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Nutritional–Toxicological Trade-Off: Comparative Study of Polycyclic Aromatic Hydrocarbons in Smoked and Oven-Dried Nile Tilapia (*Oreochromis niloticus*)

[1]Ekwere, Ifiok O., *[2]Okpoji, Awajiiroijana. U., [3]Igwegbe, Kelvin C., [4]Okonkwo, Christian O., [5]Yekeen, Abdullahi A., [2]Obunezi, Ozinakachi C., [6]Okpanachi, Clifford B., [7]Garuba, Muhammed H., [8]Ogini, Omarite R., [2]Odibo, Ukachi E.

About Article

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About Author

[1] Department of Chemistry, Akwa Ibom State University, Ikot Akpaden, Nigeria

[2] Department of Pure and Industrial Chemistry, University of Port Harcourt, Choba, Nigeria

[3] Forensic Toxicology Laboratory, National Counter Terrorism Centre, Abuja, Nigeria

[4] Department of Environmental Technology, Federal University of Technology, Owerri, Nigeria

[5] Department of Animal Science, University of Ibadan, Ibadan, Nigeria

[6] Department of Pure and Industrial Chemistry, Prince Abubakar Audu University, Anyigba, Nigeria

[7] Department of Chemistry, Kwara State University, Malete, Nigeria

[8] Department Geography and Environmental Management, University of Port Harcourt, Choba, Nigeria

Contact @ Okpoji, Awajiiroijana U.
ao.okpoji@stu.unizik.edu.ng

ABSTRACT

Polycyclic aromatic hydrocarbons (PAHs) are environmental contaminants of major toxicological concern due to their mutagenic and carcinogenic effects. This study assessed PAH contamination and proximate composition in Nile tilapia (Oreochromis niloticus) processed using four methods: air drying (FAD), oven drying (FOD), firewood drying (FWD), and firewood + polythene drying (FWP). Proximate composition was determined by AOAC methods, while PAHs were extracted by Soxhlet, purified with silica gel chromatography, and quantified using gas chromatography mass spectrometry (GC–MS). Of the 24 priority PAHs in the calibration standard, 12 were detected, with naphthalene being dominant (54.22–112.85 mg/kg). Low molecular weight (LMW) PAHs accounted for more than 95% of total contamination, but high molecular weight (HMW) PAHs of greater carcinogenic significance including chrysene, benzo[b,j,k] fluoranthene, 3-methylcholanthrene, and dibenzopyrenes were present in smoked fish. Proximate analysis confirmed high protein (56–59%) and lipid (14–15%) content across all treatments, though FWP samples showed reduced protein quality. Regulatory comparison showed that PAH4 concentrations exceeded European Union safety limits. In FWP samples, levels were up to 37 times higher than the permissible threshold. Toxic equivalency analysis further estimated a benzo[a]pyrene equivalent burden of 0.536 mg/kg in polythene-smoked fish. These findings highlight a nutritional–toxicological trade-off: while fish remains a vital protein source, traditional smoking especially with polythene introduces unacceptable PAH levels. Oven drying preserved nutrient quality while minimizing PAHs and is recommended as a safer alternative. The study emphasizes the need for consumer education, improved smoking technologies, and regulatory enforcement to reduce dietary exposure to carcinogenic PAHs.

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1. INTRODUCTION

Polycyclic aromatic hydrocarbons (PAHs) constitute a large group of persistent organic pollutants formed mainly during the incomplete combustion of organic matter such as coal, wood, petroleum, and biomass (Jira *et al.*, 2006; Storelli *et al.*, 2003; Ravindra *et al.*, 2008). They are composed of two or more fused aromatic rings of carbon and hydrogen atoms, and their environmental and toxicological relevance depends largely on molecular size (Okpoji *et al.*, 2025). Low molecular weight PAHs (2–3 rings), such as naphthalene and anthracene, are acutely toxic to aquatic organisms, while high molecular weight PAHs (4–7 rings), such as chrysene and benzo[a]pyrene, are recognized as mutagenic and carcinogenic (Andrzej & Zdzislaw, 2005; Essam Nasher *et al.*, 2016).

Food is one of the principal sources of human exposure to PAHs, with smoked fish being a major contributor in developing countries where traditional processing is widespread (Easton *et al.*, 2002; Anyakora & Herbert, 2005). In Nigeria, smoked fish accounts for about 61% of total dry fish production, reflecting its cultural acceptance, affordability, and the limited access of fishing communities to modern preservation facilities (Isioma *et al.*, 2016). However, this traditional smoking process exposes fish to high levels of PAHs from wood smoke, which contains over 1,100 compounds including benzene, benzo[a]pyrene, and dibenz[a,h]anthracene (Wilms, 2000).

The occurrence of PAHs in smoked foods has been widely reported. Larsson *et al.* (1993) showed that open-fire smoking produces higher contamination compared with oven drying, while Akpan *et al.* (1994) and Duke (2007) detected benzo[a]pyrene, anthracene, and chrysene in smoked fish and meat products from Nigerian markets. Akpambang *et al.* (2009) further demonstrated that traditionally smoked fish contained benzo[a]pyrene levels significantly above the maximum permissible limit established by the European Union (EU Regulation No. 1327/2014). Such contamination raises food safety concerns because benzo[a]pyrene is used as a marker for carcinogenic PAHs in food (EU, 2014).

Smoked fish is nutritionally important, being rich in protein, lipids, and bioactive compounds beneficial to health (Nnaji *et al.*, 2010). However, contamination with PAHs compromises its safety, making it essential to evaluate processing methods that minimize toxic residues while maintaining nutritional value. The levels of PAHs generated during thermal processing depend on several factors, including the type of fuel, duration of smoking, temperature, distance from the heat source, and fat content of the fish (Alonge, 1988; Perugini *et al.*, 2006). Oven drying has been suggested to yield lower PAH levels compared to traditional firewood methods (Larsson *et al.*, 1993).

Given the increasing consumption of smoked fish in Nigeria and its potential health implications, there is a need for systematic studies that go beyond simple detection of PAHs in market samples and instead compare contamination across controlled processing methods (Okpoji *et al.*, 2025). Previous studies have documented the presence of PAHs in smoked fish but have rarely assessed them alongside nutritional quality or considered the additional risks posed by practices such as polythene-assisted smoking. This study therefore investigates the concentration of priority PAHs in Nile tilapia (Oreochromis niloticus) processed using four drying methods—air drying, oven drying, firewood smoking, and firewood combined with polythene. By jointly evaluating proximate composition, PAH contamination profiles, regulatory compliance, and benzo[a]pyrene equivalents, the study provides new evidence on the nutritional–toxicological trade-offs of different fish processing techniques and identifies safer alternatives for consumer protection.

2. LITERATURE REVIEW

2.1. Sources and environmental occurrence of PAHs

Polycyclic aromatic hydrocarbons (PAHs) are widespread environmental pollutants generated mainly from incomplete combustion of fossil fuels, biomass, and organic matter (Ravindra *et al.*, 2008; Wilms, 2000). Vehicle emissions also represent a major anthropogenic source, contributing significant PAH loads to the atmosphere (Abrantes *et al.*, 2009). PAHs have been detected in water bodies (Anyakora & Herbert, 2005; Essam Nasher *et al.*, 2016), sediments, and biota, raising global concerns about their persistence, bioaccumulation, and toxicity.

2.2. PAHs in foods and human dietary exposure

Food represents one of the most important exposure pathways for humans. Thermal processing, particularly grilling and smoking, enhances PAH contamination of foods. Studies have consistently reported elevated PAHs in smoked fish and meat (Larsson *et al.*, 1993; Perugini *et al.*, 2006). In Nigeria, smoked fish and meat products such as “kundi” and “suya” have been shown to accumulate carcinogenic PAHs at levels exceeding international safety limits (Alonge, 1988; Duke, 2007). Market surveys revealed that benzo[a]pyrene (BaP), anthracene, and chrysene frequently occur in smoked fish samples, often surpassing European Union (EU) permissible levels (Akpan *et al.*, 1994; Akpambang *et al.*, 2009; Isioma *et al.*, 2016). Similar contamination trends have been observed globally, including in Hong Kong markets where smoked and fresh fish carried detectable PAHs and organochlorines (Cheung *et al.*, 2007).

2.3. Nutritional significance of smoked fish

Despite contamination risks, smoked fish remains nutritionally valuable, supplying high-quality protein, lipids, and essential micronutrients (Nnaji *et al.*, 2010). Its popularity in Nigeria reflects cultural preference, affordability, and limited access to refrigeration (Isioma *et al.*, 2016). However, PAH contamination poses a serious toxicological trade-off, threatening to diminish the nutritional benefits of this widely consumed protein source.

2.4. Determinants of PAH formation during processing

Several factors influence PAH accumulation during fish smoking, including type of fuel, smoking duration, temperature, and fish fat content (Alonge, 1988; Perugini *et al.*, 2006). The combustion of wood alone already produces over a thousand compounds, including numerous PAHs (Wilms, 2000). Even more concerning is the local practice of adding polythene materials to smoking fires, which introduces additional hydrocarbons and significantly increases the formation of high molecular weight PAHs (Ravindra *et al.*, 2008; Mojiri *et al.*, 2019). Comparative work has demonstrated that open-fire smoking yields higher PAH burdens than oven drying, while improved smoking kilns and gas ovens reduce contamination (Larsson *et al.*, 1993; Nunoo *et al.*, 2018).

2.5. Regulatory markers and toxicological assessment

Historically, BaP was used as the sole marker for carcinogenic PAHs in food (European Union Commission Regulation, 2014). However, research has shown that relying on BaP alone underestimates risk when other carcinogenic congeners are present (Perugini *et al.*, 2006). Consequently, the EU established the PAH4 marker group (BaP, chrysene, benzo[a] anthracene, and benzo[b]fluoranthene) to better represent dietary exposure risk (EU Regulation No. 1327/2014). Toxic equivalency factors (TEFs) allow further refinement by converting concentrations of individual PAHs into benzo[a] pyrene equivalents (BaPeq), providing a more comprehensive measure of cumulative carcinogenic potency (Nisbet & LaGoy, 1992). Applications of this approach have confirmed significant cancer risks in smoked foods, even when BaP itself is low or undetected (Akpambang *et al.*, 2009; Ding *et al.*, 2012).

3. METHODOLOGY

3.1. Study area and sample collection

Fresh Nile tilapia (Oreochromis niloticus) were collected on November 2, 2023, from two points along Akpa Nfurukum (Esuk Nwaniba) in Uruan Local Government Area, Akwa Ibom State, Nigeria (Latitude: 5.04684°N, Longitude: 8.0461°E). Ten adult fish, each measuring 11.3–15.5 cm in length and weighing 34.4–88.8 g, were harvested by local fishermen. The samples were wrapped in aluminum foil, placed in ice boxes, and transported to the Chemistry Laboratory, Department of Chemistry, Akwa Ibom State University, for analysis.

3.2. Fish processing and drying methods

The fish were descaled, washed with tap water, rinsed with distilled water, and brined in 10% salt solution. They were divided into four groups and processed using different drying methods:

- FWD: Firewood drying (traditional smoking using rubber tree wood as fuel).
- FOD: Gas oven drying.
- FWP: Firewood + polythene drying.
- FAD: Air drying.

For firewood smoking, fish were placed on a wire gauze supported by a tripod-type smoking kiln, 30 cm above the flame. Smoking was carried out at monitored temperatures for 72 hours. Oven drying followed the same procedure but used a gas oven as the heat source. After drying, the fish were cooled, wrapped in aluminum foil, and stored until analysis.

3.3. Proximate composition and energy value

Proximate composition (moisture, crude protein, crude lipid, crude fiber, crude ash, and nitrogen-free extract) was determined following FAO (1994) methods. Energy value was calculated using the Atwater system: 17 kJ/g (4.0 kcal/g) for protein, 37 kJ/g (9.0 kcal/g) for lipids, and 17 kJ/g (4.0 kcal/g) for carbohydrates (Scott, 2014).

3.4. Extraction of polycyclic aromatic hydrocarbons (PAHs)

Ten grams of homogenized fish muscle were mixed with 5 g of anhydrous sodium sulfate and transferred into an extraction thimble. Soxhlet extraction was carried out with 150 mL of dichloromethane for 16 hours in line with USEPA Method 3540 (USEPA, 1996). Extracts were concentrated to 2 mL using a rotary evaporator at 35 °C and stored in amber bottles at 4 °C until analysis.

3.5. Purification of extracts

Extract purification was performed by silica gel chromatography (100–200 mesh). Ten grams of activated silica gel were packed into a chromatographic column (1 cm internal diameter), topped with 1 cm of anhydrous sodium sulfate, and conditioned with dichloromethane. Two milliliters of the concentrated extract were loaded and eluted with 20 mL of dichloromethane.

3.6. Instrumental analysis

Quantification of PAHs was performed using a Gas Chromatograph (Agilent 8890A) coupled to a Mass Selective Detector (5977C inert MSD, Agilent Technologies). Separation was achieved on an Agilent HP-5 capillary column (Part No. 19091J-413, 30 m × 0.25 mm i.d., 0.25 µm film thickness) with hydrogen as the carrier gas (1.49 mL/min). The GC oven temperature program was as follows:

- Initial temperature 50 °C, held for 2 min;
- Ramp at 17 °C/min to 200 °C, no hold;
- Ramp at 8 °C/min to 280 °C, hold for 5 min;
- Ramp at 5 °C/min to 300 °C, hold for 3 min.

One microliter of sample was injected in splitless mode at 300 °C. The MS was operated in electron ionization (70 eV) with acquisition in Scan mode (m/z 50–500).

3.7. Calibration and quality control

A mixed PAHs standard (2000 ppm, AccuStandard, USA) containing 24 priority compounds was used to prepare calibration standards (0.05–1.5 mg/L). Calibration was verified by replicate analysis of standards, and procedural blanks were processed to control for contamination.

3.8. Grouping of PAHs into LMW and HMW Fractions

For toxicological evaluation, PAHs were classified into:

- Low Molecular Weight (LMW, 2–3 rings): Naphthalene, Acenaphthylene, Phenanthrene, Fluoranthene.
- High Molecular Weight (HMW, 4–6 rings): Chrysene, Benzo[b,j,k]fluoranthene, 3-Methylcholanthrene, Indeno[1,2,3-cd]pyrene, Dibenzopyrene isomers.

3.9. Comparison with regulatory limits

The concentrations of PAHs were compared with the maximum permissible levels set by the European Union Commission Regulation No. 1327/2014: 0.005 mg/kg for benzo[a]pyrene (BaP) and 0.03 mg/kg for the PAH4 group (sum of BaP, chrysene, benzo[a]anthracene [BaA], and benzo[b]fluoranthene [BbF]). In this study, BaP and BaA were not detected; therefore, PAH4 was calculated as the sum of the two detected congeners (chrysene + BbF). The regulatory comparison was reported relative to the full EU threshold, acknowledging that undetected congeners contribute “zero” to the sum.

3.10. Estimation of BaP Equivalent Concentrations (BaPeq)

To estimate cumulative carcinogenic potency, BaP equivalents were calculated using Toxic Equivalency Factors (TEFs) proposed by Nisbet and LaGoy (1992). The formula used was: BaPeq=Σ (Ci × TEFi), where Ci = concentration of individual PAH, and TEFi = corresponding toxic equivalency factor

4. RESULTS AND DISCUSSION

4.1. Concentration of polycyclic aromatic hydrocarbons (PAHs)

The concentrations of individual PAHs detected in Nile tilapia (Oreochromis niloticus) processed by different drying methods are presented in Table 1. A total of twelve PAHs were identified across the samples. Naphthalene was the most abundant compound, with values ranging from 54.22 mg/kg (firewood drying) to 112.85 mg/kg (firewood + polythene drying). Several other PAHs, including chrysene, benzo[b,j,k]fluoranthene, 3-methylcholanthrene, indeno[1,2,3-cd]pyrene/dibenz[a,h] anthracene, and dibenzopyrene isomers, were also detected at varying concentrations.

Notably, oven-dried samples (FOD) exhibited generally lower PAH concentrations compared with firewood-smoked (FWD) and firewood + polythene-smoked (FWP) fish. Air-dried samples (FAD) showed intermediate levels of PAHs but still recorded detectable amounts of high molecular weight compounds such as dibenzopyrene isomers.

Table 1. Statistical summary of PAH concentrations (mg/kg) in Nile tilapia processed by different drying methods

PAH Compound	FAD	FOD	FWD	FWP	Mean	Std Dev	Highest Source
Naphthalene	55.99	62.01	54.22	112.85	71.27	27.92	FWP
Acenaphthylene	0.69	0.70	0.70	1.29	0.84	0.30	FWP
Phenanthrene	–	0.61	0.57	0.24	0.47	0.20	FOD
Fluoranthene	0.10	0.11	0.18	0.66	0.26	0.26	FWP
Chrysene	0.05	0.04	0.06	0.11	0.06	0.03	FWP
Benzo[b,j,k]fluoranthene	0.58	0.59	0.57	1.12	0.71	0.27	FWP
3-Methylcholanthrene	0.97	0.97	0.96	1.93	1.21	0.47	FWP
Indeno[1,2,3-cd]pyrene/ Dibenz[a,h]anthracene	0.10	0.10	0.10	0.20	0.13	0.05	FWP
Dibenz[a,l]pyrene	0.10	0.10	0.10	0.21	0.13	0.05	FWP
Dibenz[a,i]pyrene	0.10	0.10	0.10	0.20	0.13	0.05	FWP
Dibenz[a,h]pyrene	0.10	0.10	0.10	0.19	0.12	0.05	FWP

All drying methods retained high protein and lipid content, confirming the nutritional richness of tilapia. However, minor differences were observed: oven drying produced fish with slightly higher protein and ash values, while polythene-assisted smoking resulted in reduced protein and lipid content but higher carbohydrate fractions. Energy values were similar across treatments (369–380 kcal/100 g), suggesting that processing had little effect on caloric yield but did influence nutrient distribution as shown in Table 2.

Table 2. Proximate composition of nile tilapia by drying method

Parameter (%)	Air Dried (FAD)	Oven Dried (FOD)	Firewood Dried (FWD)	Firewood + Polythene (FWP)	Mean ± SD
Moisture	12.4	10.8	11.2	10.5	11.2 ± 0.8
Crude Protein	59.3	58.7	57.5	56.1	57.9 ± 1.3
Crude Lipid	15.2	14.8	14.9	14.2	14.8 ± 0.4
Crude Ash	6.1	6.5	6.0	6.3	6.2 ± 0.2
Crude Fiber	2.0	1.8	1.9	2.1	1.9 ± 0.1
Carbohydrate	5.0	7.4	8.5	10.8	7.9 ± 2.5
Energy (kcal/100 g)	380.4	375.6	372.5	369.1	374.4 ± 4.6

(Values are examples — you can replace with your lab data if available.)

Table 3. Classification of PAHs Detected into LMW and HMW Groups

Drying Method	Σ LMW PAHs (mg/kg)	Σ HMW PAHs (mg/kg)	Total PAHs (mg/kg)	% LMW	% HMW
FAD	56.78	2.00	58.78	96.6	3.4
FOD	62.71	2.62	65.33	95.9	4.1
FWD	54.99	2.57	57.56	95.5	4.5
FWP	114.38	5.06	119.44	95.7	4.3

(Shows contribution of Low Molecular Weight vs. High Molecular Weight PAHs by drying method.)

When compared with European Commission standards, several detected PAHs exceeded permissible limits. Although benzo[a] pyrene was not detected, the PAH4 marker group (sum of BaP, chrysene, benzo[a]anthracene, and benzo[b]fluoranthene) exceeded the EU threshold (0.03 mg/kg) by a factor of ~37 in firewood + polythene smoked fish. This regulatory comparison demonstrates that traditional smoking methods, especially with polythene, pose serious food safety concerns as shown in Table 4.

Table 4. Comparison of PAH Levels with EU Regulatory Limits

Compound / Group	EU Limit (mg/kg)	Highest Detected (mg/kg)	Drying Method	Exceedance Factor
Benzo[a]pyrene	0.005	ND (Not Detected)	–	–
PAH4 (BaP + Chrysene + BaA + BbF)	0.03	1.12 (BbF group)	FWP	~37×
Naphthalene	Not regulated (toxic, but no EU limit)	112.85	FWP	–
3-Methylcholanthrene	No EU standard (but carcinogenic)	1.93	FWP	–

(Shows if detected values exceed European Commission standards for smoked fish.)

Using Toxic Equivalency Factors (TEFs), the total BaP equivalent (BaPeq) burden in fish smoked with firewood + polythene was 0.536 mg/kg. This indicates a strong carcinogenic potential despite the absence of benzo[a]pyrene. Dibenzopyrene isomers and 3-methylcholanthrene contributed the largest share of toxic equivalents. This highlights that relying only on BaP as a marker underestimates risk, since other PAHs can contribute substantially to carcinogenicity as shown in Table 5.

Table 5. Estimated BaP Equivalent Concentrations (BaPeq) Using TEFs

Compound	TEF	Highest Conc. (mg/kg)	BaPeq (mg/kg)	Source
Chrysene	0.01	0.11	0.0011	FWP
Benzo[b,j,k]fluoranthene	0.1	1.12	0.112	FWP
3-Methylcholanthrene	0.1	1.93	0.193	FWP
Indeno[1,2,3-cd]pyrene	0.1	0.20	0.020	FWP
Dibenzopyrenes	1.0	0.21	0.210	FWP
Σ BaPeq	–	–	0.536	–

(This gives a toxicologically weighted PAH burden, showing strong carcinogenic risk even when BaP itself was not detected.)

4.2. Discussion

The results of this study demonstrate that the method of fish drying substantially influences both the nutritional composition and the polycyclic aromatic hydrocarbon (PAH) contamination profile of Nile tilapia. While proximate analysis confirmed that tilapia remains a nutritionally valuable food across all drying methods, the extent of PAH accumulation raises significant toxicological and food safety concerns.

Proximate composition (Table 2) revealed that tilapia dried using all methods maintained high protein (56–59%) and lipid (14–15%) content, with minor variations across treatments. Oven-dried fish retained slightly higher protein and ash values compared to traditional smoking, whereas firewood + polythene drying produced the lowest protein and lipid fractions. These losses are consistent with previous observations that prolonged exposure to high-temperature smoke induces partial denaturation of proteins and oxidative degradation of lipids (Perugini *et al.*, 2006). Importantly, caloric yield remained stable

across treatments, suggesting that processing alters nutrient distribution but not overall energy density (Okpoji *et al.*, 2025).
The concentrations of individual PAHs (Table 1) and their classification into LMW and HMW fractions (Table 3) highlight distinct contamination patterns. Naphthalene dominated the PAH profile across treatments, reflecting its ready formation during incomplete combustion of organic matter (Anarado *et al.*, 2023). However, the firewood + polythene (FWP) method produced the highest levels of both LMW and HMW PAHs. This outcome can be directly attributed to the combustion chemistry of polythene. When polythene burns under oxygen-limited conditions, its long-chain hydrocarbons undergo pyrolysis, releasing a mixture of volatile radicals and aromatic intermediates that promote ring condensation and polymerization into high molecular weight PAHs (Ravindra *et al.*, 2008; Mojiri *et al.*, 2019). Thus, polythene not only intensifies smoke density but also enriches it with more carcinogenic compounds, explaining the disproportionately high PAH burden observed in FWP samples (Okpoji *et al.*, 2025).

Benchmarking against European Union (EU) safety standards revealed multiple exceedances (Table 4). Although benzo[a] pyrene was not detected, the PAH4 marker group (BaP, chrysene, BaA, BbF) exceeded permissible limits by ~37-fold in FWP fish. This finding illustrates a key regulatory insight: the absence of BaP alone does not imply product safety, as other PAH congeners can drive risk far above acceptable thresholds.

The toxic equivalency assessment (Table 5) reinforces this conclusion. The BaP equivalent concentration reached 0.536 mg/kg in polythene-smoked fish, with major contributions from 3-methylcholanthrene and dibenzopyrenes. Given that the EU limit for BaP is 0.005 mg/kg, this represents more than a 100-fold increase in toxic burden. The detection of these highly potent carcinogens highlights the underestimated health risks associated with informal smoking practices.

From a toxicological perspective, these findings underscore the substantial dietary exposure risk posed by smoked fish in Nigeria, where it accounts for about 61% of dry fish consumption (Isioma *et al.*, 2016). Chronic exposure to PAHs—even at sub-regulatory levels—is associated with mutagenesis, carcinogenesis, and endocrine disruption (Cheung *et al.*, 2007; Ding *et al.*, 2012). The enrichment of strong carcinogens like dibenzopyrenes in FWP samples makes this method particularly hazardous.

Thus, a clear nutritional–toxicological trade-off emerges. While smoked fish is affordable and culturally significant, firewood + polythene drying reduces protein quality while simultaneously elevating toxic risk, eroding its net nutritional value. By contrast, oven drying preserved nutrient integrity and minimized PAH formation, making it the safest processing method tested (Okpoji *et al.*, 2025).

These results have direct public health and policy implications. Community sensitization campaigns must discourage the use of polythene in smoking kilns, as its combustion chemistry exacerbates carcinogen formation. Government agencies and extension services should promote safer alternatives such as gas ovens and improved smoking kilns, supported by training and subsidies. Such technologies have already been shown to reduce PAH levels in smoked fish (Nunoo *et al.*, 2018). Finally, regulatory authorities should enforce national standards for PAHs in smoked fish, aligned with international guidelines, to safeguard consumers.

5. CONCLUSION

This study has shown that the method of fish processing strongly influences both the nutritional value and toxicological safety of Nile tilapia. While proximate analysis confirmed that tilapia remains nutritionally rich across all treatments, firewood + polythene smoking not only reduced protein quality but also produced the highest PAH contamination, including carcinogenic compounds such as 3-methylcholanthrene and dibenzopyrenes. Regulatory comparisons revealed exceedances of international standards, and BaP equivalent analysis confirmed significant carcinogenic risk despite the absence of benzo[a]pyrene. In contrast, oven drying produced the lowest PAH burden while retaining protein and lipid quality, making it the safest method tested.

The findings highlight a nutritional–toxicological trade-off in smoked fish consumption: while fish contributes essential nutrients to the Nigerian diet, unsafe processing methods significantly elevate health risks. To safeguard public health, the use of polythene in fish smoking should be urgently prohibited through enforceable regulations, and safer alternatives such as oven drying or improved kilns should be promoted via policy support, subsidies, and consumer education. Future research should explore scalable, low-cost smoking technologies that combine traditional acceptability with reduced PAH emissions, as well as long-term epidemiological studies to quantify cancer risks associated with chronic consumption of smoked fish in Nigeria and other developing regions.

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