



Assessment of Heavy Metal Contamination (Cd, Pb, Hg) and Typological Characterization of Smoked Fish Commonly Consumed in Abidjan, Ivory Coast

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

This study assesses contamination by cadmium, lead, and mercury (Cd, Pb, and Hg) in smoked sardines, mackerel, and tuna in Abidjan and characterises the typological structure of these concentrations at two smoking sites (Abobo-Doumé and Vridi-Zimbabwe), based on 180 fish analysed before and after smoking using ANOVA-Tukey, principal component analysis (PCA), and Pearson correlation. Smoking significantly increases Cd and Pb levels in most species, whereas Hg levels decrease, likely because of evaporation associated with moisture loss. At Abobo-Doumé, Pb levels remain within the Codex limit (0.3 mg/kg), with tuna reaching only 38% of the threshold. At Vridi-Zimbabwe, however, Pb levels exceed the limit in mackerel (+46%) and reach 80% of the threshold in tuna, indicating a real health risk. The PCA accounts for 82.37% of the total variance, structured by Hg and Cd on axis 1 and Pb on axis 2, with Cd-Pb ($r = -0.223$) and Cd-Hg ($r = -0.452$) oppositions and a Pb-Hg association ($r = 0.331$). Three distinct typological profiles emerge: a group dominated by Hg (sardines and tuna from Vridi-Zimbabwe and sardines from Abobo-Doumé), one by Pb (mackerel from Vridi-Zimbabwe), and one by Cd (mackerel and tuna from Abobo-Doumé). Mackerel, the species most exposed at both sites, is confirmed as the preferred model for future toxicological studies.

Keywords: Cadmium; lead; mercury; smoked fish; trace metals; typological characterisation; principal component analysis; food safety.

1. Introduction

Globally, fish is a food resource of paramount importance, playing an active role in ensuring the nutritional security of populations, particularly in West Africa, where it serves as an essential and economically accessible source of animal protein (FAO, 2020). In Côte d'Ivoire, and more specifically within the Abidjan metropolitan area, fish consumption is deeply rooted in dietary habits, constituting a significant portion of households' protein intake (Monney, 2022). However, the preservation of these fishery products in tropical regions faces major obstacles, linked in particular to a lack of suitable infrastructure and specific climatic conditions (Monney *et al.*, 2020). To overcome these challenges, smoking has emerged as a time-honoured and effective technique, extending the shelf life of fish and optimising their distribution in markets (Togbe *et al.*, 2019). Nevertheless, this processing method, which is often carried out on a small-scale, artisanal basis, is likely to introduce or increase the presence of undesirable substances in the finished products. Among the major environmental and health concerns, contamination by trace metals (TMs) such as cadmium (Cd), lead (Pb), and mercury (Hg) is of particular concern. These metals are known for their intrinsic toxicity, even at minute concentrations, and their deleterious effects on human health (Diaby *et al.*, 2017). Aquatic ecosystems, such as the Ébrié Lagoon in Côte d'Ivoire, are particularly vulnerable to the accumulation of these pollutants, whether of anthropogenic or natural origin, thereby promoting their bioaccumulation along the aquatic food chain, including in fish species (Kouamenan *et al.*, 2020). Several studies have already shown that the smoking process can not only alter the nutritional composition of fish but also influence ETM concentrations, with notable increases in certain metals observed following this treatment (Adherr *et al.*, 2022). A thorough understanding of these dynamics is essential for accurately assessing the health risks associated with the consumption of smoked fish, especially since previous studies have already confirmed the presence of these contaminants in fish from the region (Chahid, 2016). Recent studies of smoked and processed fish indicate that trace-metal profiles can differ between raw and processed products and among processing conditions, supporting context-specific evaluation of smoking effects (Odeyemi *et al.*, 2024; Arisekar *et al.*, 2024; Vural & Ozyurt, 2026). Evidence from artisanal smoked fish in another African setting also shows that individual trace elements may shift differently during smoking, underscoring the importance of evaluating locally used processing practices (Guillot *et al.*, 2026). More broadly, recent literature continues to identify the bioaccumulation of metals such as Cd, Pb, and Hg in fish as a food-safety issue that requires species- and context-specific assessment (Lavkush *et al.*, 2025). Within the scope of the evidence summarised above, a clear research gap remains in the simultaneous characterisation of Cd, Pb, and Hg profiles across multiple commonly consumed fish species and smoking sites in Abidjan, particularly through comparison of concentrations before and after smoking and analysis of their multivariate relationships. This research fits within this context, with the primary objective of analysing and characterising the typological structure of cadmium, lead, and mercury levels in three species of smoked fish that are highly prized in the Abidjan region of Côte d'Ivoire. By comparing the concentrations of these heavy metals before and after the smoking process, this study aims to identify the species most exposed to contamination and to determine the specific influence of smoking on these levels. This approach will enable the establishment of detailed correlations between the different metals and fish species, thereby providing a more comprehensive perspective on contamination profiles and their direct implications for food safety and local public health.

2. Materials and Methods

2.1 Biological Material

The study focused on three fish species commonly consumed in Côte d'Ivoire, specifically in the city of Abidjan: sardines (*Sardinella maderensis*), mackerel (*Scomber scombrus*), and tuna (*Euthynnus alletteratus*). The selection of the fish species studied was based on the results of field investigations. These investigations identified the most commonly consumed species in the city of Abidjan using a questionnaire designed for this purpose and administered to female vendors at the Abobo Gare and Yopougon Siporex markets (Monney, 2022).

2.2 Methods

2.2.1 Study Sites

Two smoking sites were selected for this study. These are the Vridi-Zimbabwe site, located in the Port-Bouet commune, south of Abidjan (5°16'42.3696" N; 3°59'42.294" W) and the Abobo Doumé site, located in the municipality of Attécoubé, north of Abidjan (5°18'39.5352" N; 4°2'3.8004" W) (Fig. 1). Nearly all of the smoked fish sold in Abidjan is produced at these two smokehouses (Togbe *et al.*, 2019).

2.2.2 Sample Collection and Transport

Samples were collected at two smoking sites: Abobo Doumé and Vridi-Zimbabwe. One hundred and eighty (180) fresh fish, comprising thirty (30) of each variety (mackerel, sardines, and tuna) caught in the waters of the Ebrié Lagoon near the smoking sites, were purchased directly from the fishermen. After smoking, three types of flesh samples (from the head, middle, and tail) were taken from each fish (Kayalto, 2009). These samples were placed in clean jars and transported to the Central Laboratory for Food Hygiene and Agroindustry (LCHAI).

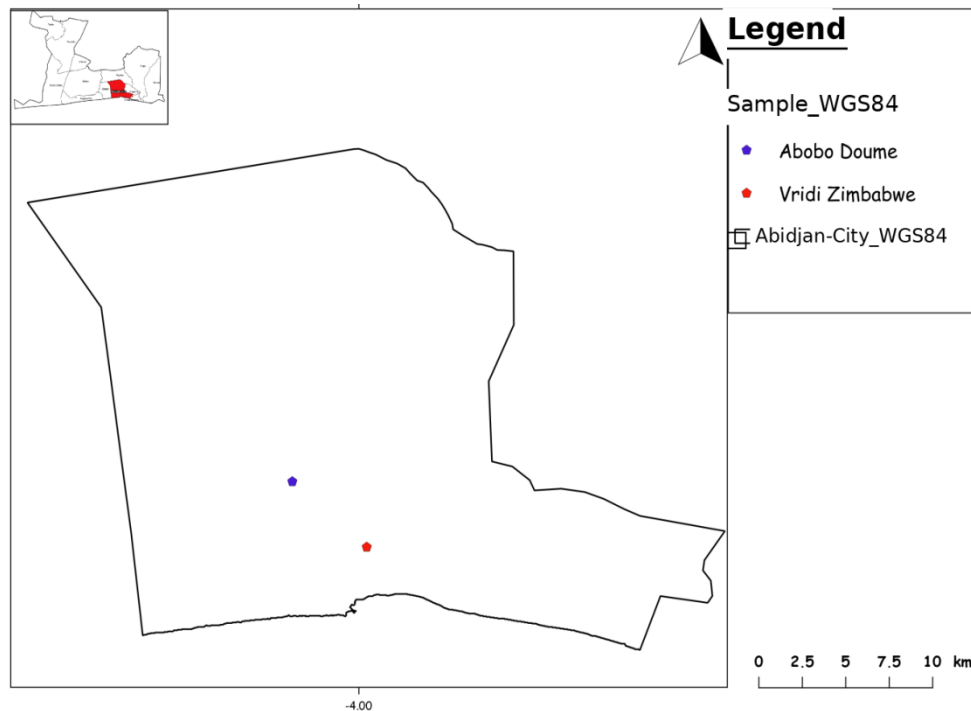


Fig. 1. Map of smoking sites (Monney, 2020)

2.2.3 Determination of Trace Metal Content

The three trace metals (TMs) analysed were lead (Pb), cadmium (Cd), and mercury (Hg) because of their high toxicity (FAO & WHO, 2011). The methods used for the determination of TME (Cd, Pb, and Hg) were those described by Chiffolleau and Truquet (1994) and by the Centre d'expertise en analyse environnementale du Québec (CEAEQ, 2006). These methods were slightly modified (Monney *et al.*, 2020).

2.2.4 Exploratory Data Analysis

Principal Component Analysis (PCA) was applied to the dataset to establish correlations among the variables (Cd, Pb, Hg). This PCA was performed on a data matrix consisting of six individuals (three types of fish: mackerel, sardine, and tuna from two smoking sites: Abobo Doumé and Vridi, Zimbabwe), for which the three variables (Cd, Pb, and Hg) were measured.

2.2.5 Statistical Analysis Method

The results were presented as mean $\pm$ standard error (M $\pm$ SEM). The mapping of the sampling sites was performed using QGIS 2.18 software.

The dataset was analysed using Principal Component Analysis (PCA) with RStudio 3.5.2 software. The results were analysed using one-way ANOVA followed by Tukey's multiple-comparison test at the 5% significance level using GraphPad Prism V5.01 software (Microsoft, USA). The difference between two variances was considered significant if $p < 0.05$.

3. Results and Discussion

3.1 Trace Metal Concentrations in Fish Before and After Smoking by Site

The average trace metal concentrations measured in tuna, sardines, and mackerel before and after smoking are presented in Table 1 for the Abobo Doumé site and in Table 2 for the Vridi-Zimbabwe site. These results allow for a comparison, for each of the three metals studied (cadmium, lead, mercury), of the effect of smoking by production site, and an assessment of whether the levels obtained comply with the maximum limit (ML) set by the Codex Alimentarius for fish (Codex Alimentarius Commission, 2025).

3.1.1 ETM Levels in Fish Before and After Smoking in Abobo Doumé

Table 1 shows that, in Abobo Doumé, smoking leads to a general increase in cadmium and lead levels in the three species studied. In tuna, the Cd concentration increases from 0.005 ± 0.001 to 0.042 ± 0.007 mg/kg ($p < 0.001$) and the Pb concentration from 0.023 ± 0.006 to 0.115 ± 0.016 mg/kg ($p < 0.0001$); in mackerel, Cd levels increased from 0.024 ± 0.007 to 0.073 ± 0.010 mg/kg and Pb levels from 0.015 ± 0.003 to 0.058 ± 0.018 mg/kg ($p < 0.001$ in both cases). In sardines, however, the increases in Cd (0.031 to 0.051 mg/kg) and Pb (0.043 to 0.081 mg/kg) are not significant. Mercury follows the opposite trend: it decreases in all three species after smoking, significantly in sardines (0.376 to 0.156 mg/kg, $p < 0.0001$) and mackerel (0.071 to 0.025 mg/kg, $p < 0.001$), but not significantly in tuna (0.062 to 0.039 mg/kg).

Compared to the Codex maximum level (ML) established for lead in fish (0.3 mg/kg), all levels measured after smoking in Abobo Doumé remain below this threshold: the highest value, observed in tuna (0.115 mg/kg), represents only 38% of the ML. Cadmium, for which the Codex does not specify a maximum level for fish, is not subject to any regulatory limits despite the significance of its increases. Mercury, meanwhile, remains well below the maximum level for methylmercury applicable to tuna (1.2 mg/kg); its decrease after smoking is likely due to partial evaporation resulting from the fish's moisture loss during the process.

Table 1. Average ETM content before and after smoking at the Abobo Doumé site

Species	Metal	Before smoking (mg/kg)	After smoking (mg/kg)
Tuna	Cd	0.005 ± 0.001^c	0.042 ± 0.007^c
	Pb	0.023 ± 0.006^d	0.115 ± 0.016^d
	Hg	0.062 ± 0.012^a	0.039 ± 0.007^a
Sardine	Cd	0.031 ± 0.007^a	0.051 ± 0.008^a
	Pb	0.043 ± 0.007^a	0.081 ± 0.011^a
	Hg	0.376 ± 0.090^d	0.156 ± 0.006^d
Mackerel	Cd	0.024 ± 0.007^c	0.073 ± 0.010^c
	Pb	0.015 ± 0.003^c	0.058 ± 0.018^c
	Hg	0.071 ± 0.014^c	0.025 ± 0.006^c

Superscript letters: a = not significant (ns); b = $p < 0.05$; c = $p < 0.001$; d = $p < 0.0001$. In each row, the same letter is used for both the "before smoking" and "after smoking" values to indicate the result of the statistical test applied to that pair of values

3.1.2 ETM Levels in Fish before and after Smoking at Vridi, Zimbabwe

Table 2 highlights a distinctly different pattern at the Vridi-Zimbabwe site. Cadmium levels never increase significantly after smoking, regardless of the species (tuna: 0.026 to 0.017 mg/kg; sardine: 0.004 to 0.012 mg/kg; mackerel: 0.010 to 0.032 mg/kg). Lead, on the other hand, increases very sharply and significantly in tuna (0.002 to 0.240 mg/kg, $p < 0.0001$) and mackerel (0.005 to 0.438 mg/kg, $p < 0.0001$), whereas the increase remains small and nonsignificant in sardines (0.002 to 0.004 mg/kg). Mercury levels decreased significantly in sardines (0.280 to 0.128 mg/kg, $p < 0.0001$) and mackerel (0.346 to 0.151 mg/kg, $p < 0.0001$), and decreased non-significantly in tuna (0.153 to 0.087 mg/kg). Compared to the Codex maximum level (ML) for lead (0.3 mg/kg), the levels measured after smoking at Vridi-Zimbabwe exceed the regulatory threshold in two out of three species: smoked mackerel exceeds it by 46% (0.438 mg/kg, or 146% of the ML), and smoked tuna reaches 80% of the ML (0.240 mg/kg), whereas the same species in their fresh state were well below this level. Only sardines, whose Pb content remains very low after smoking (0.004 mg/kg, or about 1% of the ML), remain well within compliance. The smoking process used in Vridi-Zimbabwe therefore pushes mackerel—and nearly tuna—beyond the internationally recognised safety threshold for lead, which represents a real health risk rather than merely a statistical one. As in Abobo Doumé, cadmium cannot be assessed for regulatory compliance due to the lack of a Codex maximum limit specific to fish, and mercury levels for all three species remain well below the maximum limit for methylmercury applicable to tuna (1.2 mg/kg).

Table 2. Average ETM concentrations before and after smoking at the Vridi site in Zimbabwe

Species	Metal	Before smoking (mg/kg)	After smoking (mg/kg)
Tuna	Cd	0.026 ± 0.003^a	0.017 ± 0.007^a
	Pb	0.002 ± 0.001^d	0.240 ± 0.072^d
	Hg	0.153 ± 0.012^a	0.087 ± 0.011^a
Sardine	Cd	0.004 ± 0.001^a	0.012 ± 0.002^a
	Pb	0.002 ± 0.001^a	0.004 ± 0.000^a
	Hg	0.280 ± 0.029^d	0.128 ± 0.019^d

Species	Metal	Before smoking (mg/kg)	After smoking (mg/kg)
Mackerel	Cd	0,010 ± 0,005 ^a	0,032 ± 0,008 ^a
	Pb	0,005 ± 0,001 ^d	0,438 ± 0,061 ^d
	Hg	0,346 ± 0,073 ^d	0,151 ± 0,022 ^d

Superscript letters: a = not significant (ns); b = $p < 0.05$; c = $p < 0.001$; d = $p < 0.0001$. In each row, the same letter is used for both the “before smoking” and “after smoking” values to indicate the result of the statistical test applied to that pair of values

A comparison of the two tables reveals a marked contrast between the two smoking sites. In Abobo Doumé, the increases in Cd and Pb caused by smoking are statistically significant in most species, but remain moderate in magnitude, so that no concentration exceeds the Codex limit for lead. In Vridi-Zimbabwe, by contrast, cadmium levels are never significantly affected, but lead levels in tuna and mackerel increase sharply to the point of exceeding—or even significantly exceeding—the regulatory limit. This contrast suggests that smoking-related lead contamination results not only from pre-existing environmental bioaccumulation but also from a specific contribution linked to the smoking equipment and/or fuel used at the Vridi-Zimbabwe site—a contamination mechanism also reported for smoked freshwater fish by Mielcarek *et al.* (2022). Lead thus appears to be the only contaminant for which smoking leads to regulatory thresholds being exceeded, and this occurs exclusively at Vridi-Zimbabwe. This finding is consistent with the work of Chałabis-Mazurek *et al.* (2021), who report dietary exposure to Cd, Pb, and Hg that is generally below safety thresholds, but with inter-species and inter-site variability that warrants differentiated monitoring depending on the processing site. From a public health perspective, these results indicate that while smoking as practised in Abobo Doumé does not, with regard to lead, pose a risk of exceeding regulatory limits, the smoking method used in Vridi-Zimbabwe exposes consumers of smoked tuna and, above all, smoked mackerel to lead levels exceeding the Codex maximum limit, which justifies paying particular attention to the choice of wood or smoking fuel and, if necessary, implementing stricter controls on smoked foods produced at this site.

3.2 Analysis and Typological Structure of ETM Content in Mackerel, Sardines, and Tuna

Principal Component Analysis (PCA) was used to classify and process information regarding the heavy metals studied (Cd, Pb, and Hg) by establishing correlations between the set of variables on the one hand and the set of statistical individuals on the other.

3.2.1 Coding of Statistical Individuals and Variables

For greater clarity, a coding scheme was established for the variables (Cadmium: Cd; Lead: Pb; Mercury: Hg) and statistical units according to smoking site (Abobo Doumé Mackerel: AM; Abobo Doumé Sardine: AS; Abobo Doumé Tuna: AT; Vridi Zimbabwe Mackerel: VM; Vridi Zimbabwe Sardine: VS; Tuna Vridi Zimbabwe: VT). The variable codes and their corresponding values are presented in Table 1.

Table 1. Variable codes and their attributes

Smoking site	Code	Smoked fish	Code	Variables	Code	Dim1	Dim2
Abobo-Doumé	A	Maquereau	M	Cadmium	Cd	-0.761	0.474
Vridi-Zimbabwe	V	Sardine	S	Lead	Pb	0.651	0.738
		Tuna	T	Mercury	Hg	0.823	-0.145

3.2.2 Distribution of the Inertia of the Variables Among the Studied Species

The eigenvalues of the three axes or dimensions (Dim 1, Dim 2, and Dim 3) that best represent the variables and their contribution to the total inertia are shown in Fig. 2 and Table 2. The two dimensions, Dim 1 and Dim 2, used to describe the correlations among variables related to spatial structures, account for 82.37% of the total information, with 55.98% and 26.39%, respectively (Table 2).

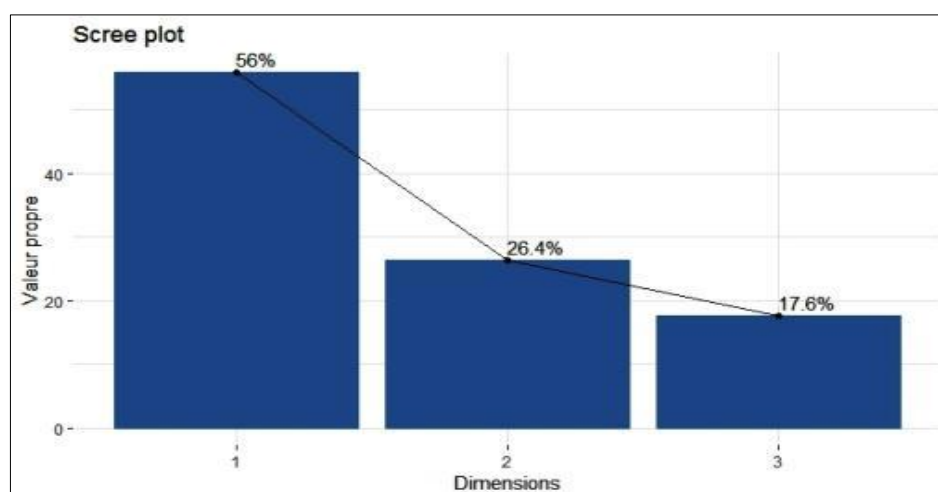


Fig. 2. Distribution of inertia between Dim1 and Dim2

Table 2. Distribution of ETM inertia among dimensions Dim 1, Dim 2, and Dim 3 for mackerel, sardine, and tuna

	Dim 1	Dim 2	Dim 3
Eigenvalue	1.679	0.791	0.5286
Variability	55.983	26.395	17.622
Cumulative Percentage	55.98	82.37	100

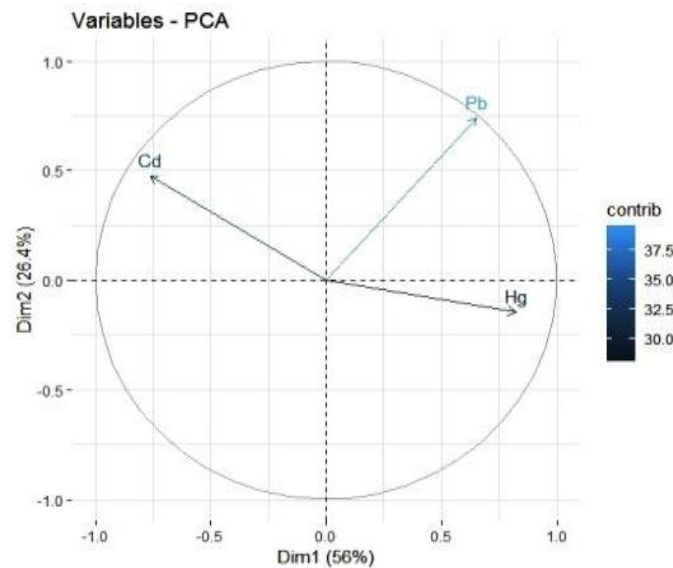
3.3 Correlation between Variables in the Studied Species

An analysis of the correlation matrix between variables (Table 3) reveals a significant negative correlation ($p < 0.05$) between Cd and Pb ($r = -0.223$) and between Hg and Cd ($r = -0.452$), and a significant positive correlation ($p < 0.05$) between Hg and Pb ($r = 0.331$). In the “dim1 x dim2” factor plane (Fig. 3), the first component (dim1 axis) accounts for 40% and 34% of the variance in Hg (0.823) and Cd (-0.761) contamination, respectively, in the smoked fish studied. With an inertia of 26.4%, the second component (dim2 axis) accounts for 68% of the variation in Pb contamination in sardines, mackerel, and tuna (0.738).

Table 3. Correlation matrix (Pearson (n)) between ETM variables in mackerel, sardine, and tuna

Variables	Cd	Pb	Hg
Cd	1	-0.223*	-0.452*
Pb	-0.223*	1	0.331*
Hg	-0.452*	0.331*	1

Significance levels are indicated as follows: * = $p < 0.05$


Fig. 3. Correlation cycle of variables

3.4 Typological Correlation between Variables and Statistical Individuals

Fig. 4 presents a typological correlation between the variables (Cd, Pb, and Hg) and the statistical individuals (AM, AT, AS, VM, VT, and VS). From this relationship, three typological zones emerge, namely:

- The zone formed by the statistical individuals VT, VS, and AS and the variable Hg (orange zone)
- The zone formed by the individual VM and the variable Pb (blue zone)
- The zone formed by the individuals AT and AM and the variable Cd (red zone)

The principal component analysis (PCA) conducted to process and describe the correlations between the set of variables on the one hand and the statistical set of individuals on the other showed that 82.37% of the information was accounted for by the two axes (dim1 and dim2). This result is slightly lower than the 92.61% reported by Chahid (2016) for Dim 1 and Dim 2 in a study of Cd, Pb, and Hg contamination in sardines. The eigenvalues show that the first axis (dim1) is the most significant because it accounts for more than half of the analysed data (56%). The negative correlations observed between Cd and Pb, and between Cd and Hg, indicate that the concentrations of Cd in smoked sardines, mackerel, and tuna, as well as those of Pb and Hg, vary in opposite directions.

The positive correlation found between Pb and Hg reveals that the concentrations of these two heavy metals in the smoked fish varieties vary in the same direction.

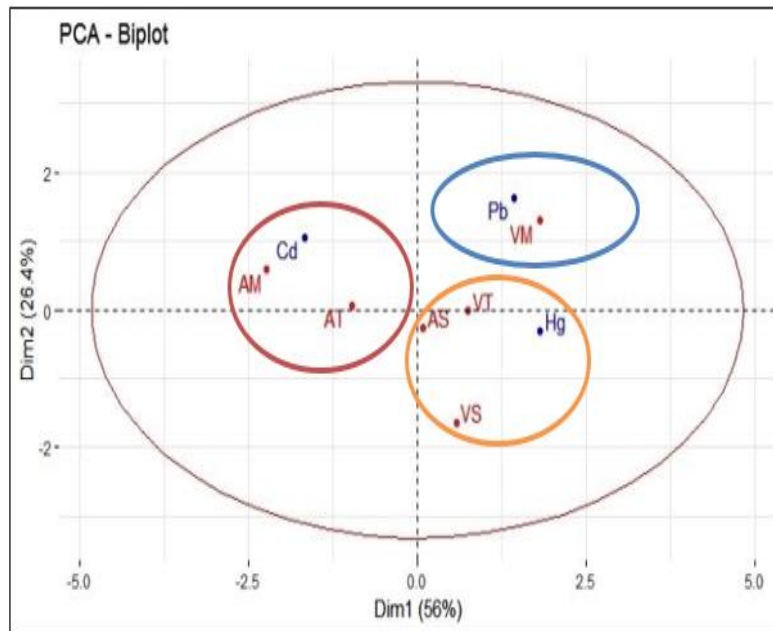


Fig. 4. Factor plot of the fish studied

From left to right, the Dim 1 axis reflects an increasing gradient of Cd and Hg contamination in sardines, mackerel, and tuna. In contrast, from bottom to top, the Dim 2 axis reflects an increasing gradient of Cd contamination in sardines, mackerel, and tuna. Thus, the typological structure revealed by the Dim1 x Dim2 plot shows the differentiation of three zones based on their degree of contamination. First, a zone comprising the following samples: smoked sardines and tuna from Vridi-Zimbabwe and smoked sardines from Abobo-Doumé (VS, VT, and AS), which exhibit significant Hg contamination. Next, a zone comprising smoked mackerel from Vridi-Zimbabwe (VM), characterized by Pb contamination. Finally, a zone comprising samples such as smoked mackerel and tuna from Abobo-Doumé (AM and AT), marked by high Cd contamination. This high cadmium content is consistent with the findings of Telahigue *et al.* (2024), who studied two species (sea bream and sea bass). These authors demonstrated that a significant accumulation of cadmium may be more prevalent than that of other metals (Pb and Hg) in the flesh of these species. Research by Diop *et al.* (2019) showed that tilapia from Hann Park (Senegal) were significantly ($p < 0.05$) more contaminated with Pb, whereas tilapia from the site near the wastewater treatment plant (Cambérène) were significantly ($p < 0.05$) more contaminated with Cd. Research conducted by Chahid (2016) also identified three distinct zones: a zone comprising liver samples, which showed moderate levels of Cd, Pb, and Hg contamination; a zone comprising gill samples, characterized by Pb and Hg contamination; and finally, a zone comprising muscle samples, which showed low levels of heavy metal contamination.

4. Conclusion

The typological analysis showed that smoked fish samples from the two Abidjan smoking sites differed in their associations with cadmium, lead, and mercury. The PCA separated the samples into three main groups: samples associated with mercury, samples associated with lead, and samples associated with cadmium. Mackerel was highlighted in two contamination profiles, with an association with cadmium in Abobo-Doumé and an association with lead in Vridi-Zimbabwe. These findings suggest that metal distribution varied by fish species and smoking site. However, interpretation should remain cautious because the PCA was based on six statistical individuals, and the manuscript does not present full concentration values or a direct comparison with food-safety limits.

5. Limitations

The study has some limitations to consider. The Principal Component Analysis is based on only six statistical individuals, which undermines the robustness of the identified typological structure, despite the 180 fish collected upstream. Geographic representativeness is also limited, as only two smoking sites were studied among all those existing in Abidjan. The correlations observed between Cd, Pb, and Hg are reported statistically but are not explored in depth from a mechanistic perspective, particularly regarding accumulation pathways or the origins of contamination sources.

Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. Grammarly and ChatGPT were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that no competing interests exist.

References

- Adherr, N. S. K., Dartey, E., Dwumfour-Asare, B., Agyapong Asare, E., & Sarpong, K. (2022). Effect of smoking and charring on toxic metal(loid) levels in tilapia from the Afram Arm of the Volta Lake. *Environmental Pollutants and Bioavailability*, 34(1), 136–145. <https://doi.org/10.1080/26395940.2022.2062453>
- Arisekar, U., Shalini, R., Shakila, R. J., Sundhar, S., Afrin Banu, A. M., Ibrahima, S. A., & Umamaheshwari, T. (2024). Trace metals in commercial seafood products (canned, pickled and smoked): Comparison, exposure and health risk assessment. *Food Research International*, 178, 113969. <https://doi.org/10.1016/j.foodres.2024.113969>
- Centre d'expertise en analyse environnementale du Québec. (2006). *Détermination du mercure : méthode par spectrophotométrie d'absorption atomique, formation de vapeur (MA. 200–Hg 1.0, rév. 4)* [Determination of mercury: Atomic absorption spectrophotometry, vapor generation method]. Ministère du Développement durable, de l'Environnement et des Parcs. <https://collections.banq.qc.ca/ark:/52327/bs35046>
- Chahid, A. (2016). *Quantification des éléments traces métalliques (cadmium, plomb et mercure total) de certains produits de la pêche débarqués dans la zone Essaouira-Dakhla : évaluation des risques sanitaires* [Quantification of trace metal elements (cadmium, lead, and total mercury) in selected fishery products landed in the Essaouira-Dakhla area: Health risk assessment] [Doctoral dissertation, Université Ibn Zohr]. <https://toubkal.imist.ma/items/ae3f9466-cec9-4e13-a821-03713f3882fd>
- Chalabis-Mazurek, A., Rechulicz, J., & Pyz-Lukasik, R. (2021). A food-safety risk assessment of mercury, lead and cadmium in fish recreationally caught from three lakes in Poland. *Animals*, 11(12), 3507. <https://doi.org/10.3390/ani11123507>
- Chiffolleau, J.-F., & Truquet, I. (1994). *Nouvelle méthode de dosage de quelques métaux-traces dans les sédiments et les matières en suspension* [A new method for determining certain trace metals in sediments and suspended matter] (Rapport DEL/94.08/NANTES). Ifremer. <https://archimer.ifremer.fr/doc/00140/25119/>
- Codex Alimentarius Commission. (2025). *General standard for contaminants and toxins in food and feed (CXS 193-1995)*. Food and Agriculture Organization of the United Nations & World Health Organization. <https://www.fao.org/fao-who-codexalimentarius/codex-texts/list-standards/en/>
- Diaby, V., Adon, A. M., Yapo, A. F., & Dosso, M. (2017). *Problématiques du cadmium en Côte d'Ivoire : pollution environnementale et risque sanitaire* [Cadmium issues in Côte d'Ivoire: Environmental pollution and health risk] [Preprint]. Academia.edu.
- Diop, C., Diatta, A., Ndiaye, A., Cabral, M., Toure, A., & Fall, M. (2019). Teneurs en métaux traces des eaux et poissons de cinq étangs de Dakar et risques pour la santé humaine [Trace metal concentrations in the water and fish of five ponds in Dakar and risks to human health]. *Journal of Applied Biosciences*, 137, 13931–13939. <https://doi.org/10.4314/jab.v137i1.1>
- Food and Agriculture Organization of the United Nations, & World Health Organization. (2011). *Report of the Joint FAO/WHO Expert Consultation on the Risks and Benefits of Fish Consumption: Rome, 25–29 January 2010* (FAO Fisheries and Aquaculture Report No. 978). Food and Agriculture Organization of the United Nations. <https://openknowledge.fao.org/items/5430199e-8e5d-43d7-87b0-ee78a4f5658d>
- Food and Agriculture Organization of the United Nations. (2020). *The state of world fisheries and aquaculture 2020: Sustainability in action*. <https://doi.org/10.4060/ca9229en>
- Guillot, A., Tona, R. N., Connan, S., Rouget, M.-L., Receveur, J., Le Croizier, G., Le Loc'h, F., Buscaglia, M., Munaron, J.-M., Aba'a, N. N., Petek, S., Lorrain, A., Schaal, G., & Sardenne, F. (2026). Smoked fish from Gabon: Nutritional benefits vs. contaminant risks. *Food Control*, 180, 111643. <https://doi.org/10.1016/j.foodcont.2025.111643>
- Kayalto, B. (2009). *Contribution à l'évaluation de la contamination par les métaux lourds de trois espèces de poissons, des sédiments et des eaux du Lac Tchad* [Contribution to the assessment of heavy metal contamination in three fish species, sediments, and waters of Lake Chad] [Diplôme d'études approfondies (DEA) thesis, Université de Ngaoundéré]. Academia.edu.
- Kouamenan, N. M., Coulibaly, S., Atse, B. C., & Goore, B. G. (2020). Bioaccumulation des métaux lourds dans les tissus de deux espèces de Cichlide (*Hemichromis fasciatus* et *Tilapia zillii* × *Tilapia guineensis*) pêchés dans la partie ouest de la lagune Ebrié, Côte d'Ivoire [Bioaccumulation of heavy metals in the tissues of two cichlid species (*Hemichromis fasciatus* and *Tilapia zillii* × *Tilapia guineensis*) caught in the western part of the Ebrié Lagoon, Côte d'Ivoire]. *Journal of Applied Biosciences*, 148, 15218–15229. <https://doi.org/10.35759/JABs.148.6>
- Lavkush, Radhakrishnan, K. V., Singh, C. P., Verma, S. K., Saroj, J., Patel, P. K., Maurya, M., Kumar, V., & Yadav, H. P. (2025). Heavy metal accumulation in Indian freshwater fish: Sources, impacts, and mitigation strategies. *Uttar Pradesh Journal of Zoology*, 46(20), 249–260. <https://doi.org/10.56557/upjoz/2025/v46i205319>
- Mielcarek, K., Nowakowski, P., Puścion-Jakubik, A., Gromkowska-Kępa, K. J., Soroczyńska, J., Markiewicz-Żukowska, R., Naliwajko, S. K., Grabia, M., Bielecka, J., Żmudzińska, A., Moskwa, J., Karpińska, E., & Socha, K. (2022). Arsenic, cadmium, lead and mercury content and health risk assessment of consuming freshwater fish with elements of chemometric analysis. *Food Chemistry*, 379, 132167. <https://doi.org/10.1016/j.foodchem.2022.132167>
- Monney, U. Y. (2020). *Cartographie de la zone d'échantillonnage* [Map]. DIVA-GIS.
- Monney, U. Y. (2022). *Impact de la technique de fumage sur la teneur en éléments traces métalliques (Cd, Hg et Pb) de trois espèces de poissons à forte consommation dans la ville d'Abidjan (Côte d'Ivoire) et effets toxicologiques chez les rats Wistar* [Impact of the smoking technique on trace metal (Cd, Hg, and Pb) levels in three widely consumed fish species in Abidjan (Côte d'Ivoire) and toxicological effects in Wistar rats] [Doctoral dissertation, Université Félix Houphouët-Boigny].
- Monney, U. Y., Diaby, V., Ake, Y. A., Sanogo, I., Yapo, A. F., & Djama, J. A. (2020). Évaluation de la teneur en cadmium, plomb et mercure avant et après fumage chez trois espèces de poisson à forte consommation dans la zone d'Abidjan, Côte d'Ivoire [Assessment of cadmium, lead, and mercury levels before and after smoking in three widely consumed fish species in the

- Abidjan area, Côte d'Ivoire]. *Revue Ivoirienne des Sciences et Technologie*, 36, 253–266. https://www.revist.ci/REVIST_36/15-ST-757.pdf
- Odeyemi, D. F., Oso, J. A., Oyejobi, S. A., & Asawe, O. E. (2024). Comparative study of the nutritive and elemental composition of smoked and raw *Clarias gariepinus* from three selected fish farms in Ado Ekiti, Ekiti State, Nigeria. *Asian Journal of Fisheries and Aquatic Research*, 26(11), 121–128. <https://doi.org/10.9734/ajfar/2024/v26i11835>
- Telahigue, K., Rabeh, I., Mdaini, Z., Ghali, R., Chouba, L., & Hajji, T. (2024). Human health risk assessment of heavy metal(oid)s in four fish species harvested from the Bizerte lagoon (Tunisia). *INSTM Bulletin: Marine and Freshwater Sciences*, 49, 61–77. <https://doi.org/10.71754/instm.bulletin.v49.1709>
- Togbe, A. M. O., Kouame, K. V., Yao, K. M., Ouattara, A. A., Tidou, A. S., & Atsé, B. C. (2019). Évaluation de la contamination des eaux de la lagune Ebrié (Zones IV et V), Côte d'Ivoire en arsenic, plomb et cadmium : variations spatio-temporelles et risques sanitaires [Assessment of arsenic, lead, and cadmium contamination in the waters of the Ebrié Lagoon (Zones IV and V), Côte d'Ivoire: Spatiotemporal variations and health risks]. *International Journal of Biological and Chemical Sciences*, 13(2), 1162–1179. <https://doi.org/10.4314/ijbcs.v13i2.45>
- Vural, S., & Ozyurt, G. (2026). Essential and toxic metals in processed seafood marketed in Türkiye: Levels, exposure and health risk assessment. *Marine Pollution Bulletin*, 231, 119894. <https://doi.org/10.1016/j.marpolbul.2026.119894>

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