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Reducing polycyclic aromatic hydrocarbon contamination in smoked fish in the Global South: a case study of an improved kiln in Ghana

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Abstract

BACKGROUND: Smoked fish is a major source of animal protein in developing countries. It is largely produced by hot-smoking on traditional kilns using fuelwood. This practice is associated with high polycyclic aromatic hydrocarbon (PAH) contamination in products, with consequences for public health. An improved kiln, comprising the FAO-Thiaroye Technique (FTT), has been introduced by the Food and Agriculture Organization of the United Nations to address such a concern. The present study investigated the efficacy of the FTT in Ghana through comparative fish smoking experiments with traditional kilns followed by determination of PAH levels [benzo(a)pyrene (BaP) and PAH4] in the products by gas chromatography–mass spectrometry. For each kiln, the effect of smoking fuel type on PAH contamination was determined. The impact of the design characteristics of the FTT on the levels of the compounds was also determined.

RESULTS: Mean BaP and PAH4 levels in the FTT products were up to 1.8 and 7.6 $\mu g\ kg^{-1}$, respectively, whereas the corresponding levels in traditional kiln products were up to 70 and 395 $\mu g\ kg^{-1}$. PAH levels in FTT products were below European Union regulatory limits, whereas levels in traditional kiln products exceed such limits by up to 33-fold. Across kiln types, the use of wood fuels caused higher PAH contamination compared to the use of fully-lit charcoal as an alternative fuel.

CONCLUSION: The improved kiln (FTT) is efficacious in yielding smoked fish with a PAH content lower than the levels in traditional kiln products and also below current regulatory limits. Kiln design and type of processing fuel have significant impacts on PAH contamination during fish smoking.

Supporting information may be found in the online version of this article.

Keywords: smoked fish; polycyclic aromatic hydrocarbons; smoking kilns; food safety

INTRODUCTION

Smoked fish is a significant contributor to food and nutrition security in the Global South. It is estimated that Africa and Asia alone account for more than 60% of global smoked fish production.[1] It is further estimated that up to 80% of domestic fish catch in Africa is processed by traditional smoking methods.[2] Other methods of traditional processing include sun-drying, deep frying, fermentation and salting.[3–5] Of these methods, traditional smoking is the most practiced.[6,7]

Although several different types of traditional fish smoking kilns may be identified in the Global South, the operational principles supporting their use are essentially the same: fish is cooked over dry heat produced by burning fuelwood. In the process, the product is flavoured by smoke emanating from the heat source. In many parts of Africa, two main types of kilns can be identified, namely the metal drum kiln and the Chorkor smoker (Fig. 1).[4,8,9] The latter was developed in Ghana in the late 1960s as an improvement on the former through the collaborative efforts of the Food Research Institute of Ghana, the Food and Agriculture Organization of the United Nations (FAO), and fish processors in Chorkor, a fishing peri-urban community in Ghana's capital

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Figure 1. Traditional kilns for fish smoking in Ghana. Metal drum kiln (left) and Chorkor smoker (right).

city.[8] The drum kiln has low capacity, low fuel efficiency, requires excessive product handling during processing and predisposes processors to burn injuries. Its low capacity invariably translates into high post-harvest losses during bumper seasons. These shortfalls were adequately addressed by the introduction of the Chorkor smoker, which currently enjoys widespread use across Africa.

Although the Chorkor smoker improved product throughput and reduced the drudgery associated with traditional fish smoking, similar to the drum kiln, it also operates on fuelwood. This practice is associated with high levels of carcinogens known as polycyclic aromatic hydrocarbons (PAHs) in products.[10–13] PAHs are organic compounds with genotoxic and mutagenic potential that are produced when organic materials are exposed to high temperatures and/or pressures.[10,14–16] They are also produced when food is processed at high temperatures. In hot-smoking with fuelwood, smoke coupled with high processing temperatures results in several PAHs on products.[17] With respect to food safety, the PAHs of interest are benzo(a)pyrene (BaP), chrysene, benzo(a)anthracene and benzo(b)fluoranthene, collectively known as PAH4.[10,18] Human exposure to PAHs occurs via inhalation, dermal contact and ingestion through food. Among these, food is considered to be the major route of exposure for non-smokers.[10] In the European Union (EU,) regulatory limits of 2 and 12 $\mu g\ kg^{-1}$ have been set for BaP and PAH4, respectively, in smoked meat and fish products.[19]

Along with Nigeria, Cote d'Ivoire and Cameroun, Ghana is a major exporter of smoked fish to the EU.[20] Product detention at ports of entry are not uncommon. In the UK alone, it has been estimated that approximately 70% of detained consignments are destroyed.[20] In the EU, several notifications on the Rapid Alert System for Food And Feed (RASFF) on smoked fish from Africa have been the result of unacceptable PAH levels in the products. Studies have also reported high levels of these compounds in smoked fish on informal markets on the continent.[21–23] These product rejections as a result of the unsatisfactory safety quality of the fish products could be considered as a post-harvest loss.[24] The PAH problem therefore presents both public health and economic challenges to the region.

To address the concern, an improved kiln called FAO-Thiaroye Technique (FTT) was developed in Senegal through the collaborative efforts of the FAO and the Senegal National Training Centre for Fisheries and Aquaculture Technicians (CNFTPA).[25,26] The design characteristics of the FTT (Fig. 2) are in line with the Codex Alimentarius Commission (CAC) guidelines for reducing PAH in smoked products.[11,27] The referenced CAC texts identify the use of wood fuels, distance between food being smoked and heat source, fat content of food, smoking duration, smoking temperature, and cleanliness and maintenance of equipment as important parameters affecting the occurrence and levels of PAHs in smoked products. By their design, the traditional kilns enhance the possibility of these parameters to facilitate the occurrence of PAH in smoked products, whereas the FTT works to the contrary. By its design, the FTT allows a shift from fuelwood to fully-lit charcoal as fuel, prevents fish fat dripping into the heat source during processing, ensures indirect contact between the heat source and the product, and allows indirect smoke flavouring with filtered smoke.[25,26]

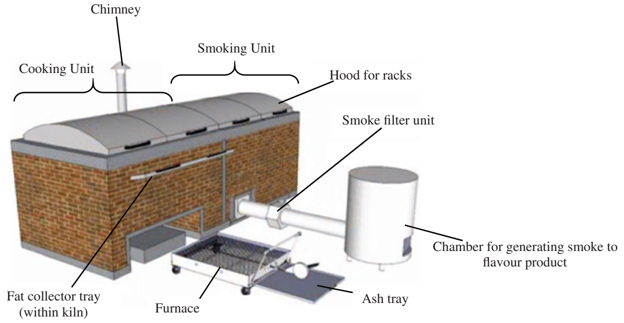

Figure 2. Schematic of FTT (Ndiaye *et al.*[25]).

Operationally, fish smoking on the FTT is separated into two distinct phases. The fish is first cooked over dry heat from a combination of fully-lit charcoal and heat retention stones (such as broken clay pottery), after which it is transferred to another unit and exposed to filtered smoke for approximately 30 min.[25] The smoke for flavouring the product is produced from moistened, lit sugarcane bagasse. Moistened luffa fibre (sponge) is used as filter to trap tar particles and to potentially reduce PAH deposits on the product.[25] By contrast, for traditional kilns, direct heat and unfiltered smoke from fuelwood simultaneously cook and flavour the fish, respectively (Fig. 1). Fish fat also drip into the heat source and contribute to PAH release by lipid pyrolysis.[28] As a result of the aforementioned features, the FTT was expected to yield smoked products with lower PAH levels than traditional kilns used in developing countries. The present study investigated the efficacy of the FTT in that regard. Specifically, the impact of kiln type, fuel type, fish product type and kiln design on PAH levels were tested through comparative fish smoking experiments among the FTT, Chorkor smoker and the metal drum kiln.

MATERIALS AND METHODS

Fish species and product types

Frozen *Sardinella* sp. (sardines, informally called 'herring' in Ghana) and *Sphyraena* sp. (barracuda) were procured from cold stores in Tema New Town, a coastal fish processing community in the Greater Accra Region of Ghana. In separate experiments, each fish species was processed into the two forms of smoked fish available in Ghana, namely smoked-soft and smoked-dry fish. The two are distinguished by their smoking duration and final moisture content. Typically, depending on size and volume, smoked-soft fish takes 2–4 h to process and has a final moisture content of ≥ 30%, whereas smoked-dry fish requires 10–18 h processing time and has ≤ 20% moisture content. Some studies have reported 40–50% and 10–15% moisture contents for smoked-soft and smoked-dry fish, respectively.[29]

Fuel types

Conventionally, traditional kilns are fueled with several species of dry wood. Two of the most patronized species in Ghana are *Pterocarpus erinaceus* (locally called '*esa*') and *Azadirachta indica* (neem) (D. Ahadzi, personal communication). In contrast, with FTT, fully lit charcoal first fuels the cooking of fish in a cooking compartment, after which the cooked fish is transferred to an adjoining compartment and flavoured with filtered smoke produced from moistened, lit sugarcane bagasse or coconut husk. To improve fuel efficiency during the cooking step, heat retention stones (such as broken clay pottery) are added to the lit charcoal.[25] The named fuels were used in different combinations in the smoking experiments depending on the study objective under consideration.

Smoking experiments

Three sets of smoking experiments were conducted over a cumulative period of 6 months (non-consecutive days) according to the general process flow shown in Fig. 3. Smoking sessions were performed by women processors with over three decades of experience in traditional fish smoking. Tests were run on actual kilns (not laboratory-scale equipment). For each batch, 18 kg of raw fish was smoked. Each experiment was conducted in five replicates.

Smoking experiments I: comparison of PAH levels in FTT and traditional kiln products

This set evaluated the performance of FTT and traditional kilns as different *systems* for fish smoking vis-à-vis product PAH levels. Traditional kilns were fueled with *P. erinaceus*. The FTT was fueled with fully-lit charcoal and broken pottery for the cooking step and sugarcane bagasse for the indirect smoke flavouring. The effect of product type (smoked-soft and smoked-dry) on PAH levels was also tested.

Smoking experiments II: impact of fuel type on PAH level

In this set of experiments, the effect of processing fuel on PAH levels in smoked-dry *Sardinella* sp. was evaluated across the three kilns. The two wood species (namely *P. erinaceus* and *A. indica*) reported by the processors to be commonly used as fuelwood were tested across the kilns. The Chorkor smoker was also operated to mimic the FTT using fully-lit charcoal and broken pottery to first cook fish, followed by flavouring with smoke from sugarcane bagasse. Products were then tested for their PAH levels.

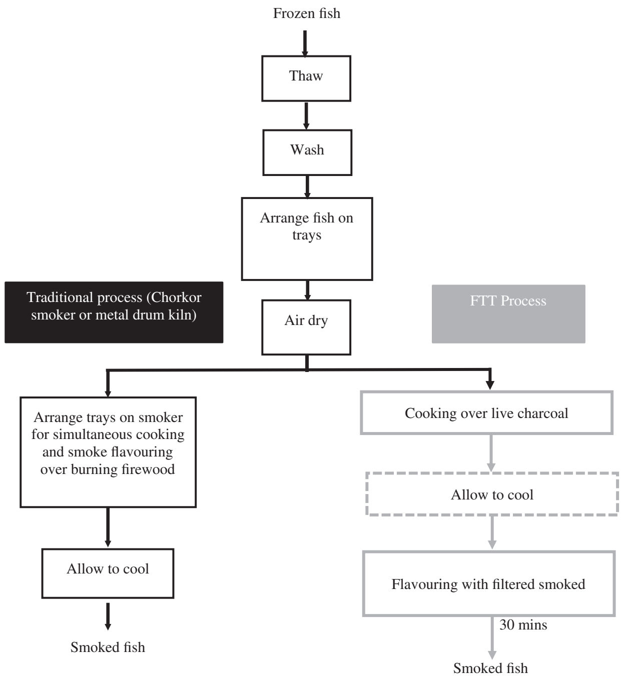

Figure 3. General process flow diagram for hot-smoked fish: traditional kilns *versus* FTT.

Smoking experiments III: impact of FTT parts on PAH levels

The final set was conducted on the FTT only. It determined the effect of the parts of the FTT on PAH level in smoked-dry *Sardinella* sp. Each experiment was conducted in five replicates as follows:

Impact of fat collector on PAH levels. The fat collector in FTT prevents fish fat from dripping into the heat source during processing. The impact of this appendage on PAH level was tested by sampling fish at the end of the cooking step with the tray in place (five replicates) and without the tray in place (five replicates). *Sardinella* sp selected with the advice of experienced traditional fish processors to be fatty based on the season were used for these tests.

Impact of smoke flavouring material on PAH levels. Batches of *Sardinella* sp smoked-dry with FTT were flavoured separately with sugarcane bagasse, coconut husk or *A. indica* smoke, and their PAH levels determined. Experiments were conducted in five replicates for each material.

Impact of smoke filter on PAH levels. This was tested by flavouring smoked-dry *Sardinella sp* with and without the filter in place, after the charcoal cooking step. Smoke for flavouring was generated from sugarcane bagasse and *A. indica*. Filter use on each material was tested in five replicates.

Fish sampling

From the products of each experiment, ten fish were collected and homogenized using a Waring® CB15V Heavy Duty Commercial

Table 1. Mean BaP and PAH4 levels in *Sardinella sp* and *Sphyraena sp* smoked on the FTT and traditional kilns (Experiment Set IL each experiment was conducted in five replicates)

Product	Kiln	Fuel[†]	Mean BaP (μg kg^{-1})	Mean PAH4 (μg kg^{-1})
Fresh *Sardinella* sp.	–	–	ND	ND
Fresh *Sphyraena* sp.	–	–	ND	ND
Smoked-soft *Sardinella* sp.	FTT	Charcoal (for cooking) and sugarcane bagasse (for smoke flavouring)	0.2 ± 0.0 a[‡]	1.5 ± 0.2 a
	Chorkor smoker	*Pterocarpus erinaceus*	26.4 ± 5.1 b	166.9 ± 5.8 b
	Metal drum	*Pterocarpus erinaceus*	11.1 ± 2.0 c	58.1 ± 4.4 c
Smoked-dry *Sardinella* sp.	FTT	Charcoal (for cooking) and sugarcane bagasse (for smoke flavouring)	0.3 ± 0.2 a	2.2 ± 0.7 a
	Chorkor smoker	*Pterocarpus erinaceus*	60.3 ± 3.9 b	394.5 ± 16.5 b
	Metal drum	*Pterocarpus erinaceus*	25.6 ± 2.1 c	135.7 ± 11.3 c
Smoked-soft *Sphyraena* sp.	FTT	Charcoal (for cooking) and sugarcane bagasse (for smoke flavouring)	0.6 ± 0.2 a	3.6 ± 0.9 a
	Chorkor smoker	*Pterocarpus erinaceus*	50.3 ± 1.4 b	270.3 ± 9.7 b
	Metal drum	*Pterocarpus erinaceus*	37.4 ± 7.4 c	167.5 ± 32.7 c
Smoked-dry *Sphyraena* sp.	FTT	Charcoal (for cooking) and sugarcane bagasse (for smoke flavouring)	1.8 ± 1.0 a	7.6 ± 3.0 a
	Chorkor smoker	*Pterocarpus erinaceus*	61.1 ± 6.1 b	360.3 ± 29.4 b
	Metal drum	*Pterocarpus erinaceus*	69.8 ± 4.4 b	327.1 ± 33.6 c

For each product, means in columns with different lowercase letters are significantly different ($P < 0.05$).
ND, not detected.
[†] On the FTT kiln, fully-lit charcoal combined with broken clay pottery was used as the heat source for the cooking step.
[‡] Values for three of five samples were below the LOQ. The values for the remaining two samples were equal to the LOQ.

blender (Waring Commercial, Stamford, CT, USA). Homogenates were vacuum packed in units of 250 g with Henkelman® JUMBO 42 vacuum packaging machine (Henkelman USA, Elmhurst, IL, USA) and kept frozen at −22 °C until analysed. Fresh forms (frozen, unprocessed) of each fish species were similarly sampled.

Determination of PAH

The analyses of PAH were carried out according to an ISO 17025 accredited method in a commercial laboratory (SGS, Hamburg, Germany). For this, 2 g of homogenized fish was treated with 20 mL of hexane and 10 μL of IS solution (a mix of isotopic labelled PAH all at 1 μg mL^{-1}: benzo[a]anthracene-d12, chrysene-d12, benzo[b]fluoranthene-d12, benzo[k]fluoranthene-d12, benzo [a]pyrene-d12, indeno[1,2,3-c,d]pyrene-d12, dibenzo[a,h] anthracene-d14 and benzo[g,h,i]perylene-d12, dibenzo[a,i] pyrene-d14). After shaking, the mixture was held for 1 h in an ultrasound bath and then placed in the freezer for 2 h at −20°C. Frozen fat and solid components were separated by centrifuging for 2 min at 5000 rpm , RCF 3,857 (Hettich Universal 320; Andreas Hettich GmbH & Co. KG, Tuttlingen, Germany). The clear supernatant was transferred to a 10-mL vial and placed into a tray of a Gerstel MPS 2XL Sampler (Gerstel GmbH & Co. KG, Mülheim an der Ruhr, Germany). An in-house and property owned clean-up method was employed using 0.25 g sodium sulphate in an MPS sample tray fitted on a BEKOlut SPE cartridge (BEKOlut GmbH & Co. KG, Hauptstuhl, Germany). After clean up, samples were immediately injected in a gas chromatograph-mass spectrometer. The gas-chromatograph (model 7890B; Agilent Technologies Inc., Santa Clara, CA, USA) consisted of a programmed temperature vaporization injector (50 °C min^{-1}, 500 °C min^{-1} to 320 °C; purge 1 min) and a Model 5977B mass spectrometer (Agilent Technologies Inc.). The column was an J&W DB 35MS (Agilent Technologies Inc.) (30 m × 0.25 mm inner diameter, 0.25 μm film) in an oven with the temperature programmed as: 50 °C, 3 min isotherm, 30 °C min^{-1} to 200 °C, 4 °C min^{-1} to 300 °C, 19 min isotherm. The carrier gas was helium at a constant flow of 1.0 mL min^{-1}. The injection volume was 100 μL.

The quantifier and qualifier ions were: 252.1 and 250.0 for benzo[a]pyrene; 228.1, 226.1 and 229.0 for benzo[a]anthracene; 228.1, 226.1 and 229.0 for chrysene; and 252.1 and 250 for benzo[b]fluoranthene. The method was calibrated in the range 0.2–10 ppb ($r^2 = 0.999$). When higher concentrations were retrieved, the analysis was repeated with diluted samples. Relative standard deviations were typically 2.6%. The limit of quantification was 0.20 μg kg^{-1}.

Statistical analysis

Data were analysed using the SPSS, version 22 (IBM Corp., Armonk, NY, USA) and Excel 2016 (Microsoft Corp., Redmond, WA, USA). When computing mean PAH levels, the limit of quantitation (LOQ) value (0.20 μg kg^{-1}) was substituted for concentrations below the LOQ. Raw data were tested for normality using the Shapiro–Wilk test. Means of normally distributed data were compared using independent *t* tests and analysis of variance, as appropriate. Non-parametric tests were used to compare means of data that were not normally distributed.

RESULTS AND DISCUSSION

Here, only BaP and PAH4 values are discussed since those are used as markers for regulating PAHs.[10] However, data on

Table 2. Mean PAHs in smoked-soft products *versus* smoked-dry products (*Sardinella* sp and *Sphyraena* sp products combined) (based on data of Experiment Set I)

	Mean BaP ($\mu g\ kg^{-1}$)		Mean PAH4 ($\mu g\ kg^{-1}$)	
Kiln	Smoked-soft	Smoked-dry	Smoked-soft	Smoked-dry
FTT	0.4 ± 0.20 a	1.0 ± 0.9 b	2.9 ± 1.1 a	4.6 ± 3.7 b
Chorkor smoker	38.4 ± 12.5 a	60.7 ± 5.1 b	218.6 ± 52.3 a	377.4 ± 29.3 b
Metal drum	24.3 ± 14.2 a	47.7 ± 22.4 b	112.8 ± 59.5 a	231.4 ± 98.9 b

For each kiln, BaP and PAH4 with different lowercase letters are significantly different ($P < 0.05$).

benzo(a)anthracene, chrysene and benzo(b)fluoranthene are provided in the Appendix S1. The results of the three experimental sets are reported in Tables 1–4. In general, a satisfactory repeatability of the PAH data (typically relative SD < 20%) was observed. It is also noteworthy that PAHs were not detected in the fresh fish samples (Table 1), thus highlighting the smoking process as the origin of the hazards in the products.

Comparing FTT and traditional kilns as smoking systems (Experiment Set I)

Among the three kilns assessed, FTT products had the lowest mean PAH levels (Table 1). BaP and PAH4 in FTT products were up to 215- and 183-fold lower, respectively, than in Chorkor smoker products, as well as 91- and 63-fold lower, respectively, than in metal drum products. FTT products also had lower PAHs than the EU maximum limits (ML) for BaP ($2\ \mu g\ kg^{-1}$) and PAH4 ($12\ \mu g\ kg^{-1}$).[19] For traditional kiln products, mean BaP and PAH4 levels exceeded the EU ML by up to 35- and 33-fold, respectively (Table 1). These results therefore suggest that, as a (fish) smoking system, FTT yields products with significantly lower PAH levels than the traditional kilns. Similar findings were made in Senegal, where BaP in FTT products ranged from 0.15–1.50 $\mu g\ kg^{-1}$, whereas levels in traditional kilns were above 5 $\mu g\ kg^{-1}$.[30]

The notably higher PAH levels in traditional kiln products may account in part for past border rejections in EU of smoked fish from the region, as notified on the RASFF. Similar to the findings of the present study, a mean BaP of 20.15 $\mu g\ kg^{-1}$ has been reported for traditionally smoked *Sardinella* sp in Ghana,[21] whereas a value of 38 $\mu g\ kg^{-1}$ has been reported for traditionally smoked mudfish in Nigeria.[31] It is noteworthy that traditional fish smoking practices are similar across the region.

Between the traditional kilns, the metal drum kiln products had significantly lower ($P < 0.05$) PAH levels than Chorkor smoker products (Table 1). This could be attributed to the higher degree of smoke retention in the latter kiln. As shown in Fig. 1, the practice of stacking several trays of fish and covering the topmost tray when using the Chorkor smoker serves to concentrate smoke around the fish.[8] This is not observed with the metal drum kiln, on which only one or two layers of fish can be smoked at a time (Fig. 1). Longer exposure to smoke has been cited as a contributor to high PAH levels in smoked products.[11]

The characteristic of better smoke retention in the Chorkor smoker was considered to be an advantage when that kiln was developed in Ghana in 1969 because this feature allowed better flavouring of products.[8] However, this apparent gain in sensory appeal led to a further compromise on the safety of products.

Effect of smoked product type on PAH level (Experiment Set I)

Across the kiln types, BaP and PAH4 levels in smoked-dry products were up to two- and 13-fold higher, respectively, than the values for smoked-soft products (Table 2). This may be a result of the longer exposure of smoked-dry products to heat and smoke during processing.

As noted in Experiment Set I, different fuels were used on the FTT and the traditional kilns. Hence, the effect of fuel type on PAH levels was evaluated in Experiment Set II.

Effect of fuel type and kiln design on PAH levels (Experiment Set II)

Generally, wood fuels resulted in significantly higher PAH levels in products than charcoal (Table 3). BaP and PAH4 in FTT products were 38- and 25-fold higher, respectively, when fuelwood was used instead of fully-lit charcoal. Similarly, for Chorkor smoker products, the levels were up to six- and ten-fold lower, respectively, when fully-lit charcoal was used in place of fuelwood. Smoke release from the fuelwood (which is not observed with fully-lit charcoal) might account for the difference.[17]

Effect of FTT parts on PAH levels (Experiment Set III)

Having determined that products from the FTT had lower PAHs levels than those from the traditional kilns, the effects of the components of the FTT on levels of the hazard were evaluated. For these experiments, smoked-dry *Sardinella* sp. were considered because smoked-dry products had higher PAH levels than the smoked-soft forms (Table 2).

Use or non-use of fat collector

When the fat collector was not used, BaP and PAH levels were six- and eight-fold higher ($P < 0.05$), respectively, than the values when it was used (Table 4). This could be accounted for by two factors. First, when the collector is not used, fish fat drips unto the heat source and could increase PAH production through pyrolysis.[28] Second, without the collector, there is a direct contact between the heat source and the products. Both factors are considered important by CAC as contributors to PAH contamination during smoking processes.[11] The fat collector therefore contributes to the observed lower PAHs in FTT products by reducing fat pyrolysis and allowing an indirect contact between the heat source and the products.

Type of material for generating smoke to flavour fish

The three materials tested (sugarcane bagasse, coconut husk and *A. indica*) yielded significantly different ($P < 0.05$) BaP and PAH4 levels (Table 4) in products, none of which violated the EU ML. Products flavoured with *A. indica* and sugarcane bagasse smoke recorded the highest and lowest PAH levels, respectively. Ndiaye *et al.*[25] classified certain fuels for the FTT using three colours: green (highly recommended), orange (use with caution)

Table 3. Effect of fuel type on PAH levels in smoked-dry *Sardinella* sp. produced on the FTT and traditional kilns (Experiment Set II: each experiment was conducted in five replicates)

Kiln	Fuel	Mean BaP (μg kg^{-1})	Mean PAH4 (μg kg^{-1})
FTT	Charcoal[†](for cooking) and sugarcane bagasse (for smoke flavouring)	0.2 ± 0.0 a[‡]	1.5 ± 0.2 a
	Pterocarpus erinaceus for both cooking and smoke flavouring	1.9 ± 0.2 b	37.0 ± 3.0 b
	Azadirachta indica for both cooking and smoke flavouring	7.7 ± 0.4 c	28.9 ± 2.0 c
Chorkor smoker	Charcoal (for cooking) and sugarcane bagasse (for smoke flavouring)	10.2 ± 0.4 a	39.4 ± 1.9 a
	Azadirachta indica	58.5 ± 7.3 b	207.0 ± 10.1 b
	Pterocarpus erinaceus	60.3 ± 3.9 b	394.5 ± 16.5 c
Metal drum	a: *Azadirachta indica*	35.8 ± 3.5 a	174.3 ± 22.8 a
	b: *Pterocarpus erinaceus*	25.6 ± 2.1 b	135.7 ± 11.3 b

For each kiln, BaP and PAH4 with different lowercase letters are significantly different ($P < 0.05$).
[†] Fully-lit charcoal combined with broken pottery was used as the heat source for the cooking step.
[‡] Values for three of five samples were below the LOQ. The values for the remaining two samples were equal to the LOQ.

Table 4. Effect of FTT parts on PAH levels in smoked-dry *Sardinella* sp. (Experiment Set III: for all experiments in this set, charcoal with broken pottery was used as cooking fuel; each experiment was conducted in five replicates)

Test	Condition/material		Mean BaP (μg kg^{-1})	Mean PAH4 (μg kg^{-1})
Effect of fat collector[†]	Fat collector used		0.5 ± 0.2 a	4.7 ± 0.1 a
	Fat collector not used		2.9 ± 0.2 b	39.4 ± 2.1 b
Effect of type of material for generating smoke to flavour products	Sugarcane bagasse		0.2 ± 0.0 a	1.5 ± 0.2 a
	Coconut husk		0.3 ± 0.2 b	2.2 ± 1.4 b
	Azadiracta indica		0.8 ± 0.3 c	7.7 ± 2.4
Effect of smoke filter	Sugarcane bagasse smoke	Filter used	0.2 ± 0.0 a	1.5 ± 0.2 a
		Filter not used	0.9 ± 0.2 b	8.0 ± 0.3 b
	A. indica smoke	Filter used	0.8 ± 0.3 a	7.7 ± 2.4 a
		Filter not used	1.4 ± 0.2 b	12.6 ± 0.9 b

For each test, means in columns with different lowercase letters are significantly different ($P < 0.05$).
[†] Smoke flavouring was not applied.

and red (avoid). In that classification, sugarcane bagasse was marked green and coconut husk orange and woody fuels were marked red. The findings of the present study are thus in accordance with that classification. Another study in Ghana found that sugarcane bagasse smoke yielded lower PAHs than hard wood.[32]

However, it must be noted that, on the FTT, the practical relevance of the differences in PAH as a result of the type of smoke flavouring material may be considered minimal because none of the materials tested raised PAH levels beyond the acceptable limits. This highlights the importance of the cooking step vis-à-vis PAH contamination in FTT products since contamination beyond that point was minimal.

Use or non-use of filter

When the smoke filter was not used, BaP and PAH4 levels were higher by up to four- and five-fold, respectively (Table 4). EU ML were not violated, however, except in the case of *A. indica* smoke, where PAH4 levels were marginally higher than the ML (12.6 μg kg^{-1} kiln *versus* 12 μg kg^{-1} ML) (Table 4). Essumang *et al.*[33] observed that filtering wood smoke reduced PAH levels in products from a traditional kiln in Ghana to which an activated charcoal filter was affixed. Although the kiln described in that study[33] is operationally different from the FTT, their finding lends support to the lessening effect of smoke filtering on PAH contamination. The use of a luffa sponge (a readily available renewable resource), as performed on the FTT, is more economically sustainable for processors and more in support of environmental sustainability than the activated charcoal option.

CONCLUSIONS

The findings suggest that the FTT is efficacious in yielding smoked products with PAH levels lower than those obtained in traditional kiln products. Good practices for ensuring low PAHs in FTT products include using fully-lit charcoal with broken pottery as the heat source, keeping the fat collector in place and using the smoke filter. The ease of adoption of the kiln in various sociocultural contexts in the Global South should be investigated.

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SUPPORTING INFORMATION

Supporting information may be found in the online version of this article.

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