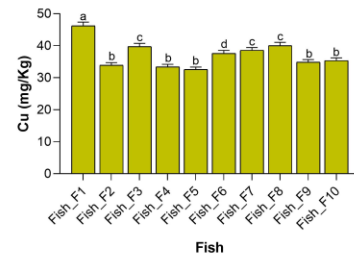
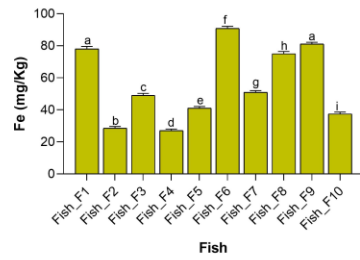


Figure 4 shows the variation of metals in fish meat

Figure 4. Variation of heavy metals according to fish samples

The data collected highlight a high variability in metal concentrations in fish tissues from the various aquaculture farms (Table 4).

Table 4. Concentrations of metals in fish meat at the level of the aquaculture farms studied (mean ± standard deviation)

	Fish									
Metals	Fish-F1	Fish-F2	Fish-F3	Fish-F4	Fish-F5	Fish-F6	Fish-F7	Fish-F8	Fish-F9	Fish-F10
Fe (mg/Kg)	78.08 ± 1.51 ^a	28.58 ± 1.06 ^b	49.01 ± 1.29 ^c	27.02 ± 1.01 ^d	41.07 ± 1.01 ^e	90.83 ± 1.36 ^f	50.91 ± 1.10 ^g	74.99 ± 1.42 ^h	81.09 ± 1.15 ^a	37.44 ± 1.13 ⁱ
Cu (mg/Kg)	46.22±1.13 ^a	33.92±0.82 ^b	39.74±1.01 ^c	33.37±0.82 ^b	32.56±0.79 ^b	37.61±0.94 ^d	30.6±0.83 ^c	40.01±1.05 ^c	34.88±0.8 ^b	35.35±0.84 ^b
Ca (mg/Kg)	1573.87±10.41 ^a	1572.02±8.8 ^a	2032.12±11.44 ^b	635.9±4.31 ^c	425.37±3.28 ^d	2425.59±12.79 ^e	3056.9±13.38 ^f	1103.5±6.11 ^g	1167.61±7.09 ^g	1355.6±7.66 ^h
K (mg/Kg)	13442.52±52.93 ^a	11458.59±40.68 ^b	16282.95±54.64 ^c	13707.46±44.74 ^a	8834.7±35.13 ^d	13663.31±48.66 ^a	11887.82±40.29 ^b	20255.35±63.51 ^e	14504.76±44.48 ^a	16645.12±48.8 ^{c4}
S (mg/Kg)	11718.21±88.8 ^a	5865.57±50.42 ^b	9639.26±74.71 ^c	7634.11±58.82 ^d	5170.94±46.62 ^e	8346.15±67.08 ^f	10108.89±68.13 ^g	12393.15±88.04 ^h	7712.53±57.01 ⁱ	7735.9±58.82 ⁱ
Zn (mg/Kg)	105.48±1.09 ^a	37.14±0.71 ^b	73.60±0.93 ^c	34.17±0.7 ^d	36.12±0.67 ^b	37.59±0.85 ^b	50.66±0.73 ^d	45.1±0.9 ^e	51.17±0.7 ^d	41.25±0.73 ^f
P (mg/Kg)	8030.67±213.13 ^a	5566.14±149.32 ^b	10198.58±204.41 ^c	6764.31±155.75 ^d	4527.62±139.54 ^e	7187.64±182.74 ^f	8103.07±159.85 ^a	12303.87±223.74 ^g	7084.23±150.85 ^f	7735.15±160.4 ^G
Rb (mg/Kg)	25±0.6 ^a	10.04±0.39 ^b	-	12.45±0.4 ^c	-	32.76±0.51 ^d	8.69±0.38 ^e	47.78±0.6 ^h	9.28±0.37 ^e	18.53±0.41 ⁱ
Br (mg/Kg)	20.15±0.68 ^a	-	15.41±0.6 ^b	11.07±0.47 ^c	-	41.67±0.6 ^e	9.58±0.46 ^d	43.01±0.68 ^b	15.09±0.46 ^e	10.41±0.48 ^e

There is a significant variation in metal concentrations in fish between different farms (Table 4). Iron levels (Fe) are higher F6, F8 and F9, while the lowest values are recorded at F4 and F5. Copper (Cu) retains a certain homogeneity, displaying maximum levels at F1 and minimum levels at F7. Calcium (Ca), potassium (K) and phosphorus (P) show notable variations, with particularly high rates in F6 to F8 farms, while F5 exploitation is distinguished by low levels for most elements. Sulfur (S) reaches its peaks at F1 and F8, while zinc (Zn) reaches its peak at F1. Rubidium (Rb) and bromine (Br) have an irregular distribution depending on locations, with peaks observed at F8.

Assessment of the bioaccumulation factor

Figure 5 represents the bioaccumulation factors (BAF) of metals contained in fish meat in relation to the environment (water). Iron was found on almost all farms (except farms 2, 5 and 10), with BAFs ranging from 0.698 to 3.58. For copper (Cu) the values are rather uniform between the farms, located between 0.966 and 1.474. Only farm F3 showed a high concentration of calcium (Ca =5.71).

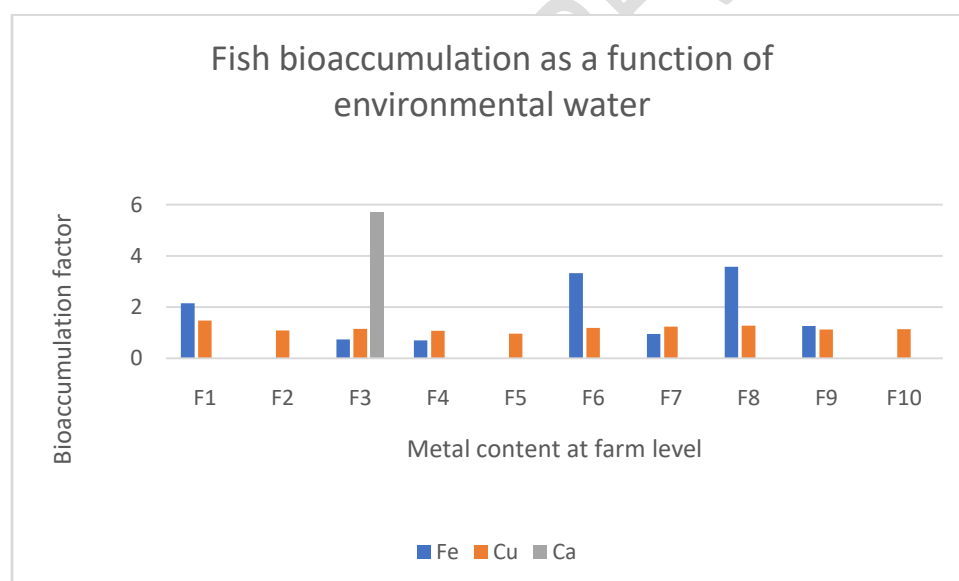


Figure 5. Bioaccumulation factor (BAF) of fish studied in relation to water

The bioaccumulation factor (BAF) in relation to sediment (Figure 6) differs from one farm to another. For iron, copper, calcium, zinc, phosphorus, bromine and strontium, BAF values remain fairly constant in all farms. With regard to potassium, it has high concentrations

ranging from 1,478 to 68,001 and Suffers with a peak of 10.137 noted on farm 1.

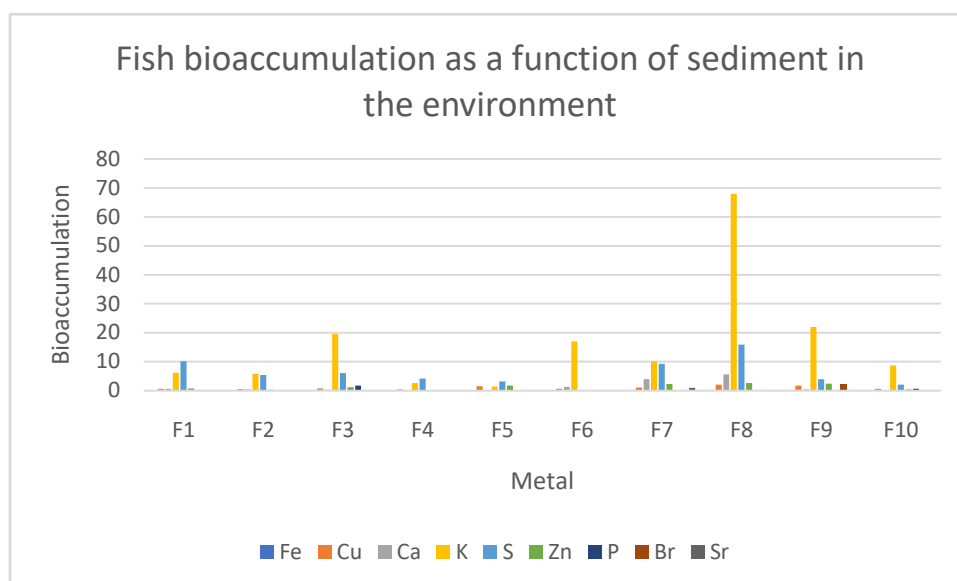


Figure 6. Bioaccumulation factor (BAF) of the fish studied in relation to the Sediment

Discussion

Variation in average TME contents in water

The results obtained highlight a heterogeneity of the levels of contamination across the sites.

The data collected show a high presence of iron and copper in the waters of the farms analyzed. The iron concentration, which fluctuates between 20.94 and 65.94 mg/L, far exceeds the indicative threshold of 0.3 mg/L established by the WHO for drinking water (WHO, 2017). High iron contents can result from the natural dissolution of iron-rich soils, but also from human-made emissions, such as the use of fertilizers and mining operations (Han & Gu, 2023; Lakra et al., 2019). Biologically speaking, a high concentration of iron in water can cause accumulations on the gills, thus reducing gas exchange and leading to oxidative stress in fish (Boyd, 2015).

With regard to copper, the levels recorded (30.83-34.72 mg/L) also exceed the limit of 2 mg/L established by the WHO (WHO, 2017). This apparent uniformity between farms indicates a source of potentially diffuse contamination, which could be associated with the use of pesticides, agricultural discharges or the deterioration of metal equipment used in aquaculture systems (Soleimani et al., 2023; Mishra et al., 2008). Copper, at high concentration levels, can harm aquatic beings by causing cellular damage and affecting the growth and sustainability of fish (Heath, 1995; Türkmen *et al.*, 2021).

The co-occurrence of high Fe and Cu concentrations indicates potential health risks, both for drinking water and for aquaculture. Indeed, these metals have the ability to accumulate in aquatic tissues, which can create risks to public health if contaminated fish are regularly consumed (Lebepe et al., 2020; Han & Gu, 2023). Copper concentrations measured in fish flesh, ranging from 20 to 50 mg/kg dry matter, correspond to approximately 5 to 12.5 mg/kg on a fresh basis. These levels are around or slightly above the threshold of 10 mg/kg fresh weight recommended by FAO/WHO (1989) for edible tissues. Although copper is an essential trace element involved in many physiological processes, its excessive accumulation in fish flesh may pose a potential risk to human health, particularly in cases of frequent consumption. Thus, the observed levels suggest a limited toxicological risk, but one that merits increased monitoring for samples with the highest concentrations, in accordance with food safety recommendations (FAO/WHO, 2003).

Variation in average TME contents in sediment

The results of this study revealed significantly higher concentrations of TMEs in sediments than in water and fish flesh. This result is in agreement with the work of Sagna and Diouf (2021) which demonstrates that sediments act as a carbon sink and a major reservoir for heavy metals in aquatic ecosystems. TMEs, once introduced into the environment, bind to suspended particles and accumulate at the bottom of the ponds. Analysis of variance (ANOVA) confirmed that iron (Fe) and zinc (Zn) concentrations in sediments differ significantly between farms ($p < 0.05$), suggesting variable sources of contamination, potentially related to livestock inputs (feed) or the geochemical characteristics of local soils (Sall and Badiane, 2019).

In aquatic ecosystems, most of the heavy metals that are drained there are deposited on soft bottoms, particularly sediments (Keumeane et al., 2013; Ekengele et al., 2014). According to Dimon et al. (2014) and Kamilou et al. (2014), sediments constitute a reservoir where metals accumulate. They form the most important environmental matrix which, through the phenomenon of release, constitutes an endogenous source of pollution of water and aquatic species.

The levels of heavy metals present in the sediments are lower than those reported by Choutiet al. (2010), where the chromium level was 97.60 mg/kg. However, for farms F1 and F4, the concentrations were higher and were 186.43 mg/kg and 125.68 mg/kg, respectively. In addition, Kaki et al. (2011) who carried out this study in Benin and Togo reported higher

copper levels than those observed in this research, with a concentration of 228.74 mg/kg for copper. The discrepancy with the results of this study could be explained by the fact that the sediments are not identical and the collection areas differ. The nature of the sediments also plays a role in their capacity to retain metals (Soro *et al.*, 2009).

The high iron concentrations detected at some locations (F1 and F6) could be associated with the geological characteristics of the soils and human contributions, including waste from agriculture and households. Indeed, numerous researches have demonstrated that sediments represent an important source of metals, which simultaneously reflects natural and human-related contributions (Zhou *et al.*, 2008; Singh *et al.*, 2017). It is likely that the high Si concentration, particularly at F3 and F7, is due to the preponderance of silicate minerals in the sediments of the region. These findings confirm the work of Ajeegahet *al.* (2017) in Cameroon, who reported a predominance of silicon and aluminum in the sediments of aquaculture regions. Regarding Zn and Mn, the detected levels remain below toxicity levels, however their presence, even at low concentrations, requires special vigilance because these metals have the capacity to accumulate in marine organisms and can represent a danger for the food chain (Ali *et al.*, 2019). It is likely that the marked variations in metals (e.g., Ca at F10 or Mn at F6) reflect human contributions that vary according to location (agriculture, fish feed, livestock waste), as Oumarou *et al.* (2021) demonstrated in aquaculture systems in Cameroon.

We identified the presence of titanium (Ti) in farm sediments. Unlike potentially toxic metals such as lead, zinc, or copper, titanium is not perceived as a problematic element for sediment quality. International sediment quality standards, such as the Canadian Sediment Quality Guidelines (CCME, 2001) and the Australian and New Zealand Sediment Quality Guidelines (ANZECC/ARMCANZ, 2000), do not set limits for Ti. This is due to its low solubility and reduced bioavailability in aquatic environments.

Variation in average TME contents in fish

The presence of heavy metals in fish products represents a real danger to consumer health (Youssaoet *al.* 2011; Aina *et al.*, 2012, Kamilouet *al.*, 2014; Bastami *et al.*, 2012). The variations observed in the metal levels of fish reflect the combined impact of water quality, soil type and aquaculture farming methods specific to each farm. Numerous studies have shown that the mineral composition of fish is closely linked to the physicochemical properties of their environment and the feed used (Tóth *et al.*, 2021). It is possible that the high iron

concentrations detected in some farms (F6, F8, F9) are due to contributions from iron-rich soils or human-induced emissions. This would confirm the findings of Pizarro *et al.* (2019), who demonstrated that iron is among the most bioaccumulated metals in terrestrial aquaculture. Thus, the fluctuation of zinc and copper, two vital trace elements, may reflect both dietary supplementation and water pollution caused by nearby agricultural activities (Ahmed *et al.*, 2019; Abdel-Khalek *et al.*, 2016).

Farms F6, F7, and F8 are characterized by high levels of calcium, potassium, and phosphorus, which are crucial for bone development and metabolism in fish. This supports research by Lall & Kaushik (2021), who demonstrated that these factors are directly affected by nutritional quality, particularly through the use of mineral-enriched meals.

Regarding sulfur, its high concentration in some farms could be related to the presence of sulfur amino acids (methionine, cysteine) in aquaculture feeds, as reported by Gatlin *et al.* (2007). Finally, the variable detection of rubidium and bromine is likely a reflection of contributions associated with local geochemistry or borehole water conditions, a phenomenon already mentioned in aquaculture systems exploiting mineral-rich groundwater (Khan *et al.*, 2022).

Bioaccumulation Factor

For Pb, the analytical LQ on a fresh weight basis (0.125 mg/kg) is well below the EU regulatory limit (0.30 mg/kg). The absence of detectable Pb therefore indicates that concentrations in the sampled fish are below the regulatory threshold, allowing us to reasonably exclude a risk of exceeding the standard at the time of sampling.

For Cd, the analytical LQ (0.125 mg/kg w.w.) is slightly higher than the EU regulatory limit (0.05 mg/kg w.w.). As a result, non-detects cannot be interpreted as compliance, nor as exceedance. The risk of exceeding the regulatory limit cannot be formally excluded, and only more sensitive methods would allow a definitive conclusion.

For Hg, the LQ of 1.25 mg/kg w.w. is more than twice the EU limit of 0.50 mg/kg w.w. for non-predatory fish. The analytical method is therefore not sensitive enough to determine compliance, and the absence of detection provides no information on the actual risk. Additional analyses using a more sensitive method would be required for regulatory assessment.

This study highlights the importance of explicitly linking analytical detection limits to regulatory thresholds. For elements where LQ values are lower than the legal limit, non-detects can reasonably be interpreted as compliance. Conversely, for elements such as Cd and Hg, where LQ values are at or above the regulatory thresholds, the absence of detection does not imply the absence of risk. Methodological sensitivity must therefore be clearly accounted for in risk assessment.

The data show marked variability in the bioaccumulation factor (BAF) among metals and locations. Iron shows remarkably high levels at F6 and F8, indicating that its accumulation depends on local sediment conditions, modulated by pH, dissolved oxygen, and speciation (Alquezar *et al.*, 2006). These differences could be explained by the tendency for moderate accumulation in fish, unlike filter-feeding organisms (Ramelowet *et al.*, 1989).

In contrast, copper exhibits fairly constant BAFs (1.0-1.3), highlighting its status as a crucial trace element and the homeostatic regulation that controls fluctuations despite environmental changes (DeForest *et al.*, 2007; Wang & Rainbow, 2008; Rainbow, 2002). Calcium is an exception, displaying significant bioaccumulation at F4, probably associated with water hardness, high carbonate content, and the physiological requirements of fish for bone mineralization and ionic control (Flik *et al.*, 1995; Skeaff *et al.*, 1995).

Overall, these results demonstrate that bioaccumulation is influenced by both the chemical characteristics of the elements and their biological role. Essential metals (Cu, Ca, K) are tightly regulated or functionally accumulated, while others, such as iron, are more influenced by environmental conditions (Ramelowet *et al.*, 1989). The observation of spatial variability, particularly for iron, demonstrates that risk assessment in aquaculture should take into account local sediment and water specificities, rather than relying solely on global concentrations (Linnik & Zubenko, 2000). Finally, some components are actively biologically accumulated according to physiological needs, while others are absorbed more passively depending on their presence in the environment (Rainbow, 2002).

Conclusion

This study highlights the importance of careful monitoring of trace metal elements (TMEs) in aquaculture systems to maintain food safety and ensure environmental sustainability. A comparative analysis conducted on ten agro-fish farms revealed heterogeneous variability in contamination levels across locations. Concentrations of iron and copper, well above WHO standards in farm waters, reflect both natural and anthropogenic pollution. Sediments were

found to be significant stores of metals, playing a crucial role in pollution dynamics and representing a possible source of release into the water column and aquatic beings. Analysis of fish shows a high concentration of various metals (Fe, Cu, Ca, K, P, S), attesting to their direct exposure to environmental conditions and the quality of ingested food. Bioaccumulation factors showed significant variation depending on location and element, with notable accumulation of iron and calcium, reflecting a particular susceptibility at certain farms. From a public health perspective, although metals such as iron and zinc are essential for fish metabolism, excessively high concentrations could create a risk of nutritional imbalance that must be monitored. These results emphasize the importance of establishing periodic monitoring and follow-up in aquaculture farms. It is also advisable to conduct long-term research to measure the lasting effect of these pollutions on fish health, and consequently, on consumer health.

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