Polycyclic Aromatic Hydrocarbons Burden of Meats Singed with Different Fuel Sources from Abattoirs in Ghana and Associated Cancer Risk Assessment

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ABSTRACT: This study evaluated the concentrations of polycyclic aromatic hydrocarbons (PAHs) and the carcinogenic risks of cattle and goat meats singed with either firewood, Liquefied Petroleum Gas (LPG) or tyres from five cities in Ghana. The meat samples, before and after singeing, as well as after scraping and washing, were collected from abattoirs and sent to Clinical Analysis Laboratory (Can-Lab) of Kwame Nkrumah University of Science and Technology (KNUST) for PAH analysis. Tyre-singed meats exhibit significantly higher PAHs concentrations ($P = .01304$) compared to those singed with firewood and LPG. Benzo[a]pyrene was the predominant PAH in tyre-singed cattle and goat meats, with concentrations of 23.1 mg/kg and 12.16 mg/kg, respectively. Washing singed meats reduced PAH levels, yet tyre-singed samples retained higher and dangerous concentrations than those singed with other fuels. Statistical analysis using ANOVA confirmed a significant effect of fuel type on PAH16 concentrations ($P = .01304$). The Tukey HSD test indicated a significant difference between LPG and tyre ($P = .0105$). Estimated daily intake (EDI) calculations highlighted potential health risks, particularly from tyre-singed meats, which exceeded regulatory limits set by health authorities. The findings emphasize the health hazards associated with consuming meats singed with tyres in Ghana and underscore the need for stringent regulatory measures and public awareness to mitigate PAH exposure.

PLAIN LANGUAGE SUMMARY: This paper highlights the health risk concern associated with polycyclic aromatic hydrocarbons in meat.

KEYWORDS: Dietary exposure, food safety, process by products, sub-Saharan Africa, primary prevention

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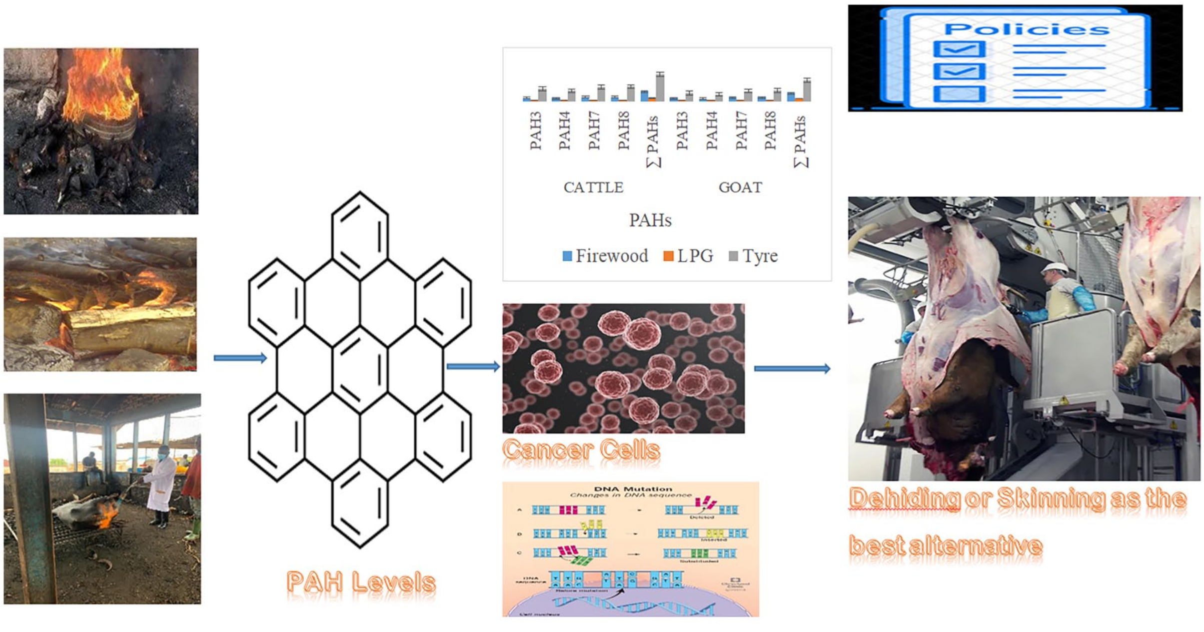

Introduction

Meat is a nutritious delicacy, often consumed for its protein content, with cattle and goat meat being particularly popular in Africa.[1,2] The FAO[3] outlines methods for skinning cattle and other ruminants and scalding pigs to ensure hygienic practices in slaughtering and meat handling. Singeing, which preserves the hide for consumption and enhances the meat's flavour, is a widespread method in Africa.[4,5] Traditionally, firewood was used for singeing, but its scarcity in urban areas has led to the use of alternative fuels such as used motor oil, car tyres and unsorted trash containing plastics.[6] These fuels can contain carcinogens like furans, dioxins and PAHs, posing health risks to consumers and processors.[7,8] Polycyclic aromatic hydrocarbons (PAHs), which consist of multiple aromatic rings, are common environmental pollutants from burning organic materials and are linked to various health issues, including cancer and decreased fertility.[9-12] In 1993, the US National Academy of Science classified seven PAH compounds as likely human carcinogens, prompting regulatory measures in the EU to limit PAH levels in food.[13,14]

This study focuses on the presence and concentrations of 16 priority PAHs in cattle and goat meat singed with firewood, scrap rubber tyres and LPG from five abattoirs in Ghana. It also evaluates the health risks for different age groups consuming these meats. Unlike developed countries with stringent regulations, Ghana's meat industry lacks strict enforcement, leading to potential health risks from unhygienic practices,[15,16] This is evident to the 2009 report by the FDA of Ghana, highlighting significant cases of food-borne disease and their associated economic costs.[17] This study outcome will enable a comparative evaluation of the meat singed with the three fuel sources and its potential health consequences in terms of carcinogenic potencies on the public's health.

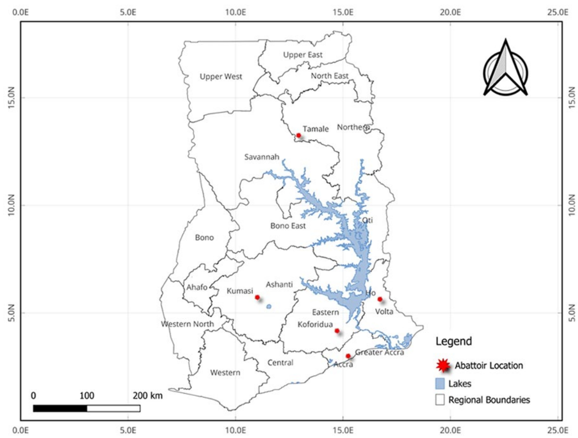

Figure 1. The map of Ghana indicating the cities where sampled abattoirs are located.

Materials and Methods

Study area

The study was conducted in Ghana's five largest cities: Kumasi, Accra, Koforidua, Tamale and Ho. With a population of 33.48 million, Ghana includes 12.4 million children under 14 years, 17.9 million adults between 18 and 60 years, and over 2 million senior citizens over 60 years.[18] The research regions have land sizes of 646.902, 254, 573.2, 225.67 and 110 km^2, respectively (Figure 1). The 2021 census reported a population of 3 490 000 in Kumasi, 2 557 000

Table 1. HPLC conditions used for separation of PAHs.

Column	Agilent ZORBAX Eclipse PAH C18 4.6 × 50 mm, 1.8 µm	
Flow rate	0.8 mL/min	
Column temperature	18°C	
Injection volume	5 µL	
Mobile phase	A = Deionized H_2O	B = CH_3CN
Gradient	T (min)	% B
	0	60
	1.5	60
	7	90
	13	100
Detection	UV at 230 nm (Acy) and varying fluorescence excitation (Ex) and emission (Em) wavelengths	
Wavelengths time (min)	Ex/Em wavelengths (nm)	PAH detected
0-5 (dark blue)	260/352	Nap, Ace, Flu, Phe, Chr
0-14 (red)	260/420	Ant, Pyr, BeP, DahA, BghiP
0-14 (light blue)	260/460	Fln, 1,2-BaA,BeA, BkF, InP

in Accra, 764 613 in Koforidua, 672 000 in Tamale and 180 420 in Ho.[18]

Sample collection

All experimental procedures were approved by the Research Ethical Committee at the University of Port Harcourt, Nigeria (UPH/CEREMAD/REC/MM73/014). Between June and August 2023, 180 samples of cattle and goat meats singed with LPG, tyres and firewood were collected from abattoirs. Three carcasses per fuel type were selected, and 25 g of meat was collected before, after singeing, and after scraping and washing. The samples were packaged in disposable paper bags, labelled, sealed and transported to the Clinical Analysis Laboratory at KNUST under iced conditions to ensure preservation. Upon arrival, they were frozen at −20°C before undergoing PAH detection and quantification.

PAHs analysis

The method for PAH analysis mimicked that of Pule et al.[19]

Reagents and chemicals. Acetonitrile (CH_3CN) and PAH standards were procured from Sigma-Aldrich (St. Louis, MO, USA). Water from a MilliQ system (Milford, MA, USA) was used. 10 mg of each PAH was dissolved in 10 mL CH_3CN, to prepare standard stock solutions (1 mg/mL) daily and kept at −20°C. A Whatman membrane filter with a 47 mm diameter and 2 µm pore size was used to filter the mobile phase.[20]

Instrument conditions. See Table 1.

Sample preparation. About 5 g homogenized meat sample was placed in a 50 mL centrifuge tube. Spike samples with 2000 µL spiking solution were shaken for 1 minutes thereafter 8 mL acetonitrile was added and shaken again for 1 minutes. SampliQ Quick, Easy, Cheap, Effective, Rugged and Safe (QuEChERS) salt packet from the Association of Official Analytical Chemist (AOAC) was added and shaken for 1 minute and centrifuged at 4000 rpm for 5 minutes. 6 mL aliquot was transferred to SampliQ QuEChERS Dispersive Solid-Phase Extraction (dSPE) 15 mL tube and shaken for 1 minute, centrifuged at 4000 rpm for 5 minutes once more. Thereafter, it was filtered through a 0.45-um polyvinylidene fluoride (PVDF) syringe filter and 1 mL extract was transferred to an autosampler vial for High-Performance Liquid Chromatography with Fluorescence Detection (HPLC-FLD) analysis.[19]

Health risk assessment

B(a)P equivalent concentration, potency equivalent concentration and screening value.

$$B(a)Peq = C_{PAH} \times TEF \qquad (1)^{17}$$

Where C_{PAH} is the concentration of individual PAH compounds and TEF is the toxic equivalent factors.

The carcinogenic potency equivalent concentration (PEC) and Screening value (SV) is shown in equations (2) and (3) below.

Table 2. Parameters for PAH Intakes through cattle and goat meat consumption.

PARAMETERS			VALUE	REFERENCES
IR_c	Cattle meat ingestion rate	Child	0.0223 kg/person/day	Tay et al[17]
		Adult	0.0171 kg/person/day	
		Elderly	0.0171 kg/person/day	
IR_g	Goat meat ingestion rate	Child	0.036 kg/ person/day	Njoga et al[22]
		Adult	0.025 kg/person/day	Muktar et al[23]
		Elderly	0.0367 kg/person/day	Hobbs-Grimmer et al[24]
BW	Body weight	Child	35 kg	Okoye et al[25]
		Adult	70 kg	Tay et al[17]
		Elderly	74 kg	Oduro et al[26]
ED	Exposure duration	Child	6 years	Tay et al[17]
		Adult	30 years	Tay et al[17]
		Elderly	70 years	Muktar et al[23]
EF	Exposure frequency		250 days/year	Tay et al[17]
[PAH]	Concentrations	PAHs	Pollutant specific	Present study
AT	Average time for non-carcinogens		365 days × ED	
MARL	Maximum acceptable risk level		10^{-5}	
CSF	Cancer slope factor (ingestion)		7.3 mg/kg/day	RAIS[27]

$$PEC = \sum B(a)Peq \tag{2}$$

$$SV = \left[(RL/SF) \times BW\right]/CR \tag{3}$$

SV is in mg/kg and SF is the oral slope factor. The RL is the acceptable maximum risk level which would result in one additional cancer death per 100 000 persons if a person consumed meat daily with the same concentrations of PAHs for a lifetime. BW is the average body weight (kg), and CR is the consumption rate expressed in kg per day.

Carcinogenic and non-carcinogenic assessment of PAHs. The Estimated Daily Intake (EDI) and Hazard Quotient (HQ) were used to assess carcinogenic and non-carcinogenic health hazards in singed meats. The EDI was calculated using equation (4), where BW is the average body weight of each group, MC is the mean concentration of each PAH in singed meats and IR is the expected amount of singed meat ingested.

$$EDI = \frac{IR \times MC}{BW} \tag{4}$$

The HQ was calculated using equation (5), where AT is the average time for non-carcinogens, RfDo is the oral reference dosage in mg/kg/day (NaP = 0.02, Acp = 0.06, Fl = 0.04, Ant = 0.3, Flu = 0.04 and Pyr = 0.03),[21] and Ef is exposure frequency.

$$HQ = \frac{Ef \times ED_{total} \times EDI}{RfDo \times BW \times AT} \times 10e^{-3} \tag{5}$$

The carcinogenic health risk of PAH contamination in singed meat was assessed using carcinogenic Toxic Equivalents (TEQs).

$$TEQs = \sum PAHi \times TEFi \tag{6}$$

where ΣPAHi is the concentration of individual PAH measured in the singed meat samples and TEFi is the toxicity equivalency factor of PAHs (Table 2).

Data analysis

GraphPad Prism® software (San Diego, California, CA, USA) was used to analyzed the relationship between fuel type and PAH occurrence. A normality test was performed before Analysis of Variance (ANOVA). The study used ANOVA to examine the impact of fuel types on PAH concentrations in meat. The data was displayed using mean values ± SEM, with a 95% confidence interval and a significance level of $P < .05$.

Results and Discussion

PAHs in singed meats in selected cities in Ghana

PAHs in singed cattle meat. The results of PAHs analysis in cattle meat exposed to different fuel/singeing methods (Firewood, Liquefied Petroleum Gas or LPG and Tyre) in the five sampled cities Kumasi, Accra, Koforidua, Ho and Tamale are shown in Figures 2i to xv. The PAHs were categorized into carcinogenic and non-carcinogenic groups, and the total PAH concentrations were measured in three stages: before singeing, after singeing and after singeing with washing.

In Kumasi (Figures 2i-iii), the total PAH concentrations increased (from 3.39 mg/kg, with 1.53 mg/kg carcinogenic, to 43.49 mg/kg, with 19.96 mg/kg carcinogenic) with firewood singeing and washing decreasing them to 19.34 mg/kg, of which 8.75 mg/kg carcinogenic. The total PAH concentrations increased (from 4.43 mg/kg, with 2.69 mg/kg carcinogenic, to 8.62 mg/kg, with 2.10 mg/kg carcinogenic) with LPG singeing. After washing, the total PAH dropped to 5.75 mg/kg, of which 1.18 mg/kg carcinogenic. The total PAH concentrations surged (from 3.53 mg/kg, with 1.75 mg/kg carcinogenic, to 81.07 mg/kg, with 42.26 mg/kg carcinogenic) with tyre singeing. After washing, they dropped to 51.35 mg/kg, with 24.69 mg/kg carcinogenic.

In Accra (Figures 2iv-vi), total PAH concentrations in unsinged cattle meat exhibited a marked increased (from 3.58 mg/kg with no carcinogenic, to 27.16 mg/kg with 11.65 mg/kg carcinogenic PAHs) after singeing with firewood. However the concentration reduced to 15.32 mg/kg with 6.24 mg/kg been carcinogenic after the singed meats were washed. The 16 PAH in the unsinged meat increased from 3.67 mg/kg with 0.08 mg/kg carcinogenic to 6.32 mg/kg with 1.23 mg/kg carcinogenic after LPG singeing, while washing reduced the concentration of the singed meat to 4.06 mg/kg with 0.96 mg/kg carcinogenic. Also, after tyre-singeing, the 16 PAH increased from 2.88 mg/kg with no detectable carcinogenic fraction in the unsinged meat to 83.36 mg/kg with a 46.96 mg/kg carcinogenic but washing reduced the concentration to 56.68 mg/kg, of which 32.43 mg/kg was carcinogenic.

In Koforidua (Figure 2vii-ix), the total PAH concentrations in unsinged meat surged from 0.29 mg/kg, with no detectable carcinogenic fraction, to 26.43 mg/kg, with 13.32 mg/kg carcinogenic, after firewood singeing. Washing decreased them to 12.48 mg/kg, with 6.01 mg/kg carcinogenic. Total PAH concentrations increased (from 1.78 mg/kg, with no detectable carcinogenic PAHs, to 6.92 mg/kg, with 2.79 mg/kg carcinogenic) with LPG singeing and washing reduced them to 3.71 mg/kg, with 1.69 mg/kg carcinogenic. Total PAH concentrations surged from 1.29 mg/kg (with no detectable carcinogenic PAHs) to 65.86 mg/kg (with 39.87 mg/kg carcinogenic) with tyre singeing, and washing reduced them to 38.94 mg/kg, with 22.35 mg/kg carcinogenic.

Overall, the results from the five cities are aligned (Figures 2i-xv), with tyre singeing yielding the highest PAH concentrations, followed by firewood, and then LPG. Tyre singeing consistently introduced a drastic concentration of both carcinogenic and non-carcinogenic PAHs, even after washing. Firewood singeing also introduces a significant amount of PAHs, and LPG singeing results in the relatively least PAH contamination.

The results demonstrate that the type of fuel used for singeing significantly influences the level of PAH contamination in meat. Tyre singeing presents the greatest health risk, with extremely high levels of both carcinogenic and non-carcinogenic PAHs, followed by firewood singeing. LPG singeing introduces fewer PAHs compared to firewood and tyre singeing, making it a relatively safer option. In all cases, washing singed meat can partially reduce PAH concentrations but does not eliminate them, underscoring the need for alternative methods to minimize the risk to consumers.

PAHs in singed goat meat. Figures 3i to xv show results in terms of concentrations and fractions of carcinogenic and non-carcinogenic PAHs in goat meat under various processing conditions in the five cities of Ghana.

In Kumasi, goat meat presents a substantial increase in total PAH from 3 mg/kg to 28 mg/kg with firewood-singing (Figure 3i), while washing reduces the total PAH to around 17 mg/kg. The proportion of carcinogenic PAHs shifted from 30% to 45% with singeing and to 52% after washing. Total PAH increased from about 3 mg/kg to 8 mg/kg with LPG singing (Figure 3ii) and decreased to 5.5 mg/kg with washing. The percentage of carcinogenic PAHs increased from 30% to 36% with singeing and declined to 33% after washing. The total PAH rose from 2.5 mg/kg to 61 mg/kg with tyre singeing and decreased to 41 mg/kg with washing (Figure 3iii). The percentage of carcinogenic PAHs shows a marked increase too, from 30% to 53% after singeing, and a maintained 54% after washing. Other cities follow a similar trend (Figures 3iv-xv). This results highlights an increase in PAH concentration in goat meats processed with firewood, LPG and tyre-singeing across the five Ghanaian cities, with tyre singeing producing the highest. Interestingly, in the case of goat meat, while washing consistently reduced the total PAHs, the proportion of carcinogenic PAHs often increased, particularly after tyre-singeing (from 30% to 54%). Washing primarily reduces surface-level contaminants that contribute to the bulk weight of the sample,[28] leaving behind more persistent and hydrophobic compounds, which include many carcinogenic PAHs embedded within the meat's fatty tissues. Although goats are generally leaner than cattle, the

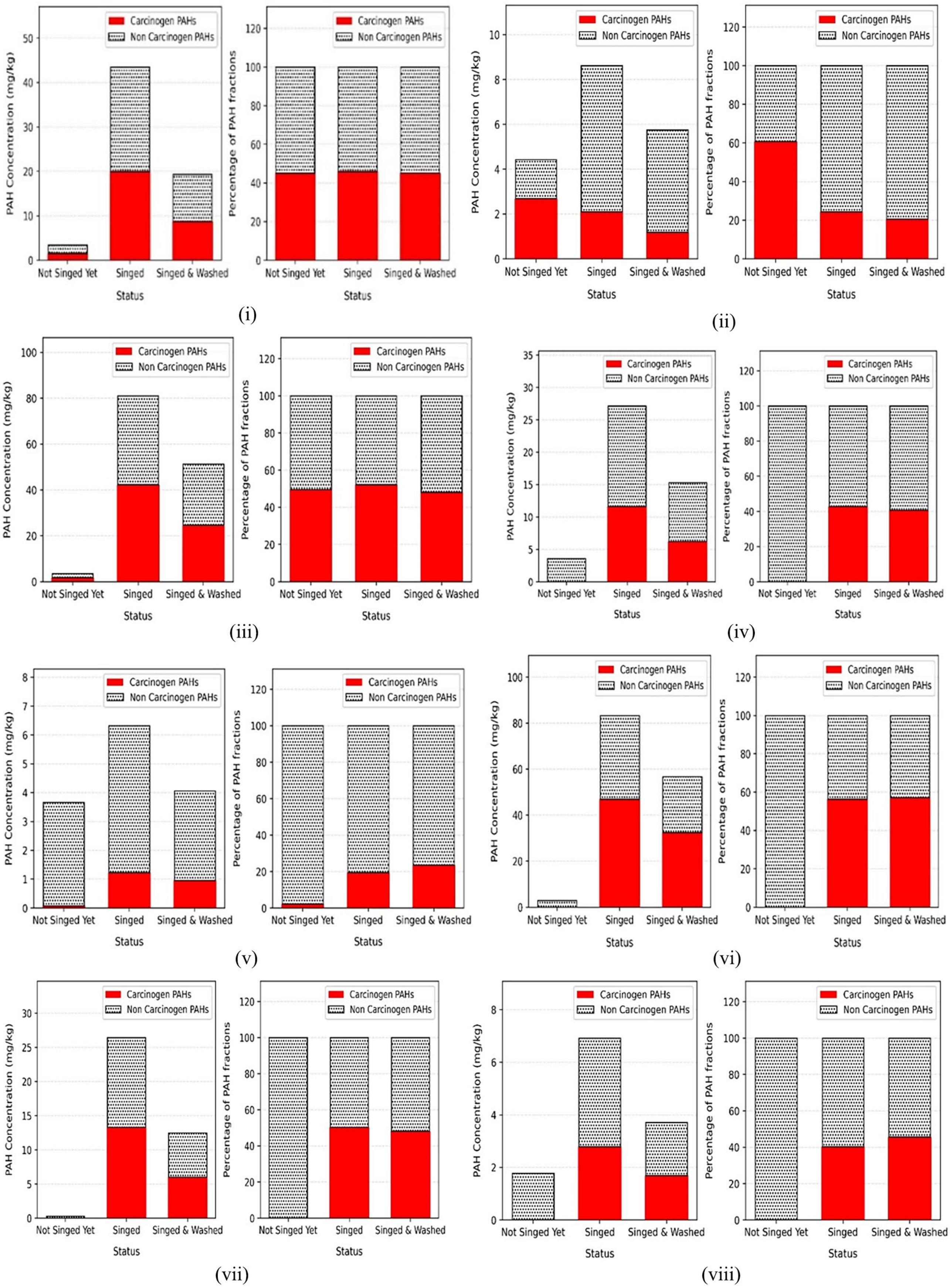

Figure 2. *(Continued)*

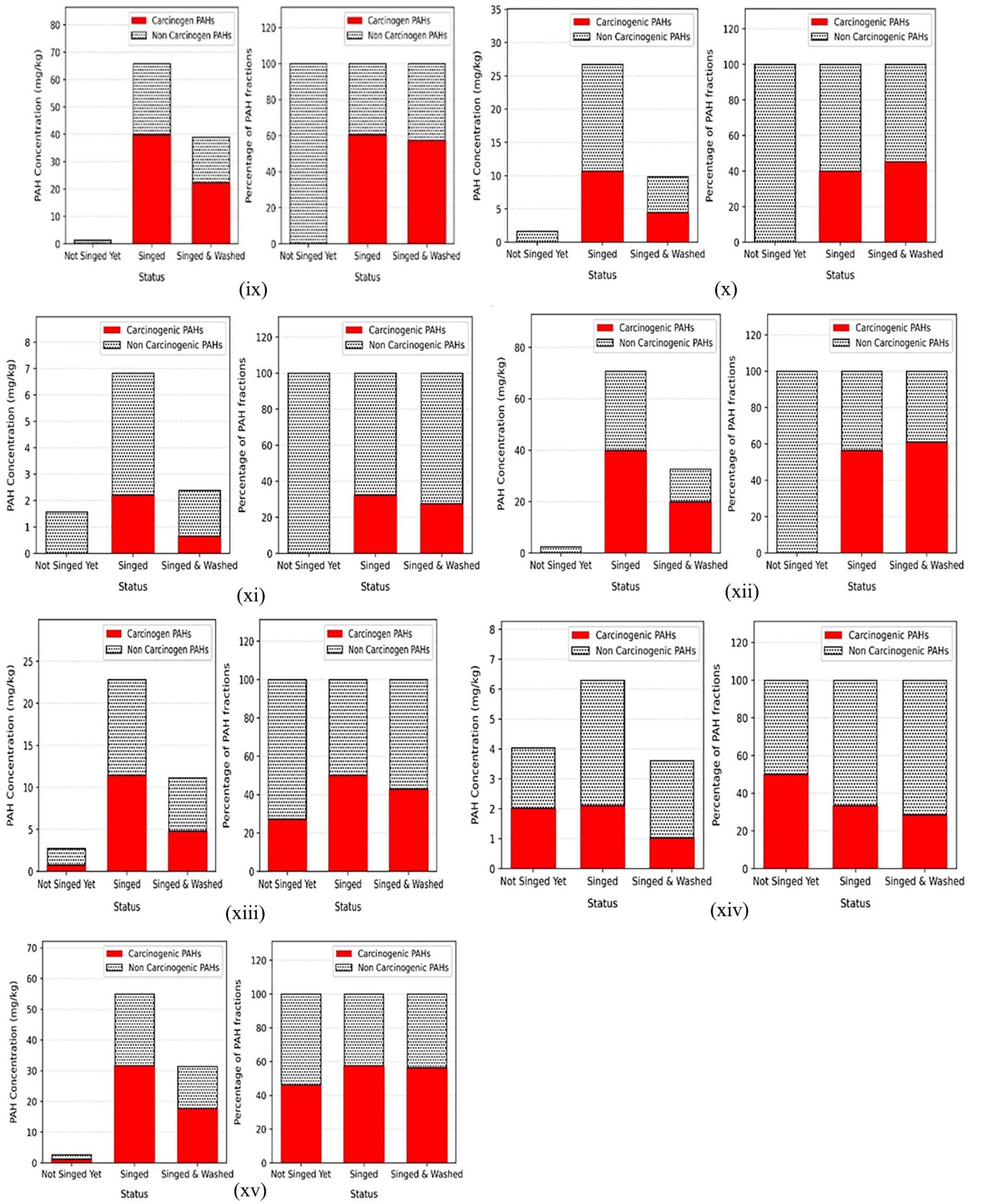

Figure 2. (i) PAHs concentration for firewood singed Cattle meat in Kumasi, (ii) PAHs concentration for LPG singed Cattle meat in Kumasi, (iii) PAHs concentration for Tyre singed Cattle meat in Kumasi, (iv) PAHs concentration for Firewood singed Cattle meat in Accra, (v) PAHs concentration for LPG singed Cattle meat in Accra, (vi) PAHs concentration for Tyre singed Cattle meat in Accra, (vii) PAHs concentration for Firewood singed Cattle meat in Koforidua, (viii) PAHs concentration for LPG singed Cattle meat in Koforidua, (ix) PAHs concentration for Tyre singed Cattle meat in Koforidua, (x) PAHs concentration for Firewood singed Cattle meat in Ho, (xi) PAHs concentration for LPG singed Cattle meat in Ho, (xii) PAHs concentration for Tyre singed Cattle meat in Ho, (xiii) PAHs concentration for Firewood singed Cattle meat in Tamale, (xiv) PAHs concentration for LPG singed Cattle meat in Tamale, and (xv) PAHs concentration for Tyre singed Cattle meat in Tamale.

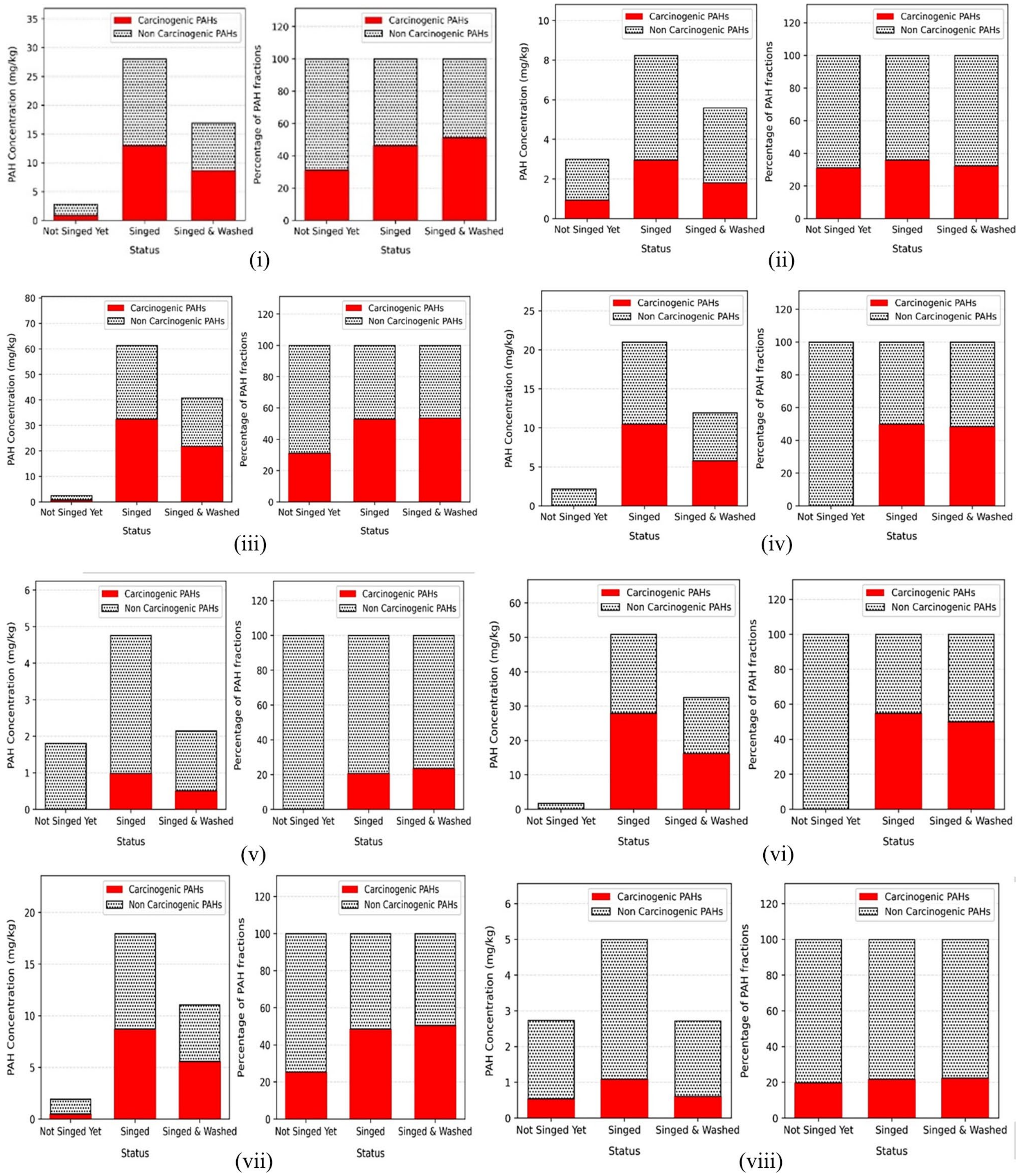

Figure 3. *(Continued)*

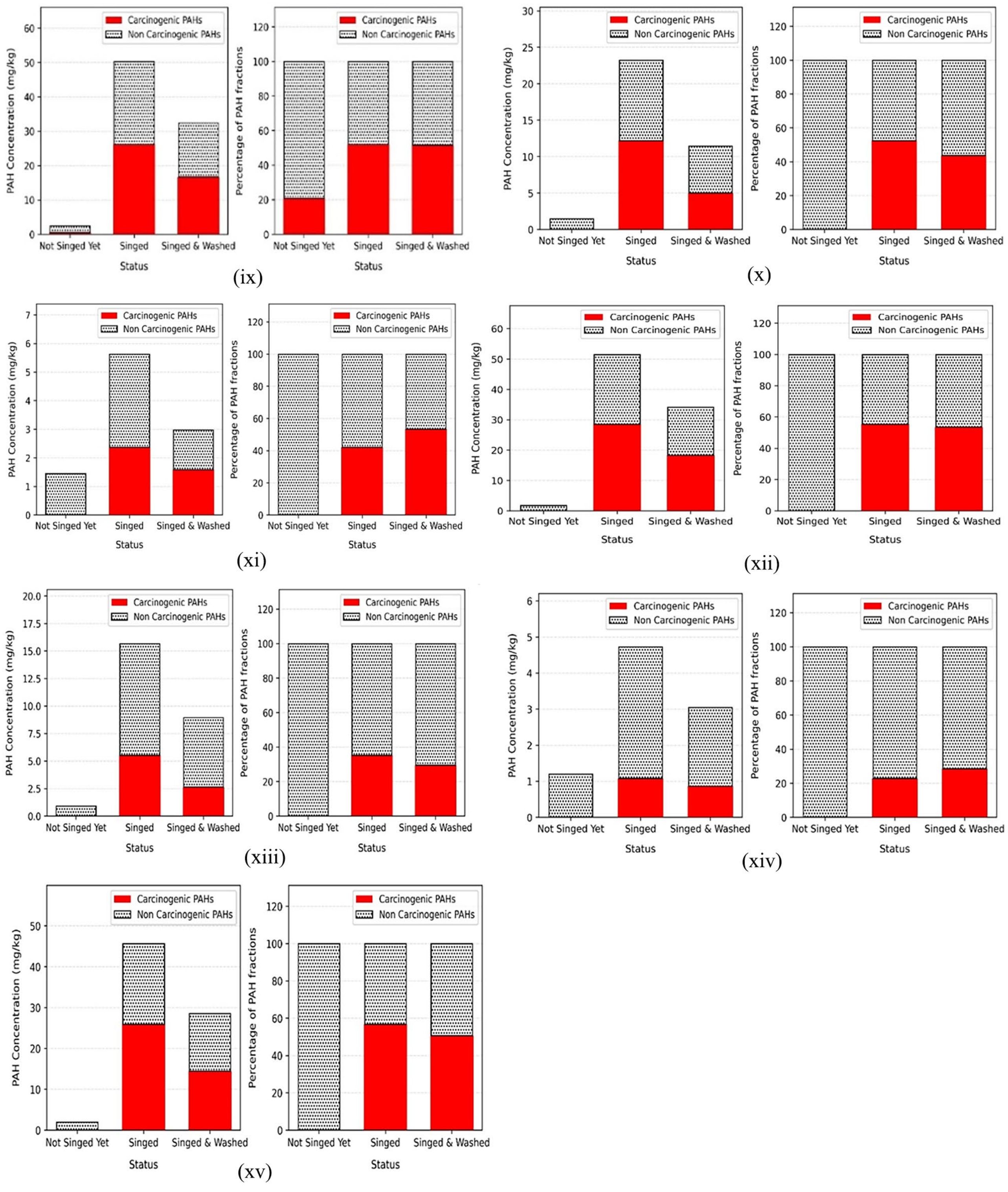

Figure 3. (i) PAHs concentration for firewood singed Goat meat in Kumasi, (ii) PAHs concentration for LPG singed Goat meat in Kumasi, (iii) PAHs concentration for Tyre singed Goat meat in Kumasi, (iv) PAHs concentration for firewood singed Goat meat in Accra, (v) PAHs concentration for LPG singed Goat meat in Accra, (vi) PAHs concentration for Tyre singed Goat meat in Accra, (vii) PAHs concentration for firewood singed Goat meat in Koforidua, (viii) PAHs concentration for LPG singed Goat meat in Koforidua, (ix) PAHs concentration for Tyre singed Goat meat in Koforidua, (x) PAHs concentration for firewood-singed Goat meat in Ho, (xi) PAHs concentration for LPG singed Goat meat in Ho, (xii) PAHs concentration for Tyre singed Goat meat in Ho, (xiii) PAHs concentration for firewood singed Goat meat in Tamale, (xiv) PAHs concentration for LPG singed Goat meat in Tamale, and (xv) PAHs concentration for Tyre singed Goat meat in Tamale.

distribution of fat in goat meat is more concentrated in specific areas, such as under the skin.[29] As these are removed, the PAHs, which are not as effectively washed away, now make up a greater proportion of the measured material. This creates an apparent increase in concentration when expressed relative to the remaining mass of the sample.

Comparative analysis among cities

PAHs in cattle meats. The comparative analysis of PAHs in cattle meat from different cities in Ghana reveals significant variations in both total PAH concentrations and proportion of carcinogenic PAHs by meat processing methods with geographical location.

Before singeing, Accra exhibited the highest total PAH (3.58 mg/kg) (with no carcinogenic PAHs for non-singed meat), followed by Kumasi with 3.39 mg/kg (with 1.53 mg/kg carcinogenic), Tamale (2.72 mg/kg), Ho (1.66 mg/kg) and Koforidua (0.29 mg/kg) (Figure 4i). Firewood singeing led to a sharp increase in PAH levels across all cities (Figure 4ii), with Kumasi experiencing the most pronounced rise (43.49 mg/kg) followed by Accra, Koforidua, Ho and Tamale (22.83-27.16 mg/kg). Carcinogenic PAHs became more prevalent after singeing, with Koforidua showing the highest proportion (50.4%), followed by Tamale (50.1%) and Kumasi (45.9%). Post-singeing washing (Figure 4iii) reduced PAH levels in all cities, but Kumasi still retained the highest concentration at 19.34 mg/kg. Other cities saw moderate reductions, with final concentrations ranging from 9.86 mg/kg in Ho to 15.32 mg/kg in Accra.

The analysis of PAHs in cattle meat processed by LPG as the fuel source across different Ghanaian cities also reveals significant variations in PAH levels and the ratio of carcinogenic to non-carcinogenic PAHs. In non-singed meat (Figure 4iv), Tamale had the highest total PAH at 4.04 mg/kg, with 2.02 mg/kg of carcinogenic PAHs, followed by Kumasi at 4.43 mg/kg (including 2.69 mg/kg carcinogenic PAHs). Accra, Koforidua and Ho showed lower total PAH concentrations, with minimal or no carcinogenic PAHs. The LPG-based singeing process led to a moderate increase in total PAH concentrations across all cities (Figure 4v). Kumasi had the highest PAH concentration at 8.62 mg/kg, followed by Ho at 6.83 mg/kg, while Accra, Koforidua and Tamale exhibited similar levels around 6.3 to 6.9 mg/kg. Carcinogenic PAHs also increased, with Koforidua showing the highest proportion (40.3%), followed by Ho and Tamale. Post-singeing washing (Figure 4vi) reduced total PAH concentrations in all cities, but Kumasi retained the highest level at 5.75 mg/kg. Carcinogenic PAHs persisted after washing, with Koforidua showing the highest percentage (45.6%), indicating that while washing reduces PAH levels, significant carcinogenic compounds remain. Washing removes surface contaminants from singed meats, but carcinogenic PAHs are retained, as these compounds are hydrophobic and accumulate in the fat tissues.[29]

The analysis of PAHs in cattle meat processed using tyres across various Ghanaian cities reveals alarming variations in total PAH levels and the proportion of carcinogenic to non-carcinogenic PAHs. In non-singed meat (Figure 4vii), Kumasi had the highest total PAH concentration at 3.53 mg/kg, with 1.75 mg/kg being carcinogenic, followed by Tamale with 2.66 mg/kg and Accra at 2.88 mg/kg, though no carcinogenic PAHs were detected in samples from Accra, Koforidua, or Ho. The tyre-based singeing process caused a dramatic increase in PAH levels (Figure 4viii), with Kumasi reaching 81.07 mg/kg, a 23-fold rise. Accra, Koforidua, Ho and Tamale also saw substantial increases, with carcinogenic PAHs accounting for more than 50% in all cities. In post-washing (Figure 4ix), while PAH levels decreased, they remained dangerously high, with Kumasi at 51.35 mg/kg and Accra at 56.68 mg/kg. Carcinogenic PAHs persisted, with Ho showing the highest percentage (61%), followed by Accra (57.2%) and Tamale (56.3%), raising serious health concerns.

PAHs in goat meats. The analysis of PAH concentrations in goat meat processed with firewood across various Ghanaian cities showed significant differences in total PAH levels and the proportion of carcinogenic PAHs. Figures 5i to iii demonstrate PAH levels in non-singed, firewood-singed and firewood singed-and-washed goat meat, respectively. Goat meat from carcasses singed with firewood from Kumasi had the highest total PAH (2.85 mg/kg, with 0.89 mg/kg carcinogenic) followed by Accra with 2.17 mg/kg (no detectable carcinogenic PAHs), Koforidua (1.93 mg/kg), Ho (1.46 mg/kg) and Tamale (0.91 mg/kg). Only Kumasi and Koforidua showed detectable carcinogenic PAHs. After firewood singeing, total PAH levels rose dramatically (Figure 5ii). Kumasi saw a nearly 10-fold increase to 28.06 mg/kg, followed by Accra (21.01 mg/kg), Ho (23.23 mg/kg), Koforidua (17.96 mg/kg) and Tamale (15.68 mg/kg). Carcinogenic PAH proportions increased too, with Ho (52.5%), Accra (50%) and Koforidua (48.6%) showing the highest percentages. After washing, total PAH levels reduced but remained elevated (Figure 5iii). Kumasi still had the highest concentration at 16.93 mg/kg, followed by Accra (11.94 mg/kg), Ho (11.45 mg/kg), Koforidua (11.06 mg/kg) and Tamale (8.95 mg/kg). Carcinogenic PAH proportions remained significant, with Kumasi (51.3%), Koforidua (50.5%) and Accra (48.5%) maintaining the highest percentages.

Figure 5iv to vi and vii to ix indicate PAH levels in non-singed, singed and singed-and-washed goat meat singed with LPG and tyre, respectively. Figures 5iv and vii, also show PAH concentrations and proportions in unsinged meat samples from Kumasi, Accra, Koforidua, Ho and Tamale. In both Figures, Kumasi consistently shows the highest PAH, with Figure 5iv displaying ~4.5 mg/kg and Figure 5vii showing ~3.2 mg/kg, with carcinogenic PAHs making up 50% and 20% of the total, respectively. Accra maintains similar total PAH (~4 mg/kg and ~2.2 mg/kg) but with no detectable carcinogenic PAHs. Koforidua has moderate concentrations (~3 mg/kg)

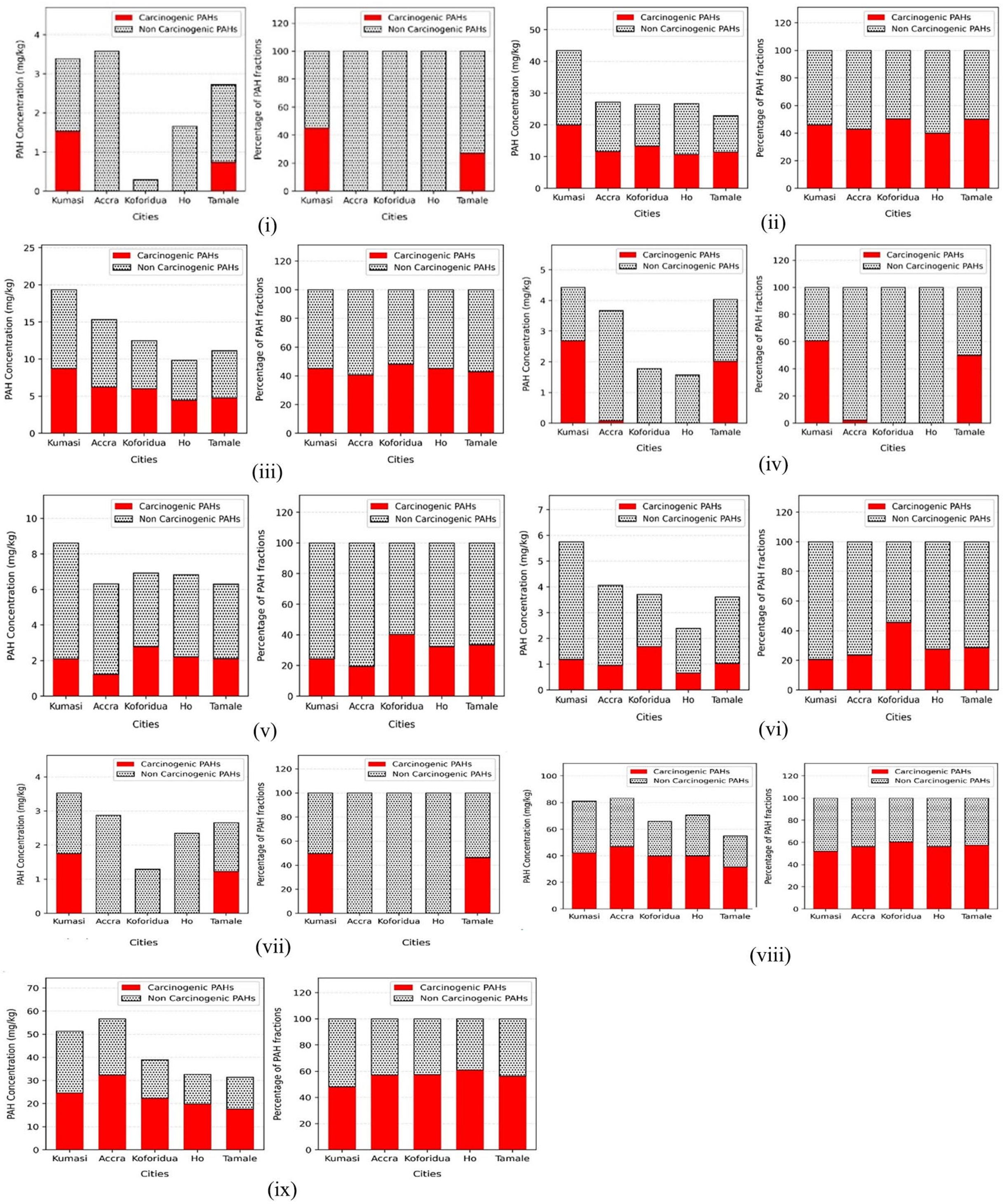

Figure 4. (i) PAHs level of firewood Non-Singed Cattle meat across different cities, (ii) PAHs level of firewood Singed Cattle meat across different cities, (iii) PAHs level of firewood Singed and washed Cattle meat across different cities, (iv) PAHs level of LPG Non-Singed Cattle meat across different cities, (v) PAHs level of LPG Singed Cattle meat across different cities, (vi) PAHs level of LPG Singed and washed Cattle meat across different cities, (vii) PAHs level of tyre Non-Singed Cattle meat across different cities, (viii) PAHs level of tyre Singed Cattle meat across different cities, and (ix) PAHs level of tyre Singed and washed Cattle meat across different cities.

in both cases, with a small carcinogenic fraction (~15%-48%). Ho and Tamale consistently show lower PAH levels (~2-1.8 mg/kg) with entirely non-carcinogenic PAHs. These Figures highlight the variability in total PAH levels and the proportion of carcinogenic PAHs across the cities, with Kumasi and Koforidua showing the most significant contamination.

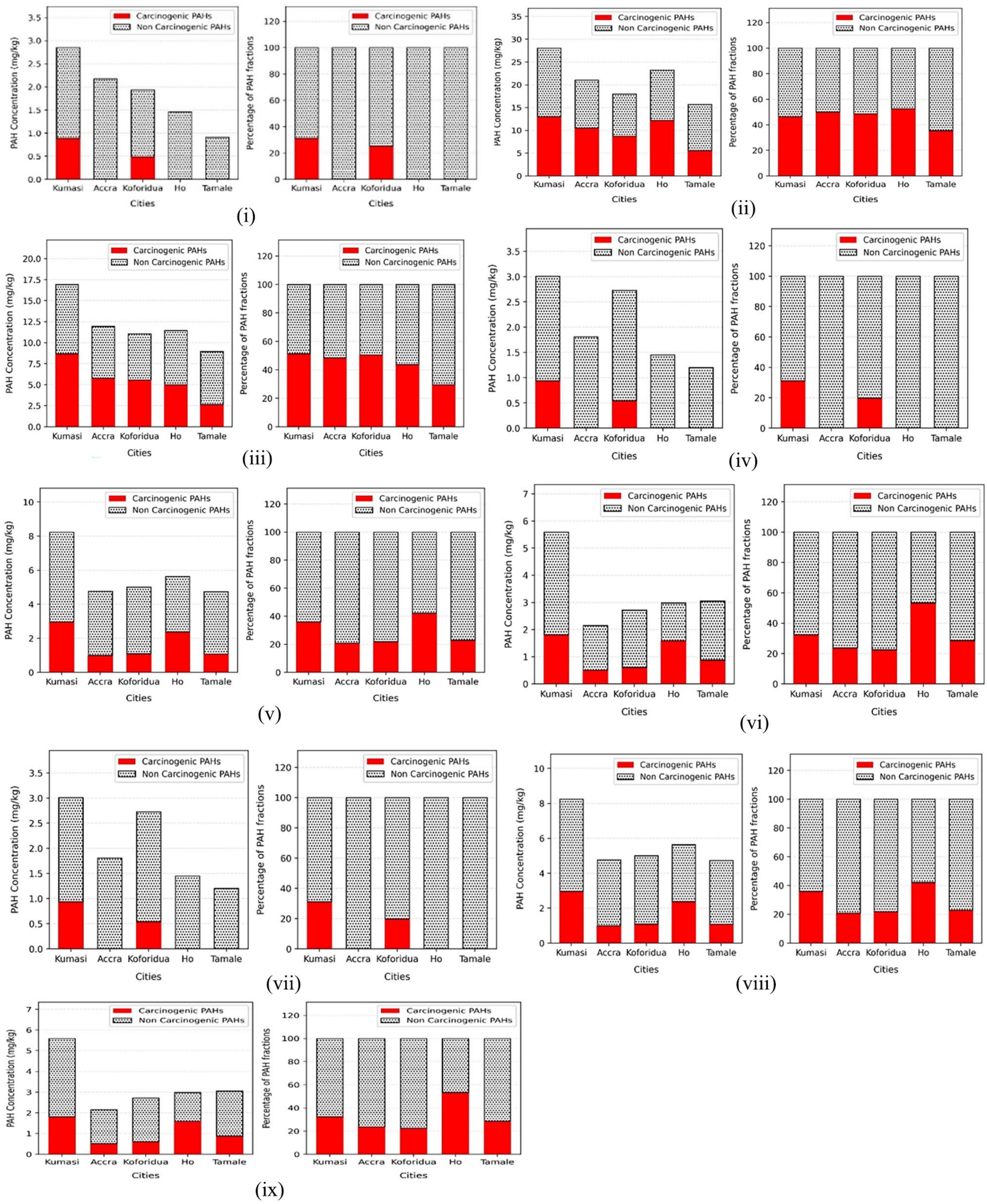

Figure 5. (i) PAHs level of firewood Non-Singed Goat meat, (ii) PAHs level of firewood Singed Goat meat, (iii) PAHs level of firewood Singed and washed Goat meat, (iv) PAHs level of LPG Non-Singed Goat meat, (v) PAHs level of LPG Singed Goat meat, (vi) PAHs level of LPG Singed and washed Goat meat, (vii) PAHs level of tyre Non-Singed Goat meat, (viii) PAHs level of tyre Singed Goat meat, and (ix) PAHs level of tyre Singed and washed Goat meat.

Source identification of PAHs in cattle and goat meat in different cities in Ghana

Figure 6i presents a diagnostic ratio plot analyzing PAH sources in cattle meat at various processing stages using the Ant/(Ant + Phe) and IcdP/(IcdP + Bghip) ratios. In raw, unsinged samples, the plot indicates petroleum-related contamination, with low Ant/(Ant + Phe) ratios and IcdP/(IcdP + Bghip) ratios around 0.5, suggesting exposure to

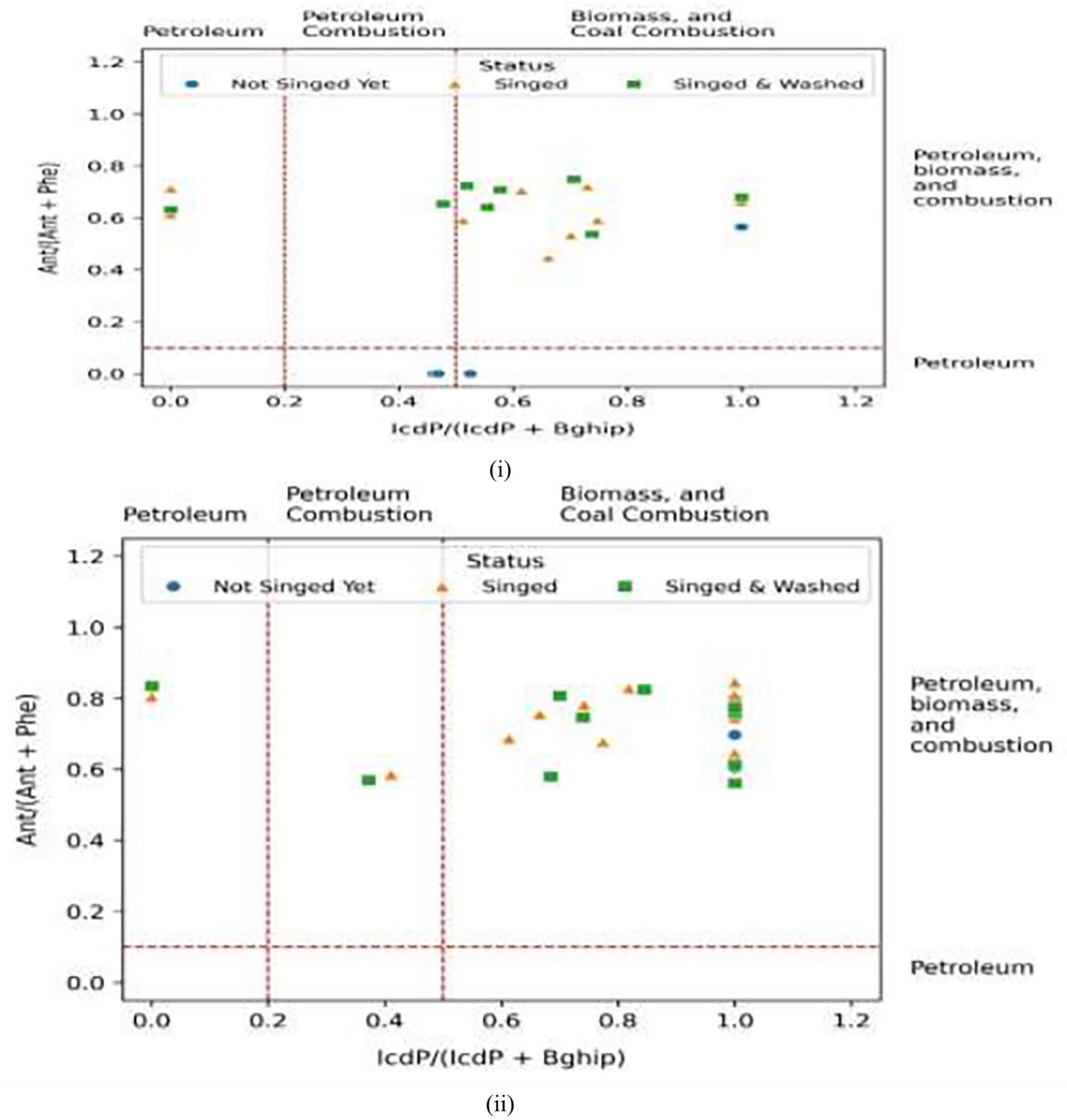

Figure 6. (i) PAHs Diagnostic ratio source identification for Cattle meat and (ii) PAHs Diagnostic ratio source identification for Goat meat.

petroleum products or contaminated feed. However, after singeing, a marked shift occurs, with higher ratios (0.4-0.8 for Ant/(Ant + Phe) and 0.2-0.9 for IcdP/(IcdP + Bghip)), indicating substantial combustion-derived PAHs, likely from different biomass or fuel sources. This pattern persists even after washing, showing that current washing methods fail to remove these PAHs, underscoring the lasting impact of the singeing process and the need for more effective mitigation strategies.

Also, Figure 6ii illustrates the diagnostic ratios used for identifying PAH sources in goat meat across different processing stages and fuel types, employing IcdP/(IcdP + Bghip) on the *x*-axis and Ant/(Ant + Phe) on the y-axis. In non-singed goat meat samples (blue circles), the data clusters in the 'Biomass and Coal Combustion' quadrant, with IcdP/(IcdP + Bghip) ratios around 0.9 to 1.0 and Ant/(Ant + Phe) ratios between 0.6 and 0.8, indicating PAHs primarily from biomass and coal sources due to environmental contamination or exposure during the goats' lifetime. This background contamination highlights that PAH presence is not solely a result of the singeing process but also reflects broader environmental factors. The singeing process (orange triangles) shifts PAH profiles, with data points dispersed across the upper quadrants, showing IcdP/(IcdP + Bghip) ratios from about 0.4 to 1.0 and Ant/(Ant + Phe) ratios between 0.6 and 0.9, suggesting PAHs from diverse sources, including petroleum combustion. Post-washing samples (green squares)

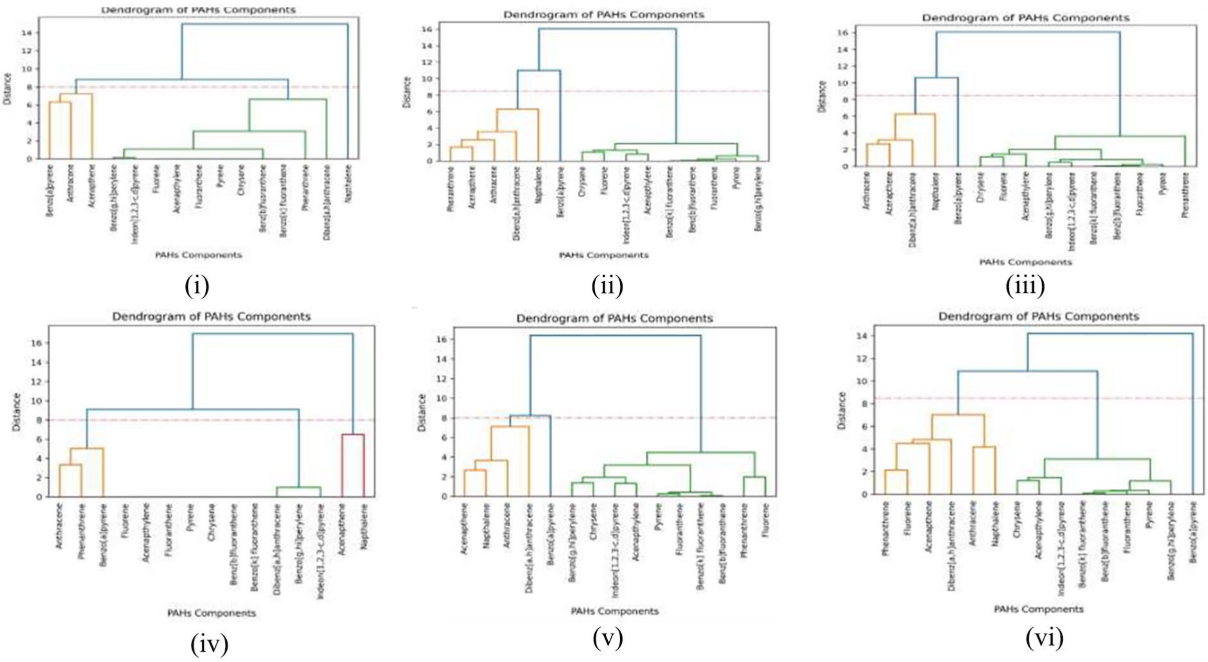

Figure 7. (i) Dendrogram of individual PAHs components for not singed yet cattle meat, (ii) Dendrogram of individual PAHs components for singed cattle meat, (iii) Dendrogram of individual PAHs components for singed and washed cattle meat, (iv) Dendrogram of individual PAHs components for not singed yet goat meat, (v) Dendrogram of individual PAHs components for singed goat meat, and (vi) Dendrogram of individual PAHs components for singed and washed goat meat.

reveal a slight regression towards non-singed profiles, with IcdP/(IcdP + Bghip) ratios of approximately 0.4 to 1.0 and Ant/(Ant + Phe) ratios ranging from 0.55 to 0.85, indicating that while washing reduces some PAH contamination, it cannot fully restore the original profile, highlighting the persistence of certain PAHs.

The hierarchical clustering analysis of PAHs in cattle meat samples at various processing stages highlights patterns related to specific source profiles, revealing how these compounds originate and change during meat preparation. In non-singed meat (Figure 7i), Cluster 3, which includes PAHs like Fluorene, Fluoranthene and Pyrene, suggests a mixed source of diesel combustion and urban air pollution. This cluster likely represents environmental contamination from vehicular emissions. Cluster 1, featuring compounds such as Acenapthene, Anthracene and Benzo[a]pyrene, may be linked to wood combustion, indicating possible exposure to biomass burning. The separation of Naphthalene in Cluster 2 could be due to its high volatility and presence in urban atmospheres, pointing to deposition from the air.

After singeing, the PAH profile shifts dramatically (Figure 7ii). Cluster 1, containing Naphthalene, Phenanthrene and Anthracene, reflects low-temperature combustion, aligning with firewood singeing, while Cluster 2, dominated by higher molecular weight PAHs like Fluoranthene and Pyrene, points to high-temperature sources such as tyre burning. The isolation of Benzo[a]pyrene in Cluster 3 after singeing suggests its unique formation during high heat processes. Post-washing (Figure 7iii), lower molecular weight PAHs, such as Naphthalene, remain resilient, while high molecular weight PAHs formed during intense singeing also persist, indicating that washing has limited impact on PAH removal. The consistent isolation of Benzo[a]pyrene across all stages highlights its stability and resistance to washing, particularly in tyre-singed samples, where carcinogenic PAHs remain seriously high.

The hierarchical clustering analysis of Polycyclic Aromatic Hydrocarbons (PAHs) in goat meat across different processing stages highlights distinct PAH groupings, revealing the sources and transformations of these compounds (Figure 7iv-vi). Non-singed meat clusters suggest contamination from both petrogenic and pyrogenic sources, while singeing shifts the profile toward high-temperature combustion PAHs, especially when intense heat fuels like tyres are used, significantly increasing carcinogenic PAH levels such as Benzo[a]pyrene. Post-washing, while some PAHs are redistributed, high molecular weight PAHs remain resistant to removal, confirming their persistence even after washing.

Human health risk assessment

Human health risk assessment has been widely conducted by calculating the possibility of severe health effects from an individual's

Table 3. Estimated daily intake (EDI) (mg/kg/day) of PAHs in singed and washed cattle meat.

PAHS	FIREWOOD			LPG			TYRE		
	CHILD	ADULT	ELDERLY	CHILD	ADULT	ELDERLY	CHILD	ADULT	ELDERLY
NaP	1.8095E−03	6.94E−04	6.56E−04	8.03E−04	3.08E−04	2.91E−04	4.1605E−03	1.6E−03	1.51E−03
AcPY	6.69E−04	2.57E−04	2.43E−04	1.98E−04	7.57E−05	7.16E−05	1.1532E−03	4.4E−04	4.2E−04
Acp	6.4351E−04	2.47E−04	2.33E−04	4.4E−04	1.69E−04	1.59E−04	1.7394E−03	6.7E−04	6.3E−04
Fl	3.2494E−04	1.25E−04	1.18E−04	1.02E−04	3.91E−05	3.7E−05	5.4157E−04	2.1E−04	2.0E−04
PA	8.7289E−04	3.35E−04	3.17E−04	1.98E−04	7.57E−05	7.16E−05	1.6438E−03	6.3E−04	6.0E−04
Ant	1.3507E−03	5.18E−04	4.9E−04	4.33E−04	1.66E−04	1.57E−04	3.3832E−03	1.3E−03	1.23E−03
Flu	—	—	—	—	—	—	9.5571E−05	3.7E−05	3.5E−05
Pyr	7.0086E−05	2.69E−05	2.54E−05	—	—	—	2.0389E−04	7.8E−05	7.4E−05
B(a)A		—	—	—	—	—	—	—	—
Chr	2.6123E−04	1.0E−04	9.47E−05	—	—		1.2297E−03	4.7E−04	4.5E−04
B(b)FL	3.8229E−05	1.47E−05	1.39E−05	—	—	—	7.0086E−05	2.7E−05	2.5E−05
B(k)FL	4.46E−05	1.71E−05	1.62E−05	—	—	—	7.0086E−05	2.7E−05	2.5E−05
B(a)P	2.8162E−03	1.08E−03	1.021E−03	5.16E−04	1.98E−04	1.87E−04	9.5954E−03	3.68E−03	3.48E−03
In(132-cd)	2.8034E−04	1.07E−04	1.02E−04	8.92E−05	3.42E−05	3.24E−05	5.798E−04	2.2E−04	2.1E−04
DB(ah)A	9.4297E−04	3.62E−04	3.42E−04	5.99E−04	2.3E−04	2.17E−04	3.4406E−03	1.32E−03	1.25E−03
B(ghi)P	1.2106E−04	4.64E−05	4.39E−05	8.28E−05	3.18E−05	3E−05	3.8866E−04	1.5E−04	1.4E−04

exposure to carcinogenic and/or non-carcinogenic substances over a particular period.[30] In this study, health risks that may arise when an individual or a population is exposed to the 16 priority PAHs in cattle and goat meat singed with LPG, firewood and tyre were estimated using the US EPA standard models.[31-33]

Estimated daily intake. The EDI of PAHs through consumption of singed and washed cattle meats (sold to the general populace) is presented in Table 3. For firewood-singed and washed cattle meat; the EDI ranged from 3.8E−05 to 2.8162E−03 for children, 1.5E−05 to 1.1E−03 for adults and 1.39E−05 to 1.021E−03 for the elderly. The EDI for LPG singed and washed cattle meat varied with a range of 8.3E−05 to 8.03E−04 for children, 3.2E−05 to 3.1E−04 for adults and 3.0E−05 to 2.9E−04 for the elderly. Also, the EDI for tyre-singed and washed cattle meat ranges from 7.0E−05 to 9.6E−03 for children, 2.7E−05 to 3.68E−03 for adults and 2.5E−05 to 3.5E−03 for elderly. Recent studies have focused on assessing PAH contamination in food due to their carcinogenic properties.[34-36] Studies have emphasized the health risks associated with different methods of food preparation, such as grilling, smoking and singeing using various fuels.[7,34-36] The EDI of PAHs in meats ranged significantly depending on the fuel source used.[17,37] Acquah-Baidoo et al[38] highlighted that the EDI values for PAHs in LPG-singed meats were generally lower compared to those singed with traditional fuels like wood and tyres, corroborating the findings of this study. The order of decreasing pattern of EDI for carcinogenic PAHs in firewood singed and washed cattle meat was: B(a)P > DB(ah)A > Indeno (1,2,3-cd)P > Chr > B(ghi)P > B(k)F > B(b)F for all age groups. The order of decreasing pattern of EDI for carcinogenic PAHs in LPG singed and washed cattle meat was: DB(ah)A > B(a)P > Indeno (1,2,3-cd)P > B(ghi)P for all age groups. The order of decreasing pattern of EDI for carcinogenic PAHs in tyre-singed and washed cattle meat was: B(a)P > DB(ah)A > Chr > Indeno (1,2,3-cd)P > B(ghi)P > B(k)F = B (b)F for all age groups. This suggests that the EDI was highest in B(a)P, which is classified as a carcinogen (1) and lowest in B (b)F which is classified as a possible carcinogen (2B) according to the IARC classification for all children, adults and the elderly populations who consumed both firewood and tyre singed cattle meat. EDI for LPG was highest in DB(ah)A (Probably carcinogenic) and lowest in B(ghi)P (Not classifiable) for all age groups. The order of carcinogenic PAHs, with B(a)P being the highest, aligns with multiple studies.[39-41,17] These studies consistently found that B(a)P levels were significantly higher in foods prepared or meat singed using traditional methods involving direct fire and smoke.

Table 4 presents the EDI of PAHs through consumption of singed and washed goat meats. EDI for firewood-singed

Table 4. Estimated daily intake (EDI) (mg/kg/day) of PAHs in singed and washed goat meats.

PAHS	FIREWOOD			LPG			TYRE		
	CHILD	ADULT	ELDERLY	CHILD	ADULT	ELDERLY	CHILD	ADULT	ELDERLY
NaP	1.4503E–03	5.04E–04	6.99E–04	8.02E–04	2.79E–04	3.87E–04	2.6229E–03	9.1E–04	1.26E–03
AcPY	5.04E–04	1.75E–04	2.43E–04	—	—	—	1.7485E–03	6.1E–04	8.4E–04
Acp	1.2549E–03	4.36E–04	6.05E–04	5.45E–04	1.89E–04	2.63E–04	3.2297E–03	1.12E–03	1.56E–03
Fl	6.9943E–04	2.43E–04	3.37E–04	2.98E–04	1.04E–04	1.44E–04	1.3885E–03	4.8E–04	6.7E–04
PA	8.0229E–04	2.79E–04	3.87E–04	2.57E–04	8.93E–05	1.24E–04	2.0057E–03	7.0E–04	9.7E–04
Ant	2.3452E–03	8.14E–04	1.131E–03	7.61E–04	2.64E–04	3.67E–04	5.0297E–03	1.75E–03	2.43E–03
Flu	—	—	—	—	—	—	2.9829E–04	1.0E–04	1.4E–04
Pyr	1.1314E–04	3.93E–05	5.46E–05	—	—		4.2171E–04	1.5E–04	2.0E–04
B(a)A	—	—	—	—		—	—	—	—
Chr	5.4514E–04	1.89E–04	2.63E–04	—		—	1.9337E–03	6.7E–04	9.3E–04
B(b)FL	5.1429E–05	1.79E–05	2.48E–05	—	—	—	1.5429E–04	5.4E–05	7.4E–05
B(k)FL	1.0286E–04	3.57E–05	4.96E–05	—	—	—	1.5429E–04	5.4E–05	7.4E–05
B(a)P	3.9291E–03	1.364E–03	1.895E–03	8.74E–04	3.04E–04	4.22E–04	9.5451E–03	3.31E–03	4.6E–03
In(132-cd)	6.3771E–04	2.21E–04	3.07E–04	1.44E–04	5.0E–05	6.94E–05	1.0594E–03	3.7E–04	5.1E–04
DB(ah)A	1.0389E–03	3.61E–04	5.01E–04	8.95E–04	3.11E–04	4.31E–04	4.6183E–03	1.6E–03	2.23E–03
B(ghi)P	3.1886E–04	1.11E–04	1.54E–04	—	—	—	7.0971E–04	2.5E–04	3.4E–04

and washed samples ranged from 5.1E–05 to 3.9E–03 for children, 1.8E–05 to 1.4E–03 for adults and 2.5E–05 to 1.9E–03 for the elderly; for LPG samples also ranged from 1.4E–04 to 9.0E–04 for children, 5.0E–05 to 3.1E–04 for adults and 6.9E–05 to 4.3E–04 for the elderly; and for tyre-singed and washed cattle meat ranges from 1.5E–04 to 9.5E–03 for children, 5.4E–05 to 3.3E–03 for adults and 7.4E–05 to 4.6E–03 for elderly. The order of decreasing pattern of EDI for carcinogenic PAHs in singed and washed goat meat for firewood-singed was B(a)P > DB(ah) A > Indeno (1,2,3-cd)P > Chr > B(ghi) P > B(k)F > B (b) F; LPG-singed was DB(ah)A > B(a)P > Indeno (1,2,3-cd) P; and tyre-singed was B(a)P > DB(ah)A > Chr > Indeno (1,2,3-cd)P > B(ghi)P > B(k)F = B (b)F for all age groups . This also suggests that the EDI was highest in B(a)P, which is classified as a carcinogen (1), and lowest in B (b)F which is classified as a possible carcinogen (2B) according to the IARC classification for all children, adults and the elderly populations who consumed both firewood and tyre singed goat meat, while EDI for LPG was highest in DB(ah)A (Probably carcinogenic) and lowest in B(ghi)P (Not classifiable) for all age groups. Health risk assessments conducted by researchers[17,42,43] have indicated that the EDI for PAHs, especially B(a)P, often exceeds the safety thresholds established by regulatory bodies such as the European Food Safety Authority (EFSA). B(a)P is absorbed into the food, particularly when high-fat meats are processed at high temperatures.[42] Since these compounds are persistent and accumulate in fatty tissues, the EDI for B(a)P can easily exceed safe levels when people consume large amounts of contaminated food over time. This is consistent with the current study regarding the high EDI of B(a)P in firewood and tyre-singed meat.

Hazard quotient and hazard indices of PAHs through ingestion of singed meats. The HQ and HI of PAHs through consumption of singed and washed cattle and goat meats is presented in Table 5. The HQ for LPG singed cattle meats ranged from 2.83×10^{-7} to 7.86×10^{-6}, 5.42×10^{-8} to 1.51×10^{-6} and 4.85×10^{-8} to 1.35×10^{-6} for children, adults and the elderly, respectively with a respective HI of 1.01×10^{-5}, 1.93×10^{-6} and 1.73×10^{-6} while HQ for tyre-singed cattle meat ranged from 4.68×10^{-7} to 4.07×10^{-5}, 8.96×10^{-8} to 7.80×10^{-6} and 8.02×10^{-8} to 6.98×10^{-6} for children, adults and the elderly, respectively with a respective HI of 5.30×10^{-5}, 1.02×10^{-5} and 9.10×10^{-6}. Also, the HQ for LPG singed goat meat ranged from 4.97×10^{-7} to 7.85×10^{-6}, 8.62×10^{-8} to 1.36×10^{-6} and 1.13×10^{-7} to 1.79×10^{-6} for children, adults and the elderly, respectively with a respective HI of 1.16×10^{-5}, 2.01×10^{-6} and 2.64×10^{-6} whiles HQ for tyre-singed goat meat ranged from 1.46×10^{-6} to 2.57×10^{-5}, 2.53×10^{-7} to 4.46×10^{-6} and 3.33×10^{-7} to 5.85×10^{-6} for children, adults

Table 5. Hazard quotient (non-carcinogenic risk) and hazard indices (HI) of PAHs through ingestion of singed meats.

CATTLE									
	FIREWOOD			LPG			TYRE		
	CHILD	ADULT	ELDERLY	CHILD	ADULT	ELDERLY	CHILD	ADULT	ELDERLY
NaP	1.7705E−05	3.3942E−06	3.0372E−06	7.8552E−06	1.5059E−06	1.3475E−06	4.071E−05	7.8042E−06	6.9833E−06
Acp	2.0989E−06	4.0236E−07	3.6004E−07	1.4339E−06	2.7488E−07	2.4597E−07	5.6732E−06	1.0876E−06	9.7318E−07
Fl	1.5897E−06	3.0476E−07	2.7270E−07	4.9874E−07	9.5611E−08	8.5554E−08	2.6496E−06	5.0793E−07	4.5451E−07
Ant	8.8111E−07	1.6891E−07	1.5115E−07	2.8262E−07	5.4180E−08	4.8481E−08	2.2069E−06	4.2308E−07	3.7858E−07
Flu	NA	NA	NA	NA	NA	NA	4.6757E−07	8.9635E−08	8.0207E−08
Pyr	4.5718E−07	8.7643E−08	7.8424E−08	NA	NA	NA	1.33E−06	2.5496E−07	2.2814E−07
HI	2.2732E−05	4.3579E−06	3.8995E−06	1.0070E−05	1.9305E−06	1.7275E−06	5.3037E−05	1.0167E−05	9.0979E−06
Goat									
NaP	1.4191E−05	2.4637E−06	3.2362E−06	7.8502E−06	1.3629E−06	1.7903E−06	2.5664E−05	4.4556E−06	5.8528E−06
Acp	4.0929E−06	7.1056E−07	9.3338E−07	1.7780E−06	3.0869E−07	4.0549E−07	1.0534E−05	1.8288E−06	2.4023E−06
Fl	3.4219E−06	5.9407E−07	7.8037E−07	1.4593E−06	2.5336E−07	3.3280E−07	6.7934E−06	1.1794E−06	1.5493E−06
Ant	1.5298E−06	2.6559E−07	3.4887E−07	4.9651E−07	8.6199E−08	1.1323E−07	3.281E−06	5.6961E−07	7.4823E−07
Flu	NA	NA	NA	NA	NA	NA	1.4593E−06	2.5336E−07	3.3280E−07
Pyr	7.3805E−07	1.2813E−07	1.6831E−07	NA	NA	NA	2.7509E−06	4.7759E−07	6.2735E−07
HI	2.3973E−05	4.1620E−06	5.4672E−06	1.1584E−05	2.0111E−06	2.6418E−06	5.0483E−05	8.7643E−06	1.1513E−05

and the elderly, respectively with a respective HI of 5.05×10^{-5}, 8.76×10^{-6} and 1.15×10^{-5}.

Ofori et al[44] and Edet et al[45] found elevated PAH levels in singed meats, with higher health risks for children due to their lower body weights and higher intake rates. Studies by Okareh et al[7] and Sunu[46] have also demonstrated that traditional methods like firewood and tyre singeing often result in higher PAH levels compared to modern methods like LPG singeing. The current study corroborates these findings, showing higher HQ and HI values for firewood and tyre singeing compared to LPG singeing. Some studies emphasized the increased vulnerability of children and the elderly to PAH exposure due to their physiological differences and dietary habits.[47-50] The HQ and HI values presented in this study reflect these age-related variations, aligning with the broader literature. The use of HQ/HI thresholds to assess potential health risks is standard practice in toxicological assessments. The European Food Safety Authority (EFSA)[51] and the European Union[52] have established that an HQ/HI value below 1 indicates negligible health risks, while values above 1 may signal potential concerns. The current study reports that HQ/HI values for all age groups and singeing methods are below 1, indicating no significant health risks from non-carcinogenic PAHs.

Carcinogenic toxic equivalents and screening values for PAHs through ingestion of singed meats. Dan et al[53] reported that the carcinogenic risk of a consuming public is assessed through the evaluation of TEQs, while SV is the threshold concentration of contaminant in edible tissue of potential public concern. Where the TEQs > SV, there is a potential health concern; if TEQs < SV, there is no potential health concern.[53] Beníšek et al[54] and Rose[55] noted that TEQs are a standardized method to quantify the toxicity of complex mixtures of dioxins and dioxin-like compounds, including PAHs. They also highlight the importance of SVs in determining the safety levels of contaminants in food.[54,54] From Table 6, the TEQ values for PAH in singed cattle meat consumption ranged from 0.01608 to 16.08 for firewood; 0.00543 to 5.43 for LPG and 0.04441 to 44.41 for tyre while, the SV for PAH through the consumption of singed cattle meat were 0.00215, 0.005608 and 0.005928 for children, adults and elderly, respectively. Apart from the TEQs for the Napth, Acenapthylene, Acenapthene, Flourene and Phenanthrene in the LPG singed cattle meats which were less than the computed SV for adults and elderly, all other TEQ values are greater than the calculated SVs, therefore a potential health concern. With the finding from Table 6 that all TEQ values for PAHs in goat meat exceed the computed SVs implies a significant health risk and underscores the importance of regulatory measures to limit PAH exposure from meat promoting safer meat processing practices.

Table 6 also presents the Benzo[a]pyrene (B[a]P) equivalent concentrations and PEC of various PAHs from consumption of cattle and goat meat singed with different fuel sources (firewood, LPG and tyre). Higher molecular weight PAHs such as Benzo[a]pyrene, Indeno[1,2,3-c,d]pyrene and Dibenzo[a,h]anthracene show significantly higher B(a)Peq, particularly from tyre-singed meat. Benzo[a]pyrene, a critical marker for carcinogenicity, shows the highest levels: 4.42 mg/kg (firewood), 0.81 mg/kg (LPG) and 15.06 mg/kg (tyre) in cattle meat. Similar trends are observed for goats, with tyre-singed meat showing 9.28 mg/kg, indicating its dominance in PAH toxicity. The PEC values highlight the overall impact of these toxicants. Tyre singeing results in the highest PEC values for both cattle (20.6665) and goat (13.9890) meats. Firewood follows with moderately high PEC values, while LPG exhibits the lowest PEC values, making it the least contaminant fuel source regarding PAH contamination in singed meat. Having all PEC values greater than SVs indicates a potential adverse health effect associated with the long-term consumption of meats from all fuel sources. PAHs are known carcinogens, and their presence in food has been linked to various health risks. The International Agency for Research on Cancer (IARC)[56] classified several PAHs, including Benzo[a]pyrene, as Group 1 carcinogens. Studies have emphasized the health risks associated with dietary exposure to PAHs, particularly from singed meats.[7,57] These studies support the concerns about the potential health impacts of consuming PAH-contaminated meat. The type of fuel used for singeing significantly affects PAH emissions. According to a study by Mentes et al,[58] tyre combustion produces higher levels of PAHs compared to other fuels, which corroborates the high B(a)P equivalent concentrations and PEC values found in the current study for tyre-singed meats. Similarly, firewood has been shown to emit considerable amounts of PAHs, while LPG is associated with lower emissions due to its cleaner and more efficient combustion,[38] making it a comparatively safer fuel source.[28,46]

Limitation of Study

The collection, processing and analysis of meat samples involved intricate procedures that might introduce variability. While the study aimed to use standardized methods for PAH analysis, the variations in laboratory equipment and calibration standards across different testing facilities could lead to inconsistencies in the data. Although the study included five abattoirs, the number of meat samples analysed from each source might not be sufficient. The limited sample size can reduce the statistical power of the study. Moreover, the diversity of samples regarding the duration of singeing and the specific conditions at each abattoir were not fully accounted for, which could influence the PAH levels and the subsequent risk assessment. This study relied on existing toxicological data and risk assessment models to estimate the potential health risks associated with PAH exposure in meat consumption. However, these models might not fully account for the unique dietary patterns, genetic factors and exposure scenarios specific to the Ghanaian population.

Table 6. Carcinogenic toxic equivalents, screening values, B(a)P equivalent concentrations and potency equivalent concentrations.

PAHS	TEF[A]	CATTLE						GOAT					
		TEQS			B(A)PEC			TEQS			B(A)PEC		
		FW	LPG	TYRE	FW	LPG	TYRE	FW	LPG	TYRE	FW	LPG	TYRE
NaP	0.001	0.01608	0.00543	0.04441	0.00284	0.00126	0.00653	0.01341	0.00445	0.03395	0.00141	0.00078	0.00255
AcPY	0.001	0.01608	0.00543	0.04441	0.00105	0.00031	0.00181	0.01341	0.00445	0.03395	0.00049	0	0.0017
Acp	0.001	0.01608	0.00543	0.04441	0.00101	0.00069	0.00273	0.01341	0.00445	0.03395	0.00122	0.00053	0.00314
Fl	0.001	0.01608	0.00543	0.04441	0.00051	0.00016	0.00085	0.01341	0.00445	0.03395	0.00068	0.00029	0.00135
PA	0.001	0.01608	0.00543	0.04441	0.00137	0.00031	0.00258	0.01341	0.00445	0.03395	0.00078	0.00025	0.00195
Ant	0.01	0.1608	0.0543	0.4441	0.0212	0.0068	0.0531	0.1341	0.0445	0.3395	0.0228	0.0074	0.0489
Flu	0.001	0.01608	0.00543	0.04441	0	0	0.00015	0.01341	0.00445	0.03395	0	0	0.00029
Pyr	0.001	0.01608	0.00543	0.04441	0.00011	0	0.00032	0.01341	0.00445	0.03395	0.00011	0	0.00041
B(a)A	0.1	1.608	0.543	4.441	0	0	0	1.341	0.445	3.395	0	0	0
Chr	0.01	0.1608	0.0543	0.4441	0.0041	0	0.0193	0.1341	0.0445	0.3395	0.0053	0	0.0188
B(b)FL	0.1	1.608	0.543	4.441	0.006	0	0.011	1.341	0.445	3.395	0.005	0	0.015
B(k)FL	0.1	1.608	0.543	4.441	0.007	0	0.011	1.341	0.445	3.395	0.01	0	0.015
B(a)P	1	16.08	5.43	44.41	4.42	0.81	15.06	13.41	4.45	33.95	3.82	0.85	9.28
In(132-cd)	0.1	1.608	0.543	4.441	0.044	0.014	0.091	1.341	0.445	3.395	0.062	0.014	0.103
DB(ah)A	1	16.08	5.43	44.41	1.48	0.94	5.4	13.41	4.45	33.95	1.01	0.87	4.49
B(ghi)P	0.01	0.1608	0.0543	0.4441	0.0019	0.0013	0.0061	0.1341	0.0445	0.3395	0.0031	0	0.0069
SV		Child	Adult	Elderly				Child	Adult	Elderly			
		0.00215	0.005608	0.005928				0.001332	0.001918	0.001306			
PEC					5.99109	1.77483	20.66647				4.94289	1.74325	13.98899

Source: [a]Oliveira et al.[59]
Abbreviations: FW, firewood; TEF, toxicity equivalency factor; T, Tyre.

Conclusion and Recommendation

This study provides a comprehensive analysis of the concentrations of PAHs in cattle and goat meats singed with firewood, LPG and tyres in Ghana. The results show significant variations in PAH concentrations depending on the fuel type used for singeing. Tyre-singed meats exhibited the highest PAH levels, particularly for Benzo[a]pyrene, a known carcinogen, which was significantly elevated compared to firewood and LPG-singed meats. This study confirms that the type of fuel used for singeing directly influences the concentration of PAHs in meat, with tyres producing the highest levels due to incomplete combustion and higher organic content. The health implications of consuming such meats are concerning, as the PAH concentrations in tyre-singed meats exceed regulatory limits set by the EFSA. This poses a significant health risk, particularly due to the carcinogenic nature of PAHs like Benzo[a]pyrene.

It is crucial to explore and promote alternative singeing methods that minimize PAH formation. LPG, which showed the lowest PAH levels among the tested fuels, could be recommended as a safer alternative to traditional fuels like firewood and tyres. Authorities should enforce stricter regulations on the use of tyres for singeing meats by imposing heavy penalties for non-compliance to protect public health. Also, continued research is essential to fully understand the impact of various singeing methods on PAH concentrations in meats. Future studies should explore additional fuel types and singeing techniques, as well as the effectiveness of various washing methods in reducing PAH levels.

Author Contributions

OEO: Conceptualization. PMA: methodology, data collection; visualization, investigation, writing original draft preparation. PMA, CO, ANE, CF, JR, OSC: Data curation, review and editing. ANE, CKF: Supervision. OEO: Supervision, writing, review and editing.

Abbreviations

AOAC, Association of Official Analytical Collaboration; EFSA, European Food Safety Authority; Em, emission; EU, European Union; Ex, excitation; FAO, Food and Agriculture Organization; FDA, Food and Drugs Authority (of Ghana); FLD, fluorescence detection; HPLC, high-performance liquid chromatography; IARC, International Agency for Research on Cancer; km^2, square kilometers; KNUST, Kwame Nkrumah University of Science and Technology; LPG, Liquefied Petroleum Gas; PAHs, Polycyclic Aromatic Hydrocarbons; PVDF, polyvinylidene fluoride; rpm, revolutions per minute; SPE, solid phase extraction; US, United States; US EPA, United States Environmental Protection Agency; UV, ultraviolet.

Data Availability

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Ethics Approval and Consent to Participate

UPH/CEREMAD/REC/MM93/0026.

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