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Full Length Research

Nutritional value and health risk assessment of metal residues in fish smoked using various kilns in Douala, Cameroon

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ABSTRACT: The nutritional value and health risk associated with metal residues in fish smoked using various kilns in Douala were investigated. Forty fish samples of *Ethmalosa fimbriata, Sphyreana afra* and *Gadus morhua,* respectively, were collected from Youpwe market, transported to the laboratory, washed with distilled water and smoked with four different kilns: Half metal drum, Banda, Altona and improved Altona (FN23). Proximate composition, mineral content, heavy metals and lipid quality were analysed using AOAC standard methods. Estimated Daily Intake (EDI), Targeted Hazard Quotient (THQ), Hazard Index (HI) and Carcinogenic Risk (CR) were used to estimate the human health risk. Fisher's PLSD were used to make comparisons between samples ($p<0.05$). Results showed that smoking significantly ($p < 0.05$) decreased moisture contents from 76.05 % to 12.24 % in *E. fimbriata* smoked with FN23 and increased mineral contents (Ca, K, Na, Mg, Fe, Zn, Cu, and Mn) compared to raw fish. Smoking with the Improved Altona kiln significantly ($p < 0.05$) reduced Cd content and health risk indices (EDI, THQ, HI, and CR) compared to other kilns. The EDI values for cadmium, zinc, and copper in smoked fish exceeded acceptable limits for human consumption. The HI < 1 suggested no potential carcinogenic effect for most samples, except for raw *Sphyreana afra* and *Gadus morhua*. However, the CR > 10^{-4} for cadmium indicated a carcinogenic health risk across all samples. The Improved Altona kiln (FN23) better preserved fish oil quality compared to the Half-metal drum, Banda, and Altona kilns. The FN23 demonstrated the most favourable benefit-risk ratio for consumer health and should be favoured over the other three smoking kilns.

Keywords: Health risk, kilns, metal residues, nutritional, smoked fish.

INTRODUCTION

Fish are highly nutritious food sources with significant health benefits. Fish contribute to human health due to their amino acid quality, minerals, n-3 and n-6 polyunsaturated fatty acids (PUFAs). Chemical indices such as acid, anisidine, iodine and peroxide are used to assess the quality of oils extracted from fish (Manz *et al.*, 2023). Minerals help catalyse numerous chemical reactions in the body, maintain the acid-base balance and participate in the formation of numerous hormones and enzymes (Papadopoulos *et al.*, 2024). Global fish production has been growing steadily for decades, reaching a new record of 185.4 million tons in 2022 (FAO, 2024). With an annual production of 335,159 tons, fish consumption per capita in Cameroon is approximately 19.4 kg/year (Nana *et al.*, 2023). The Cameroon fisheries products contribute to 46 % of the animal protein requirement (MINEPIA, 2021). Among the commonly consumed fishes, *Ethmalosa fimbriata* (Bowdich, 1825), *Sphyreana afra* (Peter, 1844) and *Gadus morhua* (Linnaeus, 1758), commonly known as "Bunga", " Pike" and "Cod", were the species targeted in this study. *Ethmalosa fimbriata* belongs to the Clupeidae family. It is a pelagic species found on the Atlantic coast of West Africa. They feed on phytoplankton, benthic invertebrates, small fish and fish eggs (Burel, 2017). *Sphyreana afra* belongs to the Sphyraenidae family. They are distributed along the coasts of West Africa, particularly in the Gulf of Guinea. It is a semi-pelagic fish that lives close to the coast. This family feeds on fish, phytoplankton, shrimps and cephalopods. *Gadus morhua* is a demersal species of the *Gadidae* family, found along the coasts of the Atlantic. Although they live close to the bottom, cod are found near the surface, where they feed on fish, bivalves and crustaceans (Nsoga, 2024).

The texture of fish flesh predisposes it to rapid deterioration, leading to high post-harvest losses (FAO, 2024). The need for processing and storage remains a crucial issue in Cameroon. According to the ACP Fish II program, 80% of artisanal maritime and inland fishing is distributed in the smoked form (Nsoga *et al*., 2021b). Due to its coastal location, the city of Douala is a major production centre of smoked fish, due to its seafront and numerous smoking sites and also for consumption due to its population. Smoking methods vary according to the availability of the material and climatic conditions, making the quality of smoked fish very fluctuating. Common smoking methods in Douala include the Half-metal drum, Banda, and Altona kilns, which differ in material design and efficiency (Omoruyi *et al*., 2017). These processing methods are likely to affect differently the organoleptic, nutritional and toxicological quality of fish (Nsoga *et al.*, 2021a; Zhuzzhassarova *et al*., 2024). Thus, despite the role of smoking in fish preservation, contaminants may remain in the final product and have an impact on human health. The aquatic environment concentrates metal residues that are bioaccumulative along the trophic chain and highly toxic (Zhuzzhassarova *et al*., 2024). These include mercury (Hg), chromium (Cr), arsenic (As), lead (Pb) and cadmium (Cd), primarily introduced through industrial effluents (Charkiewicz *et al*., 2023). In recent years, many consumers have been concerned about the presence of contaminants in fish products, which are the cause of several forms of cancer, as the nutritional benefits of their introduction into diets have become increasingly evident. It therefore seems important, in addition to their nutritional value, to estimate their potential risks for human health. The non-carcinogenic and carcinogenic effects of heavy metals developed by the United States Environmental Protection Agency (USEPA) are frequently used to assess their impact on human health (Roubie *et al*., 2024; Manz *et al*., 2024b). Other studies have shown the importance of improving traditional smoking techniques in order to maintain the nutritional quality of fish while reducing the toxicological risk to an acceptable level (Omoruyi *et al*., 2017; Arthur *et al*., 2021). However, scientific publications describing the benefit-risk of consuming smoked fish from the Cameroonian coast and their impact on human health are rare. This study, therefore, aimed to evaluate the nutritional value and assess the health risks of metal residues in fish smoked using various kilns in Douala, Cameroon, to provide evidence for safer processing methods and consumer protection.

MATERIALS AND METHODS

Biological material

Forty pieces each of the species *Ethmalosa fimbriata*, *Sphyraena afra* and *Gadus morhua* (Figure 1) were carefully selected and purchased at the Youpwe artisanal fishing port in Douala (Cameroon). The fish were identified by the veterinary services of the Ministry of Livestock, Fisheries and Animal Industries using the FAO species identification sheet. They were transported to the laboratory in three ice boxes containing an ice/fish ratio of 1:1 (w/w). The size/weight (cm/g) relationships of the fish were 21.70 ± 3.43 / 311.26 ± 8.77; 47.40 ± 4.10 / 839.44 ± 27.15; 31.04 ± 3.12 / 622.67 ± 5.54 for *E. fimbriata*, *S. afra* and *G. morhua,* respectively. The fish from each species were divided into 5 sub-batches of 8 fish. One sub-batch was analysed raw, and the other 4 were smoked with 4 different smoking methods.

Smoking methods

Three traditional kilns (Half-metal drum, Banda, Altona) commonly used in Douala, and one improved kiln (FN23) designed by our research team were used. Table 1 presents the main characteristics of each kiln.

Sample preparation

Fish were gutted, thoroughly washed and smoked using the four traditional smoking kilns with precaution to prevent cross-contamination. After smoking, different edible parts of fish were dried in an oven (Binder-78532) at 45 °C for 48 hours and ground using a laboratory Blender (Swiss Universal Mixer SW-1354-P) for proximate and metal residues analyses.

Proximate analysis

Moisture contents were obtained by placing 5 g of fish sample in an oven and drying at 103 ± 2°C until a constant weight according to the Association of Official Analytical Chemists methods (AOAC, 2005).

Crude protein contents were determined using Kjeldahl's method as described by AOAC (2005). The mixture was

Figure 1. The experimental fish samples collected from Douala fishing seaport.

Table 1. Main characteristics of the kilns used.

Features	**Kilns**			
	Banda	**Half-matal drum**	**Altona**	**FN23**
Support	Wooden logs	Half barrel	Bricks	Bricks
Nomber of separete rooms	1	1	2	2
Nomber of racks	1	1	Several (4 to 8)	10
Surface of a rack (in m^2)	2 to 10	0,4	1	1
Smoking time (hours)	8 – 72	6 - 48	4 – 8	2-3
Advantages	Can smoked > 40 kg of fish	Low manufacturing costs	Smoked large quantities of fish; Low risk of burning; Good heat conservation	Smoked large quantities of fish; Low risk of burning; Good heat conservation
Drawbacks	High heat loss; Risk of burns; Large quantities of wood	Smokes small amounts of fish; heat loss; risk of burns	High manufacturing costs	High manufacturing costs
Manufacturing costs (in XAF)	< 16 000	< 5 000	60 000	70 000

heated on a digestion plate (Büchi R-124) before titration with 0.01 N HCl.

Total lipid contents were extracted by the Soxhlet method according to the AOAC (2005) method. After complete extraction, the crude fish oil extract obtained was quantified.

Ash contents were obtained by introducing fish powder into a dish and placing it in a muffle furnace at 540°C for 5 hours. The dish was then cooled in a desiccator and its weight recorded. Ash content per 100 g of dry matter was calculated (AOAC, 2005).

Total carbohydrates were determined by subtracting the sum of fat, protein, ash and moisture contents from 100 in equation (1) (AOAC, 2005):

% Carbohydrates = 100 - % Moisture -% Proteins - % Fat -% Ash (1)

The average value of energy (AVE) was obtained by the Atwater equation.

AVE = (4 x Carbohydrate content) + (9 x Fat content) + (4 x Protein content) (2)

Chemical index analysis of fish oil

Acid indexes (AI) were obtained by the ISO standard method (NF EN ISO 660, 2020). AI was expressed as mg KOH/g of oil.

Iodine indexes (II) were obtained by NF ISO 3961, 2018 standard method.

Peroxide indexes (PI) were determined by the ISO 3960, 2017 standard method. The PI (in milli-equivalents of O_2/kg of oil) was calculated from the titration-based.

Anisidine values (AnV) were determined by the AOAC (2005) method. One gram (1 g) of oil was weighed, then dissolved and diluted with isooctane. The resulting solution was well stirred, and its absorbance (Ab) was measured at 350 nm using a spectrophotometer (Perkin Elmer, USA).

Thiobarbituric acid number (TBA) was evaluated by the AOAC (2005) method. The TBA was expressed as mg of malondialdehyde (MDA) per kg of oil.

The total oxidation values (TOTOX) was calculated from the Shahidi and Wanasundara formula taken from Manz *et al*. (2024a).

$$\text{TOTOX} = 2\ \text{PI} + \text{AnI} \quad (3)$$

Where PI: peroxide index and AnI: Anisidine index.

Minerals and heavy metals analysis

The fish meal from the various samples was first incinerated at 540°C for 5 hours. Mineral matters: calcium (Ca), sodium (Na), potassium (K), magnesium (Mg), phosphorus (P), iron (Fe), zinc (Zn), copper (Cu), manganese (Mn) and heavy metals: cadmium (Cd), mercury (Hg), lead (Pb), arsenic (As) were determined using the Energy-Dispersive X-Ray Fluorescence (EDX-7000 X-ray fluorescence spectrometer, XRF EDX - Shimadzu) as described by Masone (2015). For this purpose, 5 grams of ash from each fish sample were placed in the measuring device. Results were expressed in mg/kg dry weight.

Health risk assessment of heavy metal residues

The health risks assessment of seven metal residues (Cd, Hg, Pb, Cu, Fe, Zn, Mn) was investigated according to the United States Environmental Protection Agency (USEPA, 2000).

Estimated daily intake (EDI) is an estimation of the amount of each mineral and heavy metal absorbed daily through fish consumption. Its formula, according to USEPA, is:

$$\text{EDI} = \frac{\text{C x EF x ED x FIR}}{\text{AT x BW}} \text{ x } 10^{-3} \quad (4)$$

AT: average exposure time 21,787 days; BW: average body weight 66.65 kg; C: concentration of heavy metals in the selected fish tissues (mg/kg, ww); FIR: food ingestion rate, which is 53.11 g/person/day; EF: frequency of exposure, 365 days/year (USEPA, 2000). ED: exposure duration, 59.65 years, which is the life expectancy in Cameroon in 2022.

Non-carcinogenic health risk: THQ and HI are two methods commonly used to calculate a food consumer's exposure level based on different scenarios. THQ represents the exposure level based on a reference level, while HI represents the sum of the THQs of the chemical elements in the food. When THQ < 1, there are no expected toxic effects in consuming a food. When HI > 1, there is a high exposure to non-carcinogenic effects. Their calculation formulas are given by USEPA (2000).

$$\text{THQ} = \frac{\text{C x ED x EF x FIR}}{\text{AT x RFD x BW}} \text{ x } 10^{-3} \quad (5)$$

$$\text{HI} = \sum \text{THQ} \quad (6)$$

RFDs of Cd, Hg, Pb, As, Zn, Fe, Cu, Mn are 0.001; 0,0003; 0.00016; 0.0003; 0.3; 0.7; 0.04 and 0.14 respectively (USEPA, 2000). The other factors have been mentioned above.

Carcinogenic risk (CR): Not all metal residues in food produce carcinogenic effects. Among the metal elements studied, cadmium (Cd), lead (Pb) and arsenic (As) are recognised as carcinogens (Huang *et al*., 2022). CR = 10^{-4} is the maximum tolerable limit for carcinogenic risk. CR is calculated according to the equation developed by the USEPA (2000):

$$\text{CR} = \frac{\text{EF x ED x FIR x C x CSFo}}{\text{BW x AT}} \text{ x } 10^{-3} \quad (7)$$

CSFo (oral carcinogenic slope factor) was obtained from the database of the USEPA. Available CSFo values (mg/kg/day) are: As (1.5), Pb (0.0085) and Cd (6.3). The other factors have been mentioned above.

Quality control

All analyses were performed in triplicate using standardised or validated methods. The use of reference standards, analytical grade reagents, and blank samples ensured the accuracy and efficiency of the analytical devices. The application of good laboratory practices at all stages led to the minimisation of analytical errors.

Statistical analyses

All analyses were performed in triplicate, and results were expressed as mean ± standard deviation (M ± SD). Data were analysed using Statgraphics Centurion (v.17.2.07, Statgraphics Technologies Inc., USA). Data were analysed by one-way ANOVA, and mean differences were separated using Fisher’s Protected Least Significant Difference (PLSD) post hoc test at $p < 0.05$.

RESULTS AND DISCUSSION

Proximal composition

The water, fat, protein, carbohydrate, ash and energy contents of the different samples are presented in Table 2. The water contents of fresh fish as recorded were 76.05 %, 77.01 % and 74.13 % for E. fimbriata, S. afra, and G. morhua, respectively. These values were within the range of 66-81 % as defined by Njinkoue (2019). Similar water content was obtained by Dama *et al*. (2021): 78.18, 76.95 and 79.88 % respectively for *P. senegalensis*, *P. typus* and *P. elongatus*. The high water content in fish may explain their sensitivity to rapid spoilage, which depends on species, age, sex, diet, metabolic efficiency, size, fat

Table 2. Proximate composition and energy (Kcal) of the edible parts of different fish.

Parameters	**Species**	**Raw**	**Kilns**			
			Half-metal drum	**Banda**	**Altona**	**FN23**
Moisture (%WW)	*E. fimbriata*	76.05±0.67^{a}	26.51±0.36^{b}	21.04±0.47^{c}	13.91±0.63^{d}	12.24±0.49^{d}
	S. afra	77.01±0.90^{a}	28.37±0.87^{b}	22.08±0.10^{c}	16.99±0.88^{d}	15.25±0.97^{c}
	G. morhua	74.13±0.07^{a}	27.14±0.84^{b}	23.41±0.66^{c}	17.90±0.62^{d}	14.30±0.91^{d}
Protein (% DW)	*E. fimbriata*	76.86±1.13^{a}	68.18±2.02^{b}	70.74±1.94^{b}	71.15±1.38^{b}	71.42±0.78^{b}
	S. afra	87.08±1.08^{a}	74.22±1.30^{b}	71.29±1.26^{c}	73.54±1.09^{bc}	74.54±0.54^{b}
	G. morhua	85.96±1.83^{a}	74.29±1.27^{b}	74.23±1.77^{b}	73.75±2.07^{b}	74.36±0.71^{b}
Fat (% DW)	*E. fimbriata*	17.62±1.30^{a}	17.85±0.14^{a}	17.03±0.85^{a}	18.1±0.81^{a}	15.90±1.09^{b}
	S. afra	5.95±0.33^{a}	11.46±0.18^{b}	13.78±0.97^{c}	12.23±0.42^{d}	11.90±0.63^{ac}
	G. morhua	9.31±0.47^{a}	15.33±1.64^{b}	14.91±0.69^{b}	15.29±0.47^{b}	14.77±0.91^{a}
Carbohydrates (% DW)	*E. fimbriata*	0.47±0.06^{a}	2.98±0.28^{b}	1.86±0.02^{c}	1.5±0.16^{c}	2.63±0.55^{a}
	S. afra	1.19±0.03^{a}	3.77±0.31^{b}	3.58±0.16^{b}	3.53±0.33^{b}	3.31±0.19^{a}
	G. morhua	0.37±0.09^{a}	1.71±0.12^{b}	0.98±0.07^{c}	1.37±0.24^{b}	1.49±0.69^{ab}
Ash (% DW)	*E. fimbriata*	5.05±0.70^{a}	10.99±0.92^{b}	10.37±0.21^{b}	10.25±0.12^{b}	10.03±0.91^{a}
	S. afra	5.78±0.26^{a}	10.55±0.74^{b}	11.35±0.33^{b}	10.7±0.31^{b}	10.24±0.53^{b}
	G. morhua	4.36±0.09^{a}	9.67±0.13^{b}	9.88±0.06^{b}	9.59±0.60^{b}	9.36±0.42^{a}
Energy (Kcal/100 g DW)	*E. fimbriata*	467.9±3.2^{a}	445.29±3.1^{b}	443.67±3.3^{b}	449.5±4.9^{b}	439.38±5.60^{b}
	S. afra	406.63±2.6^{a}	415.1±4.5^{b}	423.5±2.1^{c}	418.35±4.2^{b}	418.60±9.40^{bc}
	G. morhua	429.11±3.3^{a}	319.09±2.7^{b}	435.03±3.8^{a}	438.09±2.4^{c}	436.38±7.10^{c}

Values are expressed as mean values ± standard deviation. Values in the same column with different symbols are significantly ($p < 0.05$) different. Values in the same line with different letters are significantly ($p < 0.05$) different. WW: wet weight. DW: dry weight. N = 3.

content, and spawning period. The significant decrease ($p<0.05$) of water content in all smoked samples was the effect of heat dehydration. During smoking, the flesh loses water in the first 3 hours at 80 °C (Tenyang *et al.,* 2020). After smoking, water content decreased, ranging from 28.37 % in S. afra smoked with the Half-metal drum to 10.24 % in E. fimbriata smoked with FN23. There were significant differences ($p<0.05$) in water contents depending on the smoking method used. Only fish smoked with Altona and FN23 had values below 20 %, allowing their resistance to spoilage by depriving microorganisms of water necessary for their development (Atobla *et al*., 2022). Indeed, a protective coating is formed due to the partial carbonisation of fish tissues and the deposition of phenolic compounds brought by the smoke. Bienkiewicz *et al*. (2022) achieved a decrease in water during the smoking of *Salmo salar.* Good control of time/temperature parameters could explain the values obtained with Altona and FN23.

Total lipid contents ranged from 13.18 % (*G. morhua*) to 17.62 % (*E. fimbriata*). According to the classification of Omoruyi *et al*. (2017), *E. fimbriata*, *S. afra* and *G. morhua* are considered as "semi-fatty", "lean" and "low-fatty" fish, respectively. The lipid contents in smoked fish varied respectively from 11.46 % in *S. afra* smoked with Half-metal drum to 18.10 % in *E. fimbriata* smoked with Altona. These values were lower than those found by Tenyang *et al*. (2020) on smoked *Chrysichthys nigrodigitatus* and higher than those obtained by Paul *et al*. (2021) on smoked *Gymnaruchus niloticus*. Fat content did not vary significantly ($p > 0.05$) in smoked *E. fimbriata* and *S. afra* irrespective of the smoking method. Water content has an influence on the lipid content; Biandolino *et al*. (2023) concluded that the lower the water content, the higher the lipid content. Indeed, the main influence of heat treatment leads to the coagulation of flesh proteins. Between 70 and 80°C, most of these proteins coagulate and form a structural matrix that traps the fat and water droplets released by the hot treatment. Subsequently, the water retention power decreases, and the flesh undergoes thermal weight loss due to water evaporation (Chen *et al*., 2025). The antioxidant effect of phenols provided by smoke acts on fish lipids and inhibits the propagation phase of auto-oxidation, which could explain the increases in lipid contents observed with FN23.

According to Table 2, protein contents of fresh fish varied significantly ($p<0.05$) between *E. fimbriata* (76.86%) on one hand, *S. afra* (87.08 %) and *G. morhua* (85.96%)

on the other. These values were higher than 60.98% obtained by Indur et al. (2023) on *Labeo rohita*, but lower than 88.28% obtained by Modzelewska-Kapituła *et al*. (2022) on wild *Sander lucioperca*. These results showed that the fish species studied were good sources of proteins (Modzelewska-Kapituła *et al*., 2022). Protein contents in the three smoked fish species did not vary significantly ($p>0.05$) depending on the smoking method. These protein values were higher than those obtained by Djopnang *et al*. (2018) in *C. nigrodigitatus* (38.75 %). These results contrast with those of Kiczorowska *et al*. (2019), who obtained an increase in protein contents in smoked *Abramis brama*. The differences would be linked to the action of the smoking temperature on the denaturation of the proteins in the fish flesh. According to Chen *et al.* (2025), the denaturation temperatures for the main muscle proteins are: 53 - 58 °C for myosin; 65 - 68 °C for sarcoplasmic proteins, including myoglobin and collagen and 80 - 82 °C for actin. The protective coating formed due to the partial carbonisation of fish tissues and the phenolic compounds brought by the smoke could explain the observed non-variations.

The ash contents of the different fresh fish species varied significantly ($p<0.05$) from *E. fimbriata* (9.22 %, DW) to *S. afra* (10.13 %, DW) and *G. morhua* (10.16 %, DW). These values were close to 10.90 % (DW) obtained in *C. nigrodigitatus* by Djopnang *et al*. (2018) but higher than 5.63 % (DW) in *Clarias gariepinus* by Oyeleye (2020).but lower than the 5.63 % (DW) in *Clarias gariepinus* by Oyeleye (2020). These differences could be related to the species and physiological state of each fish. No significant difference ($p<0.05$) was observed between fresh and smoked samples regardless of smoking method. These values were lower than those found by Msuku and Kapute (2018) on smoked *Diplotaxodon* (12.96 %) and higher than 1.32 % obtained by Bezuayeha and Fikada (2021) on smoked *C. gariepinus*. Low changes in ash contents after smoking suggest that the smoking temperatures had little effect on minerals, so the variations observed would be linked to water loss in each sample.

The carbohydrate contents in the fresh samples were 2.54 %, 2.04 % and 1.97 % respectively in *E. fimbriata*, *S. afra* and *G. morhua*. These low carbohydrate contents are due to the fact that glycogen does not really constitute a reserve in the fish tissues. These values are close to those found on wild *Sander lucioperca* (2.30) by Modzelewska-Kapituła *et al*. (2022). The differences are thought to be related to the physiological state of the fish, particularly its diet and some capture techniques that cause the fish to struggle, leading to the depletion of low glycogen reserves and thus, a decrease in carbohydrate levels (Manz *et al*., 2024b). Altona and FN23 significantly ($p<0.05$) increased carbohydrate levels in *E. fimbriata* and *S. afra*. These results could explain their slightly sweet flavour, and also their role in the colour of smoked fish through the Maillard reaction (Sa'ari *et al*., 2021). These reactions (glycation) often take place at the same time as protein pyrolysis, lipid oxidation and many other reactions to enhance the organoleptic qualities of smoked fish (El Hosry *et al*., 2025).

E. fimbriata, *S. afra* and *G. morhua* obtained 467.9, 406.63 and 429.11 Kcal, respectively. These values are close to 424.15 Kcal obtained by Djopnang *et al.* (2018) in *Chrysichthys nigrodigitatus* but lower than the 553.2 Kcal by Tenyang *et al*., (2020) on *C. nigrodigitatus*. The differences could be linked to species and the physiological state of the fish. After smoking, there was a significant decrease ($p<0.05$) in the energy potential of *E. fimbriata* regardless of the smoking method. In contrast, this potential increased significantly ($p<0.05$) in smoked *S. afra*. However, in *G. morhua*, significant variations ($p<0.05$) exist between the samples smoked with the Half-metal drum (319.09 Kcal) and the three other kilns. These differences would be linked to the composition of macronutrient contents in each sample (Njinkoue, 2019).

Overall, FN23 gave better proximal composition than the other kilns. Furthermore, the external appearance is one of the quality indicators for consumers' appreciation of smoked fish. Figure 2 shows that fish smoked with FN23 had a shiny and homogeneous colouration compared to fish smoked with Half-metal drum, Banda and Altona. This difference could explain consumers' choice for these fish smoked with FN23.

Chemical oil indexes

Iodine, acid, peroxide, anisidine, thiobarbituric acid indexes and total oxidation of the different samples are presented in Table 3. Iodine values of fresh *E. fimbriata*, *S. afra* and *G. morhua* are 159.81, 142.88 and 134.83, respectively. Since the iodine index (II) was >130 in all fresh samples, these results show that all fish oils extracted were drying, that is, they had several double bonds on their fatty acids. These results were lower than those obtained by Manz (2021) for *I. africana* (171.59) but higher than those of Mouokeu *et al.* (2018) for *C. nigrodigitatus* (82.64). The differences could be related to the fish species and diet. A quality diet provides polyunsaturated fatty acids, particularly through the consumption of PUFA-rich phytoplankton (Njinkoue *et al.,* 2017). Smoking significantly ($p>0.05$) reduces this index, which changes these oils from drying to semi-drying. Tenyang *et al.* (2020) showed a significant decrease in the II of *A. maculatus* lipids after smoking. These variations could be explained by the inactivation of exogenous lipoxygenase responsible for oxidation, which depends on intrinsic factors of each fish species, such as the duration and temperature of the heat treatment.

Acid index (AI) is an important indicator of rancidity and oil quality. The normal value recommended by Codex Alimentarius (2017) is AI ≤ 4 mg KOH/g of oil. Fresh *E. fimbriata* (2.17) and *S. afra* (1.52) had AIs under the Codex standard limit. These may result from low hydrolytic activity

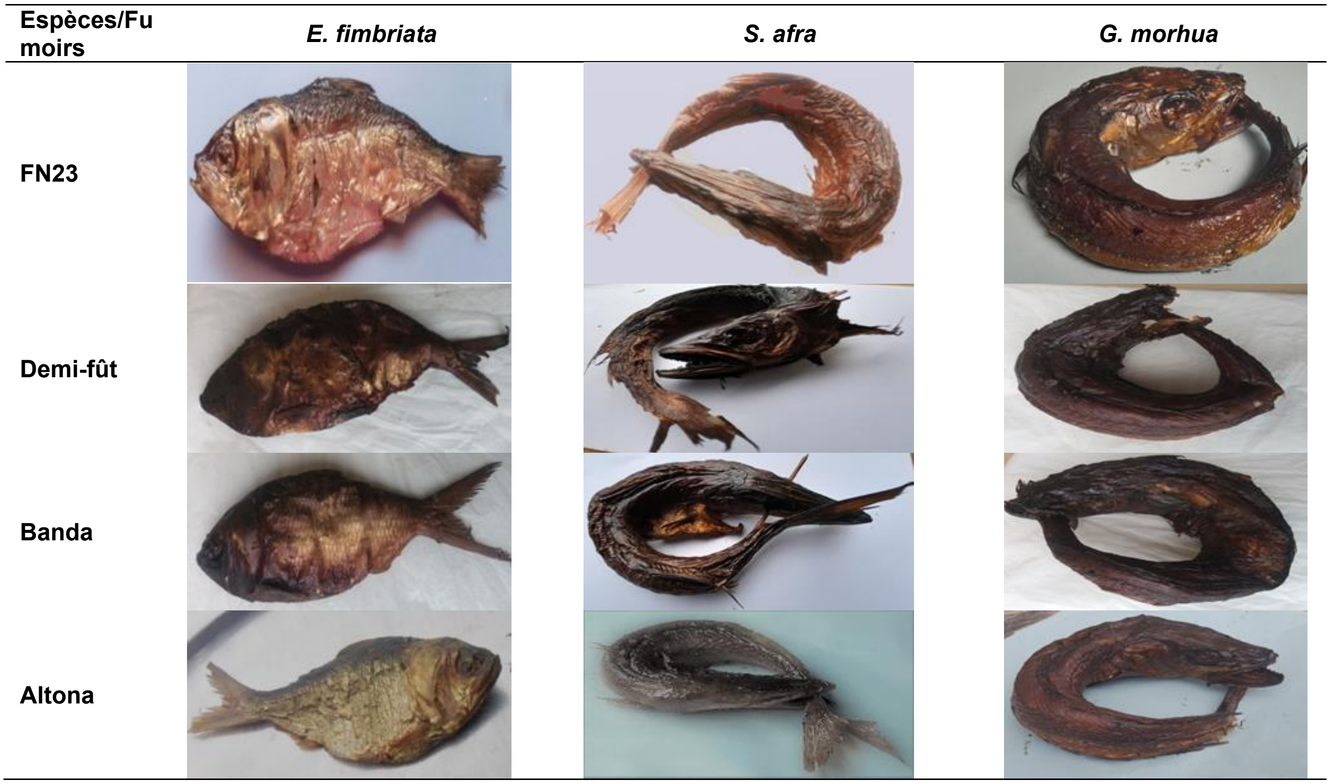

Figure 2. Effects of the different kilns on the appearance of *E. fimbriata, S. afra* and *G. morhua.*

of triglyceride lipases (Tenyang *et al*., 2020). Manz *et al.* (2024a) obtained similar results of 2.15 and 1.10, respectively, in fresh *I. africana* and *S. maderensis*. However, AI was higher than the standard limit for fresh *G. morhua* (5.48). This may be related to the fish species, which led to oxidation of the oils. After smoking, a significant increase ($p<0.05$) in AI above the threshold set by the Codex was observed in *E. fimbriata* (4.95; 4.65; 4.21; 3.78), *S. afra* (4.43; 5.30; 4.87; 4.21) and *G. morhua* (8.91; 7.17; 7.39; 7.17) smoked with the Half-metal drum, Banda, Altona and FN23 respectively. Fish lipids are oxidized at high temperatures due to strong hydrolytic activity. Tenyang *et al.* (2020) obtained 3.16 in smoked *C. nigrodigitatus*. This difference would be linked to the fish species and the smoking time/temperature ratio. Indeed, fatty acids are oxidized under the effect of certain factors such as temperature, oxygen, and the action of bacteria that transform certain sugars into acids (Djopnang *et al*., 2018).

Fresh fish oil recorded a peroxide index (PI) value of 1.98, 1.83 and 4.31 meq O_2/Kg of oil, respectively, for *E. fimbriata*, *S. afra* and *G. morhua*. These results are lower than 8.43 meq O_2/Kg of oil obtained by Ayeloja *et al*. (2024) on *Trachinotus blochii* oil, but higher than the 0.74 of Bouriga *et al*. (2020) on *Sander lucioperca* oil. The PI of smoked *E. fimbriata* and *S. afra* were lower than the standard (≤5 meq O_2/Kg) defined by the Codex Alimentarius (2017). In smoked *G. morhua*, the PI is higher than the Codex maximum limit for all smoking methods. It appears that smoking significantly increased ($p<0.05$) the primary oxidation of fish oil. This oxidation mainly leads to the formation of hydroperoxides due to autoxidation of unsaturated fatty acids. The higher the PI, the more the fat is oxidized. However, a low peroxide index does not mean that a fat is not altered because it is the combination of several indices that effectively assesses the quality of oils (Njinkoue, 2019).

The anisidine index (AnI) indicates the oxidative history of an oil. The AnI values in all fresh samples were within the standard limit, AnI ≤ 20 (Codex Alimentarius, 2017). These values were lower than 3.55 in *I. africana* (Manz *et al*., 2021). These AnIs showed that the fish used were fresh. The AnI of the three smoked fish species ranged from 7.63 (in *S. afra* smoked with Half-metal drum) to 9.18 (in *G. morhua* smoked with Banda). These results are below the normative limit of AnI ≤ 20 (Codex Alimentarius, 2017). AnI increased significantly ($p<0.05$) with smoking. This observation was also noted by Tenyang *et al*. (2020) on *Liza falcipinis* oil. Significant differences ($p<0.05$) were observed only in *S. afra* and *G. morhua* smoked with FN23. The increase in AnI reflects a conversion of unstable products (peroxides and hydroperoxides) during the secondary oxidation process into a variety of secondary compounds such as aldehydes, ketones, alcohols, and epoxides under the effect of elevated temperatures (Njinkoue, 2019). Chronic exposure to these

Table 3. Chemical indexes of the oil extracted from the fish species samples.

Oil Indexes	Species	Raw	Smoking methods			
			Half-metal drum	Banda	Altona	FN23
Iodine index (II) (g I$_2$/100g of oil)	*E. fimbriata*	159.81±4.53^{a}	107.06±2.35^{b}	110.50±1.76^{bc}	112.80±1.25^{c}	133.80±2.07^{d}
	S. afra	142.88±3.61^{a}	118.44±2.86^{b}	106.07±2.10^{c}	117.86±3.63^{b}	129.50±3.05^{d}
	G. morhua	134.83±2.30^{a}	109.20±3.31^{b}	108.90±1.74^{b}	108.86±4.27^{b}	122.75±4.07^{c}
Acid index (AI) (≤ 4 mg KOH/g of oil) *	*E. fimbriata*	2.17±0.37^{a}	4.95±0.75^{b}	4.65±0.37^{b}	4.21±0.56^{bc}	3.78±0.42^{c}
	S. afra	1.52±0.18^{a}	4.43±0.75^{b}	5.30±0.73^{b}	4.87±0.60^{b}	4.21±0.65^{b}
	G. morhua	5.48±0.99^{a}	8.91±0.37^{b}	7.17±0.65^{c}	7.39±0.38^{c}	7.17±0.32^{c}
Peroxide index (PI) (≤ 5 meq O$_2$/Kg of oil) *	*E. fimbriata*	1.98±0.63^{a}	4.88±0.14^{b}	5.23±0.26^{b}	4.03±0.12^{c}	3.13±0.58^{db}
	S. afra	1.83±0.31^{a}	4.80±0.36^{b}	4.49±0.30^{b}	3.94±0.16^{c}	2.50±0.60^{a}
	G. morhua	4.31±0.07^{a}	7.72±0.11^{b}	7.56±0.36^{b}	6.79±0.90^{bc}	5.53±0.58^{c}
Anisidine index (AnI) (≤ 20) *	*E. fimbriata*	1.89±0.21^{a}	8.42±0.89^{b}	8.21±1.11^{b}	7.89±0.98^{b}	6.91±0.98^{b}
	S. afra	1.66±0.09^{a}	7.63±1.03^{b}	8.02±0.85^{b}	8.11±1.10^{b}	6.24±0.70^{c}
	G. morhua	3.39±0.22^{a}	9.07±1.21^{b}	9.18±1.33^{b}	8.77±1.06^{b}	7.51±1.14^{c}
Thiobarbituric acid (TBARS) (≤ 10 mg MDA/kg of oil) *	*E. fimbriata*	2.03±0.26^{a}	10.09±0.87^{b}	10.12±0.56^{b}	11.02±0.32^{c}	8.46±0.23^{d}
	S. afra	1.94±0.13^{a}	9.78±0.58^{b}	8.96±0.81^{b}	8.77±0.51^{b}	7.87±0.37^{c}
	G. morhua	4.28±0.20^{a}	11.33±0.54^{b}	11.41±0.77^{b}	11.15±0.74^{b}	10.98±0.49^{b}
Total oxidation (TOTOX) (≤ 26 meq O$_2$/Kg of oil) *	*E. fimbriata*	5.85±0.16^{a}	18.18±1.02^{b}	18.67±0.69^{b}	15.95±0.37^{c}	13.17±0.58^{d}
	S. afra	5.32±0.21^{a}	17.23±1.38^{b}	17.00±0.86^{b}	15.99±0.94^{b}	11.24±0.34^{c}
	G. morhua	12.01±0.91^{a}	24.51±0.71^{b}	24.30±0.92^{b}	22.35±1.16^{c}	18.57±0.78^{d}

Values in the same line with different letters are significantly ($p < 0.05$) different. MDA: malondialdehyde; meq: milli-equivalent. (*): Maximum tolerable limit cited by Codex Alimentarius (2017)4]. N = 3.

compounds could be cytotoxic, mutagenic and carcinogenic in the long term. They can damage cells (oxidative stress), modify proteins or DNA, and have inflammatory or hepatic effects.

The thiobarbituric acid reactive substances (TBARS) index quantifies secondary lipid oxidation compounds. The TBARS obtained from fresh *E. fimbriata*, *S. afra*, and *G. morhua* were 2.03, 1.94 and 4.28 mg MDA/kg of oil, respectively. These values are lower than those obtained by Manz *et al.* (2021) on *I. africana* (6.67 mg MDA/kg of oil). These differences could be related to the time and method of fish preservation between capture and TBARS measurement. Smoking significantly increased ($p<0.05$) the TBARS of fish between 10.09 and 11.02 for *E. fimbriata*; 8.77 and 9.78 for *S. afra,* and between 11.15 and 11.41 for *G. morhua*. Heat treatments are believed to increase TBARS by accentuating unstable primary oxidation compounds (hydroperoxides) into stable secondary compounds through propagation and termination reactions. Zambou *et al.* (2024) reported that TBARS increased significantly ($p<0.05$) in *Alestes baremose* oil during smoking. Fish exposed to high temperatures exhibited high TBARS values, which accentuate lipid peroxidation. Kitts *et al.* (2023) obtained a decrease in TBARS in *Salmo salar* after smoking. This result could be explained by the antioxidants found in the smoke that might be responsible for the inhibition of Malondialdehyde formation (Bouriga *et al.,* 2023).

The total oxidation (TOTOX) was used to assess the different forms of fatty acid oxidation. The TOTOX values obtained in the fresh *E. fimbriata*, *S. afra*, and *G. morhua* were 5.85, 5.32, and 12.01 meq O$_2$/Kg of oil, respectively. These values are within the standard limit (TOTOX≤26) set for virgin fats and oils (Codex Alimentarius, 2017). Smoking significantly increased ($p<0.05$) TOTOX in *E. fimbriata* (18.18; 18.67; 15.95; 13.17), *S. afra* (17.23; 17.00; 15.99; 11.24), and *G. morhua* (24.51; 24.30; 22.35; 18.57), respectively, smoked with the Half-metal drum, Banda, Altona and FN23. However, these values remained within the Codex acceptable limits. Overall, all oils extracted from fish smoked with FN23 showed the best nutritional characteristics.

Mineral contents

Macroelement contents (calcium, sodium, phosphorus, potassium, and magnesium) in *E. fimbriata, S. afra*, and *G. morhua* are presented in Table 4. Calcium (Ca) levels in *E. fimbriata*, *S. afra*, and *G. morhua* are 15.33, 16.58 and

Table 4. Macroelement contents in the edible parts of different fish samples (g/Kg DW).

Macroelements	**Species**	**Raw**	**Smoking methods**			
			Half-metal drum	**Banda**	**Altona**	**FN23**
Calcium (Ca)	*E. fimbriata*	15.33±0.25^{a}	36.52±0.65^{b}	35.86±1.12^{b}	31.16±2.25^{c}	32.35±1.38^{c}
	S. afra	16.58±1.76^{a}	31.05±1.44^{b}	24.78±1.01^{c}	30.01±1.70^{d}	36.39±1.11^{e}
	G. Morhua	12.01±0.28^{a}	26.54±0.87^{b}	23.71±1.61^{c}	26.97±1.33^{bd}	30.13±1.87^{d}
Sodium (Na)	*E. fimbriata*	1.78±0.02^{a}	1.97±0.06^{b}	1.88±0.12^{ab}	1.98±0.14^{b}	1.98±0.09^{b}
	S. afra	1.46±0.06^{a}	1.92±0.28^{b}	2.00±0.15^{b}	1.98±0.11^{b}	2.01±0.07^{b}
	G. Morhua	1.39±0.01^{a}	1.88±0.17^{b}	1.91±0.18^{b}	1.99±0.20^{b}	1.98±0.11^{b}
Phosphorus (P)	*E. fimbriata*	2.94±0.08^{a}	6.78±0.95^{b}	5.59±0.77^{b}	5.97±0.56^{b}	6.10±0.32^{b}
	S. afra	3.21±0.06^{a}	6.26±0.62^{bc}	7.19±0.64^{b}	5.95±0.76^{bc}	6.10±0.15^{c}
	G. Morhua	2.89±0.14^{a}	6.80±0.48^{bc}	6.09±0.82^{b}	6.18±0.54^{b}	7.29±0.08^{c}
Potassium (K)	*E. fimbriata*	3.60±0.60^{a}	6.63±0.39^{b}	6.49±0.35^{b}	6.94±0.50^{b}	6.05±0.53^{b}
	S. afra	3.90±0.92^{a}	7.37±0.50^{b}	10.17±0.95^{c}	8.33±0.74^{b}	6.07±0.14^{d}
	G. Morhua	3.31±0.57^{a}	7.02±0.11^{b}	9.54±0.06^{c}	7.06±0.67^{b}	4.84±0.87^{d}
Magnésium (Mg)	*E. fimbriata*	0.93±0.03^{a}	1.02±0.04^{b}	1.11±0.01^{c}	1.51±0.01^{d}	1.48±0.03^{d}
	S. afra	0.88±0.07^{a}	1.03±0.05^{b}	1.52±0.02^{c}	1.48±0.03^{c}	1.50±0.10^{c}
	G. Morhua	0.74±0.01^{a}	1.51±0.05^{bc}	1.54±0.02^{b}	1.44±0.07^{c}	1.57±0.07^{bc}
Na/K	*E. fimbriata*	0.49±0.05^{a}	0.29±0.02^{bc}	0.29±0.06^{bc}	0.28±0.02^{b}	0.32±0.01^{c}
	S. afra	0.37±0.01^{a}	0.26±0.02^{b}	0.19±0.04^{c}	0.23±0.11^{bcd}	0.33±0.00^{d}
	G. Morhua	0.42±0.04^{a}	0.26±0.04^{b}	0.20±0.09^{b}	0.28±0.07^{b}	0.41±0.03^{a}
Ca/P	*E. fimbriata*	5.20±0.12^{a}	5.38±0.06^{a}	6.40±0.28^{b}	5.21±0.26^{a}	5.30±0.11^{a}
	S. afra	5.16±0.09^{a}	4.95±0.13^{a}	3.44±0.15^{b}	5.03±0.12^{a}	5.95±0.54^{a}
	G. Morhua	4.14±0.21^{a}	3.90±0.30^{a}	3.89±0.17^{a}	4.36±0.41^{a}	4.13±0.63^{a}

Values are expressed as mean values ± standard deviation. Values in the same line with different letters are significantly ($p < 0.05$) different. DW: dry weight. N = 3.

12.01 (g/Kg, DW), respectively. These values are higher than 7.92 g/Kg obtained by Djopnang *et al*. (2018) in *C. nigrodigitatus* but lower than those of Bouriga *et al.* (2020) on *Clarias gariepinus* (90.78 g/Kg). These differences are related to the species and diet of the fish and the edible part (flesh, flesh and bones) used for analysis. Smoking significantly ($p<0.05$) increased calcium levels in the fish. The following values were obtained with the Half-metal drum, Banda, Altona and FN23 ovens: (36.52, 35.86, 31.16, and 32.35) in *E. fimbriata*, (31.05, 24.78, 30.01, and 36.39) in *S. afra* and (26.54, 23.71, 26.97 and 30.13) in *G. morhua*. These results are close to those obtained by Zambou *et al.* (2024) on smoked *Alestes baremoze* (31.00 g/Kg DW) and higher than those of Njinkoué (2019), between 0.40 and 1.50 (g/Kg) in *Pseudotholitus typus*. The fish species and the analytical method used could justify the variations. The smoked fish in this study represent good sources of Calcium. The consumption of 21.9; 22.3; 25.67; 24.72 g of *E. fimbriata*, 25.75; 32.27; 26.64; 21.98 g of *S. afra* and 30.14; 33.73; 29.65; 26.54 g of *G. morhua* smoked respectively with Half-metal drum, Banda, Altona and FN23 cover the daily calcium requirement of 800 mg.

Sodium (Na) contents of *E. fimbriata*, *S. afra* and *G. morhua* are respectively 1.78, 1.46, and 1.39 g/Kg. Manz *et al.* (2024b) obtained lower Na contents (1.61 and 1.11 g/Kg), respectively, for *Ilisha africana* and *Sardinella maderensis*. Smoking significantly increased ($p<0.05$) the Na levels in fish. These values were higher than 1.38 g/Kg obtained by Djopnang *et al.* (2018) for *C. nigrodigitatus*. The difference would be linked to the biotope of these species. Indeed, *C. nigrodigitatus* is a freshwater species, unlike the species in this study, which come from marine, salty waters. Sodium is the main regulator of extracellular fluid, necessary for maintaining acid-base balance, activating enzymes, and maintaining osmotic pressure (Manz *et al.,* 2024b).

Phosphorus (P) contents were lower than the 7.09 g/Kg reported for fish by-products by Ndômbôl *et al.* (2021). The difference is linked to the composition of these by-products, which are a composite of flesh, bones, and

Table 5. Microelement contents in the edible parts of different fish (mg/100 g, DW).

Microelements	Species	Raw	Smoking methods			
			Half-metal drum	Banda	Altona	FN23
Fe (186 mg/kg)*	*E. fimbriata*	5.67 ± 0.14^{a}	14.18 ± 1.50^{b}	24.07 ± 1.88^{c}	24.77 ± 1.78^{c}	43.26 ± 1.85^{d}
	S. afra	2.34 ± 0.07^{a}	9.04 ± 1.35^{b}	15.01 ± 0.93^{c}	6.85 ± 0.10^{d}	31.19 ± 0.79^{d}
	G. morhua	5.46 ± 0.23^{a}	4.66 ± 1.01^{a}	7.18 ± 0.16^{b}	8.52 ± 0.18^{b}	12.03 ± 0.05^{c}
Zn (30 mg/kg)*	*E. fimbriata*	0.69 ± 0.01^{a}	9.62 ± 0.58^{b}	13.25 ± 0.41^{c}	12.85 ± 0.27^{c}	16.33 ± 0.92^{d}
	S. afra	4.64 ± 0.32^{a}	8.56 ± 0.62^{b}	14.69 ± 1.57^{c}	9.55 ± 0.44^{bd}	9.81 ± 0.10^{d}
	G. morhua	6.31 ± 0.22^{a}	9.87 ± 0.28^{b}	10.40 ± 0.82^{b}	9.56 ± 0.19^{b}	7.26 ± 0.06^{c}
Cu (10 mg/kg)$^{\#}$	*E. fimbriata*	3.71 ± 0.08^{a}	7.20 ± 0.42^{b}	6.69 ± 0.60^{b}	5.89 ± 0.08^{c}	10.60 ± 0.38^{d}
	S. afra	2.77 ± 0.14^{a}	8.09 ± 0.17^{b}	11.52 ± 0.25^{c}	9.15 ± 0.43^{d}	8.01 ± 0.58^{b}
	G. morhua	3.48 ± 0.28^{a}	6.33 ± 0.26^{b}	9.31 ± 0.76^{c}	9.19 ± 0.35^{c}	6.06 ± 0.49^{b}
Mn (12.97 mg/kg)*	*E. fimbriata*	2.54 ± 0.11^{a}	ND	4.33 ± 0.16^{b}	3.89 ± 0.09^{c}	9.39 ± 0.31^{d}
	S. afra	ND	ND	ND	ND	ND
	G. morhua	ND	ND	ND	ND	ND

Values are expressed as mean values ± standard deviation. Values in the same line with different letters are significantly ($p < 0.05$) different. DW: dry weight. N = 3. (*): Tolerable limit (FAO/WHO, 1989). (#): Tolerable limit (USEPA, 2000). ND: Not detected.

cartilage rich in mineral elements. Smoking concentrates phosphorus in fish tissues. The different smoking methods increased significantly ($p<0.05$) phosphorus in all fish samples. Djopnang *et al.* (2018) obtained 0.34 g/Kg in smoked *Chrysichthys nigrodigitatus*. These differences would be related to the fish species.

The average potassium (K) contents were 3.60, 3.90, and 3.31 g/Kg, respectively, in fresh *G. morhua*, *E. fimbriata* and *S. afra*. These results are lower than those obtained by Njinkoue (2019) on *Pseudotholitus senegalensis* (14.80 g/Kg). Smoking significantly ($p<0.05$) increased K contents in fish. These values were higher than those reported by Djopnang *et al*. (2018) for *C. nigrodigitatus* (0.01 g/kg). These differences would be linked to the species, the general condition and the diet of the fish.

Magnesium (Mg) levels were 0.93, 0.88 and 0.74 g/Kg, respectively, for fresh *E. fimbriata*, *S. afra* and *G. morhua*. These values are higher than those of Djopnang *et al.* (2018) on *C. nigrodigitatus* (0.01 g/Kg) but lower than those of Manz *et al.* (2023) on *Sardinella maderensis* (13.64 g/Kg). Smoking increased significantly ($p<0.05$) Mg contents in all smoked samples. The results obtained from smoked fish were higher than those of Djopnang *et al.* (2018), who obtained 0.03 g/Kg in *C. nigrodigitatus,* but close to the values of Odiko and Obirenfoju (2017) on various smoked fish (between 1.46 and 1.98 g/Kg). In addition to its alkalizing effect, magnesium is essential for facilitating the absorption of calcium and potassium (World Health Organisation-WHO, 2012).

The high calcium levels compared to phosphorus levels in all species studied result in Ca/P ratios greater than 1 (Ca/P > 1). The values obtained were (5.38, 6.40, 5.21, 5.30) in *E. fimbriata*, (4.95, 3.44, 5.03, 5.95) in *S. afra*, and (3.90, 3.89, 4.36, 4.13) in *G. morhua*. It is a good indicator of the level of calcium fixation by bones and teeth. These fish, therefore, presented a nutritional asset for the calcification of bones and teeth in children, pregnant women and adults (Manz *et al*., 2024b).

The low Na levels compared to K levels observed in these three raw and smoked samples give a Na/K ratio lower than 1. The values obtained were (0.29, 0.29, 0.28, 0.32) in *E. fimbriata*, (0.26, 0.19, 0.23, 0.33) in *S. afra* and (0.26, 0.20, 0.28, 0.41) in *G. morhua*. The low Na/K ratio is suitable and better indicated for the diet of people suffering from cardiovascular diseases. It is indeed a key parameter in maintaining the body's water balance and blood pressure (Bou M'handi *et al*., 2015).

Table 5 presents microelement contents (Iron, zinc, copper and manganese) in *E. fimbriata, S. afra*, and *G. morhua*. Iron (Fe) levels are 5.67, 2.34, and 5.46 mg/100 g for fresh *E. fimbriata*, *S. afra*, and *G. morhua*, respectively. These values are lower than those found by Manz *et al*. (2024b) in *Ilisha africana* (6.55 mg/100 g). Smoking significantly increased ($p<0.05$) Fe contents. These results were lower than the 65.10 mg/100 g obtained by Manz *et al.* (2024b) in *P. quadrifilis*. Akinwumi (2014) reported that the iron content of *C. gariepinus* increased significantly compared to the raw samples during smoking. These differences could be linked to the fish species, physiological state and the concentration of mineral matter during smoking.

Zinc (Zn) levels were 0.69, 4.64, and 6.31 mg/100 g, respectively, for fresh *E. fimbriata*, *S. afra*, and *G. morhua*. Manz *et al.* (2024b) obtained 39.43 mg/100 g in *A. parkii*. The different smoking methods significantly increased ($p<0.05$) their concentration in the different fish. Zn contents obtained with the four different smoking methods were lower than those of Manz *et al*. (2024b) in *P. quadrifilis* (76.28 mg/100 g). The differences could be linked to the fish species and the concentration of mineral matter during smoking. Zinc deficiency is associated with obesity, diabetes, depression, etc., as well as infectious diseases such as respiratory infections, malaria, HIV, or tuberculosis (WHO, 2012).

Copper (Cu) levels were 3.71, 2.77, and 3.48 mg/100 g, respectively, for fresh *E. fimbriata*, *S. afra*, and *G. morhua*. These values were close to those obtained by Manz *et al.* (2024b) (3.97 and 3.36 mg/100 g for *E. fimbriata* and *P. quadrifilis*, respectively). The different smoking methods increased Cu levels in fish. The following values obtained were higher than those of Manz *et al.* (2024b) in *E. fimbriata* (2.65 mg/100 g) and *P. quadrifilis* (4.05 mg/100 g). The differences could be linked to the concentration of mineral matter during smoking. Abnormally high levels of Cu can cause Mediterranean anaemia, hemochromatosis, liver cirrhosis and nephrosis (Njinkoue *et al*., 2017).

Manganese (Mn) levels were 2.541 mg/100 g in fresh *E. fimbriata* but were not detected in fresh *S. afra* and *G. morhua*. Manz *et al*. (2024b) obtained 6.31 mg/100 g in *E. fimbriata*. The difference was significant ($p<0.05$) between fresh and smoked *E. fimbriata*: 4.33, 3.89, and 9.39 mg/100 g in samples smoked with Banda, Altona and FN23, respectively. These results were lower than those of Manz *et al*. (2024b) in *E. fimbriata* (13.72 mg/100 g) and *P. quadrifilis* (6.30 mg/100 g). Manganese is an activator of pyruvate carboxylase and binds minerals.

Overall, smoking processes increased significantly ($p<0.05$) the microelement contents in fish. The diet (meat, pasteurised dairy products, baked goods, trans fats and cooked oils, refined sugars, soft drinks, alcohol, etc.), lifestyle (stress, anxiety, fear), and certain external factors (pollution, ageing) are highly acidifying for the body. This has a direct negative impact on our health (Njinkoue, 2019). The human body eliminates weak acids through the lungs, kidneys via urine, and skin via sweat. However, our bodies can only process a limited amount of acids, especially strong acids. Minerals such as calcium, magnesium, potassium, sodium, manganese, and iron have an alkalizing role to neutralise harmful acids in the body (Razzaque and Wimalawansa, 2025).

Heavy metal contents

Table 6 presents heavy metal contents (cadmium, mercury and lead) in different fish samples. In all samples, arsenic (As) residues were non-detectable. Cadmium (Cd), mercury (Hg) and lead (Pb) residues obtained from raw fish samples were (1.40; 0.02; 0.07 mg/Kg, DW) in *E. fimbriata*, (0.70; 0.04; 0.12 mg/Kg, DW) in *S. afra* and (1.12; 0.04; 0.10 mg/Kg, DW) in *G. morhua*. These values are below the limits authorised by WHO (2; 0.5-1 and 0.3 mg/kg) respectively for Cd, Hg, and Pb (Codex Alimentarius, 2017). These fish are therefore suitable for human consumption. Manz *et al*. (2024b) obtained higher values for Hg (0.36 mg/Kg) and Pb (0.13 mg/Kg) but lower for Cd (0.14 mg/Kg) in *Cyprinus carpio*. The differences could be attributed to the diet and level of pollution in which these species were found. Indeed, species that feed on sea urchins, molluscs, crustaceans, etc. (which accumulate heavy metals through their diet by filtering the silt) bioaccumulate more heavy metals than others (Huang *et al*., 2022).

After smoking, Cd ranges from 1.01 mg/Kg in *S. afra* (smoked with FN23) to 2.52 mg/kg in *G. morhua* (smoked with Banda). *S. afra* smoked in a Half-metal drum (2.34 mg/Kg) and *G. morhua* smoked in Banda (2.52 mg/Kg) obtained values above the maximum threshold (2 mg/Kg). These results are higher than those of Helmy *et al*. (2018), between 0.14 and 0.25 mg/Kg in 9 fresh fish species of Egypt. Younis *et al*. (2021) reported higher cadmium levels, between 1.70 and 5.10 mg/Kg in fresh fish from Saudi Arabia. These results were an indicator of the water pollution level and could be a consequence of anthropogenic activities. The effects of cadmium consumption in humans are kidney failure, accumulation in bones leading to calcium loss, and dysfunction of the peripheral and central nervous system (Peana *et al*., 2023).

Mercury (Hg) was found in trace amounts and varied very little (0.02; 0.05) depending on the species and smoking method. This stability of mercury levels was observed in all species regardless of the smoking method. The mercury values after smoking may be linked to its physicochemical properties. Mercury (Hg) is the only metal that remains liquid at room temperature. It can easily change to a gaseous or vaporous state (Monney *et al.,* 2022). Thus, during the smoking process, mercury evaporated in the form of vapour and/or droplets, thus stabilising its concentration. These mercury values were lower than the limit of 1 mg/Kg recommended (Codex Alimentarius, 2017). Helmy *et al.* (2018) obtained lower values, of 0.73–1.62 ng/kg for some Egyptian fish. Water pollution may explain the observed disparities. Mercury is one of the most toxic heavy metals, and ingestion of high doses can cause brain damage, kidney failure, infertility, and coma (Manz *et al*., 2023).

Lead (Pb) levels in smoked fish varied from 0.11 mg/Kg (*S. afra* smoked with FN23) to 0.21 mg/Kg (*E. fimbriata* smoked with Altona). These values were higher than those obtained by Arthur *et al.* (2021) on smoked *Sciaenops ocellatus* (0.07 mg/kg) and lower than those found by Dee *et al.* (2019) on smoked *Corbicula fluminea* (0.62 mg/kg). Smoking with all kilns studied did not significantly ($p > 0.05$) increase the lead contents in smoked *S. afra* and *G. morhua* compared to the raw samples, unlike in *E. fimbriata*. Jolaoso *et al*. (2016) showed that smoking increased lead content compared to fresh *Monoductylus sebae*. Fish smoked with FN23 had the lowest levels of lead. Bwala *et al.* (2023) reported that lead content in fish collected from fish markets in Baga decreased during smoking compared to raw fish. Water loss, evaporation or conversion of heavy metals to other compounds during heat treatments could explain such results (Kwaghvihi *et al.,* 2020). Industrial and agricultural discharges are the

Table 6. Heavy metal contents in the edible parts of different fish (mg/kg DW).

Heavy metal	Species	Raw	Smoking methods			
			Half-metal drum	Banda	Altona	FN23
Cadmium (2 mg/Kg)*	*E. fimbriata*	1.40±0.01^{a}	1.68±0.02^{b}	1.44±0.11^{ac}	1.59±0.09^{bc}	1.49±0.08^{ac}
	S. afra	0.70±0.02^{a}	2.34±0.02^{b}	1.52±0.09^{c}	1.68±0.02^{d}	1.01±0.01^{e}
	G. Morhua	1.12±0.04^{a}	1.97±0.03^{b}	2.52±0.01^{c}	1.63±0.06^{d}	1.32±0.07^{e}
Mercure (0,5-1,0 mg/Kg)*	*E. fimbriata*	0.02±0.00^{a}	0.02±0.00^{a}	0.03±0.00^{b}	0.02±0.00^{a}	0.02±0.00^{a}
	S. afra	0.04±0.00^{a}	0.05±0.00^{b}	0.05±0.00^{b}	0.05±0.00^{b}	0.04±0.00^{a}
	G. Morhua	0.04±0.00^{a}	0.05±0.00^{b}	0.05±0.00^{b}	0.04±0.00^{a}	0.04±0.00^{a}
Plomb (0,3 mg/Kg)*	*E. fimbriata*	0.07±0.01^{a}	0.13±0.01^{b}	0.15±0.03^{b}	0.21±0.01^{c}	0.13±0.04^{b}
	S. afra	0.12±0.04^{a}	0.18±0.02^{ab}	0.19±0.02^{b}	0.15±0.03^{ab}	0.14±0.07^{ab}
	G. Morhua	0.10±0.02^{a}	0.15±0.04^{a}	0.13±0.03^{a}	0.11±0.00^{a}	0.11±0.01^{a}

Values are expressed as mean values ± standard deviation. Values in the same line with different letters are significantly ($p < 0.05$) different. DW: dry weight; ND: non determined. N = 3.

main sources of Pb pollution. Lead has deleterious effects on hematopoiesis, as well as the nervous, reproductive, and urinary systems. It can also impair cognitive development, cause intellectual disability, increase blood pressure, and lead to cardiovascular disease in adults (Codex Alimentarius, 2017).

The concentration of metal residues in fish could depend on the feeding habits of benthic and pelagic species. For Huang *et al.* (2022), demersal species generally accumulate more heavy metal residues than pelagic species. Heavy metals are probably of waterborne origin, but their concentration during smoking should not be neglected (Yang *et al.* 2022). Wood and materials such as racks and metal structures oxidise at high temperatures in the presence of oxygen to release metal oxides belonging to its alloys (Monney *et al.,* 2022). Humidity, ventilation and temperature during smoking influence these heavy metal contents. The metals, even at low concentrations, can accumulate in the body over time and lead to chronic toxicity or other harmful effects. Ultimately, FN23 presented the lowest concentrations of metallic residues compared to Half metal-drum, Banda and Altona and is positioned as the best smoking method to limit these contaminants.

Health risk assessment

Table 7 presents EDI values for seven metal residues (Cd, Hg, Pb, Cu, Fe, Zn, Mn) calculated for the three fish species. The EDIs for Hg, Pb, Fe, and Mn in each smoked fish sample were below the tolerable daily intake (TDI), which are 1.0×10^{-3}; 2.5×10^{-3}; 0.80 and 0.36 mg/kg/day, respectively (USEPA, 2000). This suggests that their daily intake through ingestion does not pose a detrimental risk to human health. Adegbola *et al.* (2021) showed that the EDI of lead and mercury were below the standards on raw *Sarotherodon melanotheron*. EDI values for Lead and iron reported by Sani *et al.* (2022) were greater than the standard limits (USEPA, 2000). EDI values for cadmium in *E. fimbriata* and *G. morhua* (raw and smoked) were above the standard limit (0.2×10^{-3} mg/kg/day). For zinc, the EDI values found on raw and smoked fish exceed the USEPA standard of 30×10^{-3} mg/kg/day. EDIs for copper in *E. fimbriata* (smoked with Banda, Altona and FN23) and *G. morhua* (smoked with the four kilns) are greater than the standards (10×10^{-3} mg/kg/day). These results suggest a high health risk for consumers. This could be linked to the degree of water pollution. Similar results were obtained by Kortei *et al.* (2020), who reported that EDI values for cadmium and zinc in *Clarias anguillaris* and *Oreochromis niloticus* are above standards. Different results were obtained by Huang *et al.* (2022), who reported that EDI for Cd, Zn and Cu in raw *Sebastiscus marmoratus* were below standard. These results could be related to the initial concentration of the residues in fresh fish.

Table 8 presents targeted hazard quotient (THQ), hazard index (HI) and carcinogenic risk (CR). THQ values increased with smoking, and FN23 reduced THQ compared to the other kilns. THQ values of the different metal residues in the raw and smoked samples were below the acceptable level (< 1). These results imply no potential adverse health effects from the intake of these fish species. Similar results were obtained by Kumar *et al.* (2023), who found THQ values of Mn, Zn, Cu, As, Cd, Pb and Hg lower than 1 on raw fish. The registered values were different to those obtained by Sabouang *et al*. (2022), who reported that THQ values of Cd were higher (1.1 for *Ethmolosa fimbriata* and 1.2 for *Cynoglossus browni*).

HI values were lower than 1 on raw *S. afra* and *G.morhua*. Similar results were reported by Hossain *et al.* (2022), who found HI<1 for *Polynemus paradiseus*. Values

Table 7. Estimated daily intake of metal residues (EDI) (mg/kg/day).

Species	Methods	Cd	Hg	Pb	Fe	Zn	Cu	Mn
E. fimbriata	Raw	0.47x10^{-3}	3.18x10^{-6}	0.55x10^{-6}	52.31x10^{-3}	38.16x10^{-3}	6.44x10^{-3}	18.99x10^{-3}
	Half-metal drum	0.70x10^{-3}	3.18x10^{-6}	0.95x10^{-6}	128.87x10^{-3}	60.78x10^{-3}	9.57x10^{-3}	ND
	Banda	0.53x10^{-3}	3.98x10^{-6}	119.52x10^{-6}	143.96x10^{-3}	65.74x10^{-3}	10.30x10^{-3}	34.53x10^{-3}
	Altona	0.31x10^{-3}	3.18x10^{-6}	159.37x10^{-6}	149.53x10^{-3}	70.56x10^{-3}	10.34x10^{-3}	30.98x10^{-3}
	FN23	0.28x10^{-3}	3.18x10^{-6}	103.59x10^{-6}	148.60x10^{-3}	66.40x10^{-3}	10.39x10^{-3}	74.82x10^{-3}
S. afra	Raw	0.15x10^{-3}	3.18x10^{-6}	95.62x10^{-6}	34.60x10^{-3}	37.02x10^{-3}	4.55x10^{-3}	ND
	Half-metal drum	0.87x10^{-3}	3.98x10^{-6}	143.43x10^{-6}	71.98x10^{-3}	68.24x10^{-3}	8.70x10^{-3}	ND
	Banda	0.81x10^{-3}	3.98x10^{-6}	143.43x10^{-6}	73.34x10^{-3}	69.25x10^{-3}	8.93x10^{-3}	ND
	Altona	0.61x10^{-3}	3.98x10^{-6}	119.52x10^{-6}	76.85x10^{-3}	76.09x10^{-3}	9.17x10^{-3}	ND
	FN23	0.40x10^{-3}	3.18x10^{-6}	111.56x10^{-6}	89.13x10^{-3}	75.01x10^{-3}	8.87x10^{-3}	ND
G. morhua	Raw	0.49x10^{-3}	3.18x10^{-6}	79.68x10^{-6}	43.53x10^{-3}	50.32x10^{-3}	8.66x10^{-3}	ND
	Half-metal drum	0.87x10^{-3}	3.98x10^{-6}	119.52x10^{-6}	76.98 x10^{-3}	78.67x10^{-3}	10.65x10^{-3}	ND
	Banda	0.96x10^{-3}	3.98x10^{-6}	95.62x10^{-6}	73.15 x10^{-3}	74.92x10^{-3}	10.47x10^{-3}	ND
	Altona	0.74x10^{-3}	3.18x10^{-6}	79.68x10^{-6}	67.86x10^{-3}	76.19x10^{-3}	10.35x10^{-3}	ND
	FN23	0.49x10^{-3}	3.18x10^{-6}	79.68x10^{-6}	73.54x10^{-3}	57.86 x10^{-3}	10.10 x10^{-3}	ND

Table 8. Targeted hazard quotient (THQ), hazard index (HI) and carcinogenic risk (CR) in the edible parts of different fish.

Species	Methods	THQ (mg/kg/day)							HI	CR	
		Cd	Hg	Pb	Fe	Zn	Cu	Mn		Cd	Pb
E. fimbriata	Raw	0.478	0.019	0.013	0.074	0.127	0.161	0.135	1.009	30x10^{-4}	0.49 x10^{-6}
	Half-metal drum	0.701	0.019	0.023	0.184	0.202	0.239	ND	1.370	44x10^{-4}	0.85 x10^{-6}
	Banda	0.533	0.024	0.029	0.205	0.219	0.257	0.246	1.516	33x10^{-4}	1.06 x10^{-6}
	Altona	0.310	0.019	0.039	0.213	0.235	0.258	0.221	1.298	19x10^{-4}	1.41 x10^{-6}
	FN23	0.286	0.019	0.025	0.212	0.221	0.259	0.534	1.559	18x10^{-4}	0.92 x10^{-6}
S. afra	Raw	0.159	0.019	0.023	0.049	0.123	0.113	ND	0.489	10x10^{-4}	0.85 x10^{-6}
	Half-metal drum	0.876	0.024	0.035	0.102	0.227	0.217	ND	1.484	55x10^{-4}	1.27 x10^{-6}
	Banda	0.812	0.024	0.035	0.104	0.230	0.223	ND	1.431	51x10^{-4}	1.27 x10^{-6}
	Altona	0.613	0.024	0.029	0.109	0.253	0.229	ND	1.260	38x10^{-4}	1.06 x10^{-6}
	FN23	0.406	0.019	0.027	0.127	0.250	0.221	ND	1.053	25x10^{-4}	0.99 x10^{-6}
G. morhua	Raw	0.494	0.019	0.019	0.062	0.167	0.216	ND	0.980	31x10^{-4}	0.70 x10^{-6}
	Half-metal drum	0.876	0.024	0.029	0.109	0.262	0.266	ND	1.568	55x10^{-4}	1.06 x10^{-6}
	Banda	0.964	0.024	0.023	0.104	0.249	0.261	ND	1.628	60x10^{-4}	0.85 x10^{-6}
	Altona	0.741	0.019	0.019	0.096	0.253	0.258	ND	1.389	46x10^{-4}	0.70 x10^{-6}
	FN23	0.494	0.019	0.019	0.105	0.192	0.252	ND	1.084	31x10^{-4}	0.70 x10^{-6}

obtained differed from those reported by Ghosh *et al.* (2022) and Saputri *et al*. (2023), who found HI > 1 for raw *Epinephelus hexagonatus* and *Cirrhinus cirrhosus*. The difference could be explained by environmental pollution levels and the impact of processing methods. Long-term consumption of *E. fimbriata (r*aw and smoked*)*, *S. afra* (smoked) and *G. morhua* (smoked) might pose some health problems; so it is imperative to monitor levels of these metal residues.

Due to their high carcinogenic risk, the target cancer risk (CR) of Cd and Hg was calculated as shown in Table 8. CR value of Cd and Pb ranged from (10 to 60) × 10^{-4} and (0.49 to 1.41) × 10^{-6}, respectively. These results showed that CR values were within the acceptable range of 10^{-6} to 10^{-4} for Pb, and consumers were less prone to carcinogenic risks. However, the CR values for Cd were above 10^{-4}. Therefore, these fish could pose carcinogenic risks to humans through consumption. Similar results were found by Sabouang *et al*. (2022), on raw *Sardinella,* while Uguru *et al.* (2023) reported CR<10^{-4} for Cd and Pb on smoked *Oreochromis niloticus*. High metal residues in raw fish suggest contamination of their environment, and this should be a serious concern.

Conclusion

The nutritional value and health risk assessment of metal residues in three fish species smoked using various kilns were studied. The three raw fish species were good sources of proteins, fats, minerals and the oils extracted from them are of good quality. The four smoking processes led to an increase in mineral contents (Ca, Na, P, K, Mg, Zn, Fe, Cu, Mn). The Na/K ratio provides assurance regarding their consumption by hypertensive patients. Lipid oxidation was revealed by increases in several oil indexes such as the peroxide and TBARS. However, the values were below the maximum limits set by the standard, confirming their nutritional quality. The concentrations of metal residues remained below the recommended limits. However, cadmium posed a carcinogenic risk with prolonged consumption of these fish. To reduce the risks, it is important to inform the population about the toxicity associated with the long-term overconsumption of these fish. The FN23 ensured better heat distribution in the smoking chamber, resulting in fish with a uniform and shiny color appreciated by consumers. This kiln also reduced contamination linked to metal oxidation by heat. Considering the benefit/risk ratio, the FN23 represents a good alternative for ensuring the sanitary quality of smoked fish. Ultimately, it is important for processors to adopt the use of FN23 kiln and the consumers to choose fish smoked with FN23.

CONFLICT OF INTEREST

The authors declare that they have no competing interests related to this article.

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