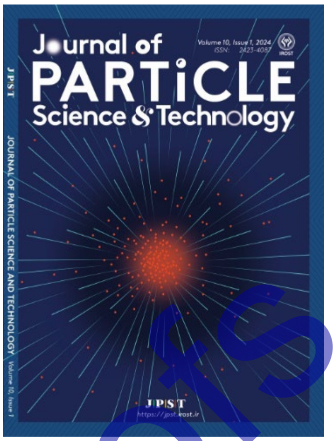

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# Toxicity and carcinogenic potentials of particulate-bound polycyclic aromatic hydrocarbons emitted at the epicenter of major abattoirs in Ilorin Metropolis, Kwara State, Nigeria

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## Abstract

Abattoirs have been identified as significant sources of aromatic hydrocarbons, particularly polycyclic aromatic hydrocarbons (PAHs), due to the combustion-intensive nature of meat processing activities, especially in developing countries such as Nigeria. These compounds are recognized as persistent environmental pollutants with carcinogenic, mutagenic, and toxicological effects, thereby posing substantial risks to both human health and ecological systems. Both passive and active air sampling techniques were employed to determine particulate-bound PAHs. A fabricated polyurethane foam (PUF) disk sampler, an air quality monitor, and Gas Chromatography-Mass Spectrometry analysis were used. The particle-bound polycyclic hydrocarbons measured at the abattoirs in Kwara State, Nigeria were 121-1557 µg/m³, 139-1744 µg/m³, and 265-3301 µg/m³, respectively, for the Sobi abattoir, and 165.25-684.5 µg/m³, 196.25-726.25 µg/m³, and 265-1178.25 µg/m³ for the Ipata abattoir.The toxicity potential (TP) for the particulate emissions at the Sobi abattoir ranged between 0.47 and 30.54, while the Ipata abattoir ranged between 0.54 and 18.75.The incremental cancer inhalation risk assessment (ILRC) for exposure within the Sobi and Ipata abattoirs was estimated at $3.319\times10^{-7}$ and $5.01\times10^{-7}$, respectively. The adverse non-cancer health risk was 1.481 and 0.300 for Sobi and Ipata, respectively. The study confirms that PAH emissions from these abattoirs pose measurable non-cancer health risks to exposed vulnerable populations and recommends adopting cleaner technologies, such as a solar or biogas-heated scalding system, to mitigate emissions and protect the vulnerable.

**Keywords:** Environmental Protection, Environmental Sampling, Environmental carcinogenesis, Developing Nation

## 1. Introduction

Aromatic hydrocarbon compounds, as air pollutants, form a distinctive category of organic molecules characterized by the presence of one or more benzene rings [1]. Their cyclic structure, featuring alternating single and double bonds, results in delocalized π-electron systems that impart exceptional stability and unique reactivity compared to non-aromatic hydrocarbons [2]. These conjugated systems exhibit characteristic ultraviolet-visible (UV-Vis) absorption spectra, reflecting their electronic and chemical behaviors. Aromatic compounds encompass diverse classes, including aromatic amines, heterocyclic aromatic compounds, and polycyclic aromatic hydrocarbons (PAHs), each with distinct physicochemical properties [3]. Atmospheric aging transforms these hydrocarbons into more reactive and toxic derivatives. These derivatives, often co-emitted and co-existfrom shared sources, pose significant health risks due to their mutagenic and carcinogenic potential [4]. The incomplete combustion of organic materials, particularly fossil fuels and biomass, introduces these compounds into the atmosphere. Their affinity for adsorption onto fine particulate matter enhances environmental distribution and human exposure risks [5].

Aromatic amines, defined by an amine group ($-NH_2$, $-NHR$, or $-NR_2$) attached to an aromatic ring, arise from industrial emissions, vehicular exhaust, and natural events like wildfires and microbial degradation [6]. Once airborne, they undergo photooxidation and adsorb onto particulates, contributing to secondary organic aerosol formation. These processes exacerbate health risks such as respiratory disorders, neurotoxicity, and cancer, necessitating stringent environmental control measures [7]. Heterocyclic aromatic amines (HAAs), which incorporate heteroatoms such as nitrogen, oxygen, or sulphur into their aromatic frameworks, are primarily byproducts of high-temperature combustion and pyrolysis [8]. HAAs are persistent, undergo atmospheric photochemical reactions, and adsorb onto particulate matter, contributing to long-range environmental transport. Exposure to HAAs is linked to severe health outcomes, including carcinogenicity and respiratory dysfunctions, reinforcing the imperative for regulatory interventions [9]. Polycyclic aromatic hydrocarbons (PAHs) are a major subgroup of persistent organic pollutants, composed of multiple fused benzene rings. Generated largely through the incomplete combustion of fossil fuels, biomass, and industrial processes [7]. PAHs occur in both gaseous and particulate phases, influencing their atmospheric transport and deposition [10]. Natural sources, such as wildfires, volcanic activity, and crude oil seepage, also contribute to PAH emissions [11].

The toxicological and environmental significance of PAHs has prompted extensive investigation [12]. Urban areas experience higher PAH concentrations primarily due to vehicular emissions, with additional contributions from industrial activities and domestic combustion [13]. Seasonal variations, particularly elevated wintertime concentrations, arise from reduced atmospheric mixing and increased heat-related combustion [14]. The atmospheric chemistry of PAHs is highly dynamic. Oxidative processes involving ozone and nitrogen oxides produce nitrated and oxygenated PAHs, compounds often exhibiting enhanced mutagenicity compared to their parent molecules [15]. Photochemical transformations also generate secondary organic aerosols, further contributing to particulate pollution and complicating air quality management [16]. Toxicologically, PAHs induce damage through DNA adduct formation, oxidative stress, and disruption of critical cellular signaling pathways [17]. Exposure has been epidemiologically linked to respiratory diseases, cardiovascular conditions, and multiple cancer types [18]. Given their bioaccumulative potential and persistence, PAHs are designated as persistent organic pollutants (POPs), necessitating global regulatory frameworks for their monitoring and control [19]. Monitoring atmospheric PAH concentrations is essential for air quality assessment and pollution management. Analytical techniques such as gas chromatography-mass spectrometry (GC-MS) are widely employed to detect and quantify PAHs [20]. These assessments inform source attribution, pollution mitigation strategies, and predictive modeling efforts [21].

The operational activities of abattoirs in Nigeria contribute substantially to the atmospheric emission of particulate-bound polycyclic aromatic hydrocarbons (PAHs). Research has shown that abattoirs, particularly those using biomass and fossil-fuel-based singeing methods, contribute significantly to local air pollution [22]. Heavy smoke and soot, primarily from biomass and fossil fuel combustion during the singeing of cattle, sheep, and goats, elevate local pollution levels. Workers and residents near abattoirs face heightened exposure to PAHs and thermal stress, posing serious health and environmental concerns. PAHspossess the ability to bind to critical human cellular components and enter the human body primarily through inhalation or ingestion [23]. Their role as markers of biomass combustion makes them critical for air quality monitoring. However, PAH emissions from abattoirs remain understudied. Thus, this study assesses the toxicity and carcinogenic risks of PAHs from major abattoirs in Ilorin Metropolis, Nigeria, and explores mitigation strategies. Two abattoirs using distinct singeing methods are analyzed for PAH composition, concentrations, and environmental impacts, aiming to inform pollution control measures.

## 2. Materials and Methods

### *2.1. Study Area*

Ilorin, the capital of Kwara State, Nigeria, has an estimated population of approximately 777,667, making it the seventh-largest city in Nigeria, according to the National Population Commission [24]. The geographical coordinates of Ilorin are 8.4799° N latitude and 4.5418° E longitude. The metropolis comprises three Local Government Areas (LGAs): Ilorin West, Ilorin East, and Ilorin South, covering an estimated land area of 105 $km^2$.Ilorin experiences a tropical climate characterized by two distinct seasons: the wet season, from April to October, and the dry season, from November to March. The annual rainfall varies between 1,000 mm and 1,500 mm, with peak precipitation occurring between September and early October. The mean monthly temperature remains relatively high throughout the year, ranging between 23°C and 28°C [25].

### *2.2. Sampling Sites*

For this study, two major abattoirs within Ilorin metropolis have been selected as sampling sites:

*A. Ipata Abattoir (Ipata Market)*: Ipata Abattoir is a highly populated meat processing center known for the large-scale slaughtering and singeing of goats and sheep for daily human consumption, utilizing kerosene as fuel. It is a major commercial hub in Ilorin, accommodating approximately 1,000 individuals at any given time, including traders, butchers, and customers, but fewer than 50 people in the abattoir section. The abattoir is located in close proximity to residential buildings. The geographical coordinates of the Ipata Abattoir are 8°29'58.49"N latitude and 4°33'43.13"E longitude.

*B. Dr. Abubakar Sola Saraki Memorial Abattoir*: The Dr. Abubakar Sola Saraki Memorial Abattoir, located along Sobi Road, Ilorin, is the largest and busiest abattoir in Kwara State. It primarily processes and singes cows for human consumption using dried biomass as fuel on a daily basis. The abattoir accommodates approximately 500 individuals at a time, including workers and meat traders. The geographical coordinates of this site are 8°31'36.90"N latitude and 4°33'08.61"E longitude.

### *2.3. Sampling Location*

PAH assessment was conducted at the epicenter of each abattoir, where slaughtering, singeing, and animal processing occur using both passive and active sampling simultaneously. An air sampling system was deployed at the core of the abattoir for one month.The air sampling system was positioned 1.5 meters above ground level, above the typical human breathing zone, to ensure representative measurements. Particulate sampling was conducted specifically during the singeing process, with a sampling duration of eight hours per day over four days at each abattoir. This method provided a comprehensive assessment of airborne particulate-bound PAHs emitted during meat-singeing operations.

### *2.4. Fabricated Polyurethane Foam Disk (PUF) Sampler: Passive sampling*

A fabricated passive sampler composed of two stainless steel bowls, one larger than the other, with diameters of 24 cm and 19 cm, respectively, was employed for air sampling. These bowls were mounted on a common axis that also supported the polyurethane foam (PUF) disk**,** ensuring stability and efficienct capture of airborne particulate emissions.The PUF passive samplers were suspended at a typical human breathing height of 1.5 to 2.0 meters above ground level in an open space, ensuring optimal air circulation without any obstructions. This setup facilitated the free movement of air around the sampler, allowing for effective pollutant collection through natural convection. The sampler was deployed for an exposure period of 30 days (one month**)** before retrieval for subsequent analysis.

The fabricated PUF sampler was selected due to its several advantages, including affordability, low maintenance costs, and the absence of electrical power requirements**,** making it suitable for long-term atmospheric monitoring. Additionally, the porous structureof thepolyurethane foam diskallows efficient entrapment of airborne particulates within its matrix. Once captured, these particulates are significantly less prone to re-suspension, ensuring reliable sample retention and analysis [26].The polyurethane foam disk sampler proved effective at capturing smoke deposits and airborne aromatic hydrocarbonsin the selected abattoirs, making it an essential tool in this research study.

**Figure 1.** Passive Sampler.

### *2.4.1. Polyurethane Foam (PUF) Sampling Method*

The preparation of the polyurethane foam (PUF) disk for sampling was conducted in accordance with the guidelines outlined by [27] and [28]. The procedure comprised the following sequential steps:

*a. Initial Cleaning*: The PUF disk was thoroughly rinsed with distilled water by immersing it in a 500 mL beaker filled with distilled water, ensuring complete saturation. Excess water was subsequently drained, and this process was repeated to enhance the removal of potential impurities.

*b. Solvent Conditioning*: The cleaned PUF disk was conditioned using acetone through a Soxhlet extraction process to eliminate residual contaminants.

*c. Secondary Extraction*: Following the acetone extraction, the foam underwent a second Soxhlet extraction using petroleum ether under identical conditions. The selection of petroleum ether was based on its effectiveness in extracting the target compounds intended for subsequent analysis.

*d. Drying and Storage*: Upon completion of the second extraction, excess solvent was carefully drained, and the PUF disk was placed in a desiccator for 24 hours to remove any remaining moisture. The dried foam was then securely wrapped in aluminum foil, labeled appropriately, and stored in a light-protected container until deployment for sampling.

### *2.4.2. Foam Disk Collection and Sampler Disassembly*

Upon completion of the sampling period, the polyurethane foam (PUF) disks were carefully collected to prevent contamination and ensure sample integrity for further analysis. The disassembly procedure followed the [28] and [29] protocol and was conducted as follows:

a. Thepassive sampler was carefully dismounted from its hanging support.

b. The hanging hook and hook adaptor were detached.

c. The upper bowl was removed by unscrewing the wing nut and detaching the nut.

d. The first flat washer and the longer distance tube were taken out, followed by the second flat washer using sterilized tweezers. The polyurethane foam disk was carefully extracted using tongs wrapped in aluminum foil to prevent contamination and then placed in a double-layered aluminum foil sheet.

e. The wrapped foam disk was labeled with a unique identifier code for proper tracking.

f. Finally, the remaining components of the sampler—including the shorter distance tube, flat washers, lower bowl, nut, and axis were fully disassembled for storage and maintenance.

*2.5. Air Sampler Monitoring: Active Sampling*

Active air sampling was conducted at the abattoir's epicenter using aparticulate matter (PM) air quality monitor to quantify the mass concentration of emissions generated during the singeing process. This approach enabled real-time measurement of airborne particulates, providing critical data on emission levels and atmospheric pollutant load within the abattoir environment.

**Figure 2.** Particulate Air Monitor.

Air sampling was conducted using an active monitoring approach at the designated meat singeing sites. Sampling was performed hourly over eight hours, from 5:30 AM to12:30 PM, the main time for meat singeing processing,for four consecutive daysat each study location(Ipata and Sobi abattoirs). The air quality monitor was utilized to measure and record particulate matter (PM) concentrations,specifically $PM_{2.5}$, $PM_{10}$, and Total Suspended Particles (TSP), to assess the extent of atmospheric emissions from the singeing process of meat.

### *2.5.1. Sample Analysis*

Based on established research methodologies, following the passive sampling of aromatic hydrocarbons in the selected study areas, the polyurethane foam (PUF) disks were carefully retrieved from the sampling equipment. The trapped particulate-bound aromatic hydrocarbons were subsequently extracted using Soxhlet extraction with dichloromethane (DCM) as the organic solvent. The extracted samples were then prepared for analysis using Gas Chromatography-Mass Spectrometry (GC-MS)

A Gas Chromatograph (GC) from Agilent Technologies, USA, coupled with a Mass Spectrometer (5975C) equipped with a triple-axis detector and an auto-injector (10µLsyringe), was utilized for compound identification and quantification. Helium gas served as the carrier gas. Chromatographic separation was performed using a capillary column with the following specifications: 30 m length, 0.2 µm internal diameter, and 250 µm film thickness, treated with phenyl methyl siloxane.The GC-MS operational parameters were as follows: Ion Source Temperature (EI): 250°C, Interface Temperature: 300°C, Column Pressure: 16.2 psia, Injection Mode: Split mode (split ratio 1:50), Injection Temperature: 300°C, Oven Temperature Program: Initial temperature: 35°C (held for 5 min); Ramp 1: Increased to 150°C at 4°C/min; Ramp 2: Increased to 250°C at 20°C/min and held for 5 min;Total elution time: 47.5 minutes.The system was controlled, and data acquisition was conducted using MS Solution software provided by the instrument manufacturer. The identification of aromatic hydrocarbon compounds was carried out by comparing the mass spectra of detected compounds with reference spectra from the National Institute of Standards and Technology (NIST) Library

## 3. Results and discussion

### *3.1. Particulate Sampling Results*

The results of the particulate matter (PM) sampling conducted at the Sobi and Ipata abattoirs are presented in Tables 1 to 6. These tables provide a detailed account of the daily and hourly concentrations of particulate emissions recorded over four consecutive days. The recorded values include $PM2.5_{2.5}$, $PM10_{10}$, and Total Suspended Particles (TSP), along with their corresponding average concentrations.

**Sobi Abattoir**

Table 1 presents the hourly $PM_{2.5}$ concentrations over the four-day sampling period. $PM_{2.5}$ ranges between 121µg/m³ and 1557µg/m³, while Table 2 displays the hourly $PM_{10}$ concentration that ranges from 139 µg/m³ to 1744µg/m³. Table 3 summarizes the hourly TSP concentrations that range from 265µg/m³ to 3301µg/m³

**Ipata Abattoir**

Table 4 presents the $PM_{2.5}$ concentrations over four days, which range from 165.25 µg/m³ to 684.5 µg/m³,and Table 5 details the $PM_{10}$ concentrations, which range from 196.25 µg/m³ to 726.25 µg/m³.Table 6 outlines the TSP concentrations, which range from 265µg/m³ to 1178.25 µg/m³.

**Table 1**. $PM_{2.5}$ (µg/m³) particulate concentrations from singeing operation at Sobi abattoir.

| S/N | Day 1 (µg/m³) | Day 2 (µg/m³) | Day 3 (µg/m³) | Day 4 (µg/m³) | Average (µg/m³) |
|---|---|---|---|---|---|
| 1 | 190 | 281 | 191 | 267 | 232.25 |
| 2 | 447 | 714 | 646 | 849 | 664 |
| 3 | 464 | 749 | 889 | 939 | 760.25 |
| 4 | 1140 | 822 | 944 | 999 | 976.25 |
| 5 | 994 | 907 | 1221 | 1338 | 1115 |
| 6 | 584 | 974 | 705 | 1557 | 955 |
| 7 | 210 | 138 | 149 | 126 | 155.75 |
| 8 | 114 | 121 | 135 | 119 | 122.25 |

**Table 2.** $PM_{10}$ (µg/m$^3$) particulate concentrations from singeing operation emissions at Sobi abattoir.

| S/N | Day 1 (µg/m$^3$) | Day 2 (µg/m$^3$) | Day 3 (µg/m$^3$) | Day 4 (µg/m$^3$) | Average (µg/m$^3$) |
|---|---|---|---|---|---|
| 1 | 208 | 327 | 226 | 281 | 260.5 |
| 2 | 492 | 865 | 740 | 936 | 758.25 |
| 3 | 544 | 824 | 1060 | 962 | 847.5 |
| 4 | 1565 | 968 | 1565 | 880 | 1244.5 |
| 5 | 830 | 802 | 1345 | 1638 | 1153.75 |
| 6 | 728 | 1375 | 821 | 1744 | 1167 |
| 7 | 247 | 160 | 139 | 154 | 175 |
| 8 | 174 | 148 | 146 | 146 | 153.5 |

**Table 3.** TSP (µg/m$^3$) particulate concentrations from singeing operation emissions at Sobi abattoir.

| S/N | Day 1 (µg/m$^3$) | Day 2 (µg/m$^3$) | Day 3 (µg/m$^3$) | Day 4 (µg/m$^3$) | Average (µg/m$^3$) |
|---|---|---|---|---|---|
| 1 | 398 | 608 | 417 | 548 | 492.75 |
| 2 | 939 | 1579 | 1386 | 1785 | 1422.25 |
| 3 | 1008 | 1573 | 1949 | 1901 | 1607.75 |
| 4 | 2705 | 1790 | 2509 | 1879 | 2220.75 |
| 5 | 1824 | 1709 | 2566 | 2976 | 2268.75 |
| 6 | 1312 | 2349 | 1526 | 3301 | 2122 |
| 7 | 457 | 298 | 288 | 280 | 330.75 |
| 8 | 318 | 269 | 281 | 265 | 283.25 |

**Table 4.** $PM_{2.5}$ (µg/m$^3$) particulate concentrations from singeing operation emissions at Ipata abattoir.

| S/N | Day 1 (µg/m$^3$) | Day 2 (µg/m$^3$) | Day 3 (µg/m$^3$) | Day 4 (µg/m$^3$) | Average (µg/m$^3$) |
|---|---|---|---|---|---|
| 1 | 128 | 176 | 186 | 171 | 165.25 |
| 2 | 200 | 388 | 228 | 295 | 277.75 |
| 3 | 356 | 437 | 371 | 374 | 384.5 |
| 4 | 402 | 780 | 526 | 526 | 558.5 |
| 5 | 451 | 920 | 726 | 641 | 684.5 |
| 6 | 340 | 622 | 611 | 441 | 503.5 |
| 7 | 186 | 211 | 202 | 315 | 228.5 |
| 8 | 178 | 195 | 131 | 203 | 176.75 |

**Table 5.** $PM_{10}$ (µg/m$^3$) particulate concentrations from singeing operation emissions at Ipata abattoir.

| S/N | Day 1 (µg/m$^3$) | Day 2 (µg/m$^3$) | Day 3 (µg/m$^3$) | Day 4 (µg/m$^3$) | Average (µg/m$^3$) |
|---|---|---|---|---|---|
| 1 | 156 | 206 | 215 | 208 | 196.25 |
| 2 | 235 | 397 | 268 | 337 | 309.25 |
| 3 | 418 | 503 | 403 | 423 | 436.75 |
| 4 | 492 | 799 | 611 | 577 | 619.75 |
| 5 | 530 | 912 | 760 | 703 | 726.25 |
| 6 | 400 | 748 | 728 | 549 | 606.25 |
| 7 | 217 | 274 | 271 | 389 | 287.75 |
| 8 | 208 | 229 | 215 | 250 | 225.5 |

**Table 6.** TSP (µg/m$^3$) particulate concentrations from singeing operation emissions at Ipata abattoir.

| S/N | Day 1 (µg/m$^3$) | Day 2 (µg/m$^3$) | Day 3 (µg/m$^3$) | Day 4 (µg/m$^3$) | Average (µg/m$^3$) |
|---|---|---|---|---|---|
| 1 | 284 | 382 | 401 | 379 | 361.5 |
| 2 | 435 | 785 | 496 | 632 | 587 |
| 3 | 774 | 940 | 774 | 797 | 821.25 |
| 4 | 894 | 1579 | 1137 | 1103 | 1178.25 |
| 5 | 981 | 1832 | 1486 | 1341 | 1410 |
| 6 | 740 | 1370 | 1339 | 990 | 1109.75 |
| 7 | 403 | 585 | 473 | 704 | 541.25 |
| 8 | 386 | 424 | 346 | 453 | 402.25 |

The measured hourly concentration of the particulate at the Sobi abattoir, tabulated in Table 7, is the average hourly concentration of the particulate calculated in Tables 1, 2, and 3, and the extrapolated concentration was calculated from the measured concentration using the air stability formula.

The measured hourly concentrations of the particulate concentrations at the Ipata abattoir, tabulated in Table 8,the average hourly concentrations of the particulate emissions from Tables 4, 5, and 6, and the extrapolated concentration was calculated from the measured concentration using the air stability formula.

The air stability formula is expressed mathematically from [30] and [31].

$$C_2 = C_1 \times F$$

where $C_2$ is the concentration of particulate at time $t_2$, $C_1$ is the concentration of particulate at time $t_1$, andF is the factor to convert from the concentration at time $t_1$ to time $t_2$, which is expressed mathematically as:

$$F = \left(\frac{t_1}{t_2}\right)^n$$

where $n$ is the stability-dependent exponent and is a constant (0.28), $t_1$ is the time period at concentrations $C_1$ (1 hour), and $t_2$ is the time period at concentration $C_2$ (24 hours).

**Table 7.** Measured concentration (1-hour) vs. Extrapolated concentrations (24-hours) from the singeing operation emissions at Sobi abattoir.

| **S/N** | **PM2.5 (µg/m$^3$)** | **PM10 (µg/m$^3$)** | **TSP (µg/m$^3$)** | **PM2.5 (µg/m$^3$)** | **PM10 (µg/m$^3$)** | **TSP (µg/m$^3$)** |
|---|---|---|---|---|---|---|
| | | **1 HR** | | | **24 HR** | |
| 1 | 232.25 | 260.5 | 492.75 | 95.41 | 107.01 | 202.421 |
| 2 | 664 | 758.25 | 1422.25 | 272.77 | 311.49 | 584.26 |
| 3 | 760.25 | 847.5 | 1607.75 | 312.31 | 348.15 | 660.46 |
| 4 | 976.25 | 1244.5 | 2220.75 | 401.04 | 511.24 | 912.28 |
| 5 | 1115 | 1153.75 | 2268.75 | 458.04 | 473.96 | 932 |
| 6 | 955 | 1167 | 2122 | 392.31 | 479.4 | 871.72 |
| 7 | 155.75 | 175 | 330.75 | 63.98 | 71.9 | 135.87 |
| 8 | 122.25 | 153.5 | 283.25 | 50.22 | 63.06 | 116.36 |

**Table 8.** Measured concentration (1-hour) vs Extrapolated concentrations (24-hours) from the singeing operation emissions at Ipata abattoir.

| S/N | $PM_{2.5}$ (µg/m$^3$) | $PM_{10}$ (µg/m$^3$) | TSP (µg/m$^3$) | $PM_{2.5}$ (µg/m$^3$) | $PM_{10}$ (µg/m$^3$) | TSP (µg/m$^3$) |
|---|---|---|---|---|---|---|
| | | 1 HR | | | 24 HR | |
| 1 | 165.25 | 196.25 | 361.5 | 67.88 | 80.62 | 148.5 |
| 2 | 277.75 | 309.25 | 587 | 114.1 | 127.04 | 241.14 |
| 3 | 384.5 | 436.75 | 821.25 | 157.95 | 179.42 | 337.37 |
| 4 | 558.5 | 619.75 | 1178.25 | 229.43 | 254.59 | 484.03 |
| 5 | 684.5 | 726.25 | 1410 | 281.19 | 298.34 | 579.23 |
| 6 | 503.5 | 606.25 | 1109.75 | 206.84 | 249.04 | 455.89 |
| 7 | 228.5 | 287.75 | 541.25 | 93.87 | 118.21 | 222.35 |
| 8 | 176.75 | 225.5 | 402.25 | 72.61 | 92.64 | 165.24 |

Table 9 shows the statutory limits concentration used in the calculation of the potential toxicity of particulate emitted at the sampling sites are from the EPA (Environmental Protection Agency), WHO (World Health Organization), ASHRAE (American Society of Heating, Refrigerating and Air-condition Engineers), and FMENV (Federal Ministry of Environment) for the three different particulates ($PM_{2.5}$, $PM_{10}$, and TSP).

According to [32] and [33], the toxicity potential of particulate matter is a quantitative measure of the severity of the potential physical harm a unit pollutant emission poses to the environment, and it is expressed mathematically as a ratio of the measured PM concentration to the statutory limit concentration.

$$TP = \frac{C_i(t)}{SL_i(t)}$$

where TP represents the toxicology potential of pollutant *I*, $C_i$ (*t*) is the measured concentration of particulate matter *i* at time *t* (µg/m$^3$), and$SL_i$ (*t*) is the statutory concentration limits of particulate matter *i* (µg/m$^3$) (The guideline limit set for $PM_{10}$ and $PM_{2.5}$).

**Table 9.** Air quality standard for maximum 24-hourconcentration (µg/m³) of inhalable particulates

| **AUTHORITIES** | **$PM_{10}$** | **$PM_{2.5}$** | **TSP** |
|---|---|---|---|
| USEPA (µg/$m^3$) | 150 | 35 | - |
| WHO (µg/$m^3$) | 50 | 25 | - |
| ASHRAE (µg/$m^3$) | 50 | 15 | - |
| FMENV (µg/$m^3$) | 100 | - | 250 |

**Note:** U.S. Environmental Protection Agency (USEPA); World Health Organisation (WHO); American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE); Federal Ministry of Environment in Nigeria (FMENV).

**Table 10.** Toxicity potentials of particulates from singeing operations emissions at Sobi abattoir.

| **S/N** | **PM2.5 (µg/$m^3$)** | | | **PM10 (µg/$m^3$)** | | | | **TSP (µg/$m^3$)** |
|---|---|---|---|---|---|---|---|---|
| | **$TP_{EPA}$** | **$TP_{WHO}$** | **$TP_{ASHRAE}$** | **$TP_{EPA}$** | **$TP_{WHO}$** | **$TP_{ASHRAE}$** | **$TP_{FMENV}$** | **$TP_{FMENV}$** |
| 1 | 2.73 | 3.82 | 6.36 | 0.71 | 2.14 | 2.14 | 1.07 | 0.81 |
| 2 | 7.79 | 10.92 | 18.18 | 2.08 | 6.23 | 6.23 | 3.11 | 2.34 |
| 3 | 8.92 | 12.49 | 20.82 | 2.32 | 6.96 | 6.96 | 3.48 | 2.64 |
| 4 | 11.46 | 16.04 | 26.74 | 3.41 | 10.22 | 10.22 | 5.11 | 3.65 |
| 5 | 13.086 | 18.32 | 30.54 | 3.16 | 9.48 | 9.48 | 4.74 | 3.73 |
| 6 | 11.21 | 15.69 | 26.15 | 3.2 | 9.59 | 9.59 | 4.79 | 3.49 |
| 7 | 1.828 | 2.56 | 4.27 | 0.48 | 1.44 | 1.44 | 0.72 | 0.54 |
| 8 | 1.435 | 2.0 | 3.35 | 0.42 | 1.26 | 1.26 | 0.63 | 0.47 |

**Table 11.** Toxicity potentials of particulates from singeing operations emissions at Ipata abattoir.

| **S/N** | **$PM_{2.5}$ (µg/$m^3$)** | | | **$PM_{10}$ (µg/$m^3$)** | | | | **TSP (µg/$m^3$)** |
|---|---|---|---|---|---|---|---|---|
| | **$TP_{EPA}$** | **$TP_{WHO}$** | **$TP_{ASHRAE}$** | **$TP_{EPA}$** | **$TP_{WHO}$** | **$TP_{ASHRAE}$** | **$TP_{FMENV}$** | **$TP_{FMENV}$** |
| 1 | 1.94 | 2.72 | 4.52 | 0.54 | 1.61 | 1.61 | 0.81 | 0.59 |
| 2 | 3.26 | 4.56 | 7.61 | 0.85 | 2.54 | 2.54 | 1.27 | 0.96 |
| 3 | 4.51 | 6.32 | 10.53 | 1.2 | 3.59 | 3.59 | 1.79 | 1.35 |
| 4 | 6.56 | 9.18 | 15.3 | 1.7 | 5.09 | 5.09 | 2.55 | 1.94 |
| 5 | 8.03 | 11.24 | 18.75 | 1.99 | 5.97 | 5.97 | 2.98 | 2.32 |
| 6 | 5.91 | 8.27 | 13.79 | 1.66 | 4.98 | 4.98 | 2.49 | 1.82 |
| 7 | 2.68 | 3.75 | 6.26 | 0.79 | 2.36 | 2.36 | 1.18 | 0.89 |
| 8 | 2.07 | 2.9 | 4.84 | 0.62 | 1.85 | 1.85 | 0.93 | 0.66 |

### *4.2. GC-MS Sample Analysis Results*

Figures 3 and 4 show the GC/MS sample analysis results from the Sobi and Ipata abattoirs, respectively. Tables 12 and 13 show the aromatic compounds present in the foam samplers from the Sobi and Ipata abattoirs, respectively. Both show the identified PAHs and their concentrations for Sobi and Ipata abattoirs, respectively.

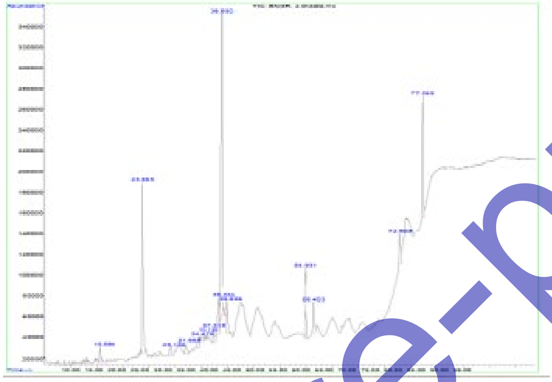

**Figure 3.** GC/MS result from the Sobi abattoir.

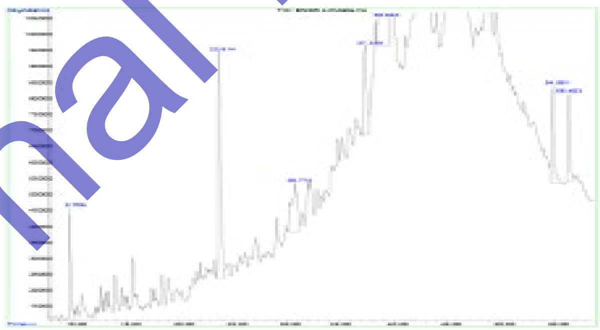

**Figure 4.** GC/MS result from the Ipata abattoir.

**Table 12.** GC/MS analysis result from Sobi abattoir.

| Spec line | Peak height | Mass peak | Compound name | Compound group |
|---|---|---|---|---|
| 1 | 14894 | 15.594 | 2,2,4-trimethyl-3-nitromethylpentanoic acid | Aromatic amines |
| 2 | 164719 | 23.665 | 2,4-bis(1,1-dimethyl)phenol | Heterocyclic aromatic compounds |
| 3 | 8899 | 29.146 | 6-amino-[1,3]dioxolo[4,5-g]quinoline-7-carboxamide | Aromatic amines |
| 4 | 9550 | 31.989 | 3,6-dibutyl-2,5-dimethylpyrazine | Aromatic amines |
| 5 | 10665 | 34.476 | 2-methyl-1H-phenanthro[3,4-d]imidazol-10-ol | PAH |
| 6 | 8382 | 35.136 | Bicyclo[2.2.2]octane-1,4-dicarboxylic acid | Heterocyclic aromatic compounds |
| 7 | 12423 | 37.318 | 10-methylanthracene-9-carboxyaldehyde | PAH |
| 8 | 34629 | 38.334 | 4,5,9,10-tetrahydro-pyrene | PAH |
| 9 | 292965 | 38.892 | 8-cyano-6,7-dihydro-2-dimethylaminoimidazo[1,2-a]-1,3,5-triazin-4-(8H)-one | Aromatic amines |
| 10 | 31668 | 39.856 | 1-(4-methylphenyl)-4-phenylbuta-1,3-diene | Heterocyclic aromatic compounds |
| 11 | 68173 | 54.931 | 1-acenapthylenone | PAH |
| 12 | 28798 | 56.403 | 2,6-dinitro-benzenamine | Aromatic amines |
| 13 | 28907 | 72.9 | 2-ethyl phenanthrene | PAH |
| 14 | 117094 | 77.265 | 3,5-bis(1,1-dimethylethyl) | Heterocyclic aromatic compounds |

**Table 13.** GC/MS analysis result from Ipata abattoir.

| Spec line | Peak height | Mass peak | Compound name | Compound group |
|---|---|---|---|---|
| 1 | 35234 | 9.706 | Isopropylbabituric acid | Aromatic amines |
| 2 | 70648 | 23.614 | 2,6-bis(1,1-dimethylethyl)phenol | Heterocyclic aromatic compounds |
| 3 | 15112 | 30.771 | 9-ethyl-1,9-dihydro-6H-purine-6-thione | Aromatic amines |
| 4 | 27574 | 37.319 | 6,7,8,8-benzo[b]fluorene | PAH |
| 5 | 307556 | 38.943 | 8-cyano-6,7-dihydro-2-dimethylaminoimidazo[1,2-a]-1,3,5-triazin-4(8H)-one | Aromatic amines |
| 6 | 30476 | 54.881 | 1,3-dinitrobenzene | Aromatic amines |
| 7 | 27203 | 56.403 | 1,1-diphenylmethanol | Heterocyclic aromatic compounds |

**Table 14.** The identified PAHs and their percentage concentration in the foam extract.

| Site | Spec Line | Identified PAH Compounds | Percentage Concentration |
|---|---|---|---|
| Sobi | 5 | 2-methyl-1H-phenanthro[3,4-d]imidazol-10-ol | 2.13% |
| | 7 | 10-methylanthracene-9-carboxyaldehyde | 2.13% |
| | 8 | 4,5,9,10-tetrahydro-pyrene | 4.44% |
| | 11 | 1-acenapthylenone | 5.49% |
| | 13 | 2-ethyl phenanthrene | 4.68% |
| Ipata | 4 | 6,7,8,8-benzo[b]fluorine | 4.82% |

Patel *et al.* assessed the toxicity of the polycyclic aromatic hydrocarbon compounds of the contaminated air samples analyzed with GC/MS by calculating for the incremental cancer risk inhalation (ILRC) assessment using the following equations [1]:

$$ILRC = CD_i \times CSF$$

where $CD_i$ is the chronic daily intake (mg/kg/day) and CSF is the cancer slope factor for each individual aromatic hydrocarbon compound (mg/kg/day)$^{-1}$.

The cancer slope factor is given as:

$$CSF = C_A \times TEF$$

where $C_A$ is the concentration of aromatic hydrocarbon compounds in air (mg/m$^3$) andTEF is the toxicity equivalent factor for each of the identified polycyclic aromatic hydrocarbon compounds.

The chronic daily intake is calculated from:

$$CD_i = \frac{C_A \times IR \times ET \times ED \times EF}{BW \times AT}$$

where $IR$ is the inhalation rate for adults (m$^3$/hr), $BW$= body weight (57.8 kg, the average BW of workers from the questionnaire), $ET$ is theexposure time (8 hrs/day for workersfrom the questionnaire), $EF$is the exposure frequency (355 days/year for workersfrom the questionnaire), $ED$is the exposure duration (25 years for workersfrom the questionnaire),and $AT$ is the average time for cancer estimation (60 years × 365 day/year from the questionnaire).

The adverse non-carcinogenic health risk associated with inhalation of aromatic hydrocarbon compounds was assessed using the Hazard Quotient Index (HQ)

$$HQ = \frac{EDI}{RfC}$$

where EDI is the estimated daily intake of polycyclic aromatic hydrocarbon compounds (mg/m$^3$) and $RfC$ is the reference dose concentration of a polycyclic aromatic hydrocarboncompound (mg/m$^3$).

The estimated daily intake is calculated as:

$$EDI = \frac{C_A \times IR \times ED \times EF}{AT \times BW}$$

**Table 15.** Cancer Inhalation Risk Assessment and the Hazard Quotient factor.

| **Sample site** | **(C*i*) mg/m$^3$** | **CA (mg/m$^3$/day)** | **CDI (mg/kg/day)** | **CSF (mg/kg/day)-1** | **ILRC** | **EDI (mg/m$^3$)** | **HQ** |
|---|---|---|---|---|---|---|---|
| **Sobi** | 1.767 | 0.059 | 0.0027 | 0.000059 | 1.59×10$^{-7}$ | 3.34×10$^{-4}$ | 0.167 |
| | 1.77 | 0.059 | 0.0027 | 0.00059 | 1.60×10$^{-6}$ | 3.34×10$^{-4}$ | 0.167 |
| | 3.687 | 0.123 | 0.0056 | 0.000123 | 6.89×10$^{-7}$ | 6.97×10$^{-4}$ | 0.348 |
| | 4.564 | 0.152 | 0.0069 | 0.000152 | 1.04×10$^{-7}$ | 8.61×10$^{-4}$ | 0.431 |
| | 3.885 | 0.13 | 0.0059 | 0.00013 | 7.67×10$^{-7}$ | 7.36×10$^{-4}$ | 0.368 |
| **Total** | | | | | 3.319×10$^{-7}$ | | 1.481 |
| **Ipata** | 3.194 | 0.106 | 0.0048 | 0.000106 | 5.01×10-7 | 6.00×10$^{-4}$ | 0.300 |
| **Total** | | | | | 5.01×10-7 | | 0.300 |

Table 7 shows hourly measured concentrations of particulate emissions for the Sobi abattoir ranging from 122.25 to 1115 µg/m$^3$ for PM$_{2.5}$, 153.5-1244.5 µg/m$^3$ for PM$_{10}$, and 283.5-2268.75 µg/m$^3$ for TSP, with the extrapolated 24-hour concentrations of the particulate emissions rangingfrom 50.22 -458.04 µg/m$^3$ for PM$_{2.5}$, 63.06-511.24 µg/m$^3$ for PM$_{10}$, and 116.36-912.28 µg/m$^3$for TSP. Similarly,Table 8 shows the measured concentrations ranging from 165.25- 684.5 µg/m$^3$ for PM$_{2.5}$, 196.25-726.25 µg/m$^3$ for PM$_{10}$, and 361.5-1178.25 µg/m$^3$ for TSP, with the extrapolated 24-hour concentrations ranging from 67.88-281.19 µg/m$^3$ for PM$_{2.5}$, 80.62-298.34 µg/m$^3$ for PM$_{10}$, and 148.5-455.89 µg/m$^3$ for TSP.

Table 9 shows the standard set used by environmental authorities USEPA, WHO, ASHRAE, and FMENV) for the daily concentration limit of particulate concentrations in air. As shown, the extrapolated values failed to comply with the guidelines, and all their concentrations exceeded the standard.

Table 10 shows the evaluated toxicity potentials (TP) of $PM_{2.5}$, $PM_{10}$,and TSP, ranging from 1.435- 30.54, 0.42-10.22, and 0.47-5.11, respectively, for the Sobi abattoir using USEPA, WHO, ASHRAE, and FMENV guidelines. The most exceed limit was the FMENV for $PM_{2.5}$, and the least was the EPA for $PM_{10}$.

Table 11 shows the TP of $PM_{2.5}$, $PM_{10}$,and TSP ranging from 1.94-18.75, 0.54-5.97 and 0.66-2.98, respectively, for the Ipata abattoir based on the guidelines of USEPA, WHO, ASHRAE and FMENV. The most breached limit was the FMENV for $PM_{2.5}$, and the least breached was USEPA for $PM_{10}$.

The majority of the toxicity potential values were found to exceed unity, indicating that meat singeing and charring operations at both Sobi and Ipata abattoirs occur under hazardous conditions characterized by intense heat (elevated temperatures). These conditions pose significant health risks to workers, butchers, and the surrounding environment, potentially causing skin and eye irritation as well as adverse effects on the overall human physiological system. Therefore, it is imperative to adopt a non-polluting alternative for meat charring to mitigate these health and environmental risks.

Table 15 shows that the incremental cancer inhalation risk assessment (ILRC) for workers and traders in the Sobi abattoir area was estimated at $3.319 \times 10^{-7}$ an adverse non-cancer health risk (HQ) of 1.481. For the Ipata abattoir, the ILRC is $5.01 \times 10^{-7}$ with an HQ of 0.300. The estimation of the ILRC for the Sobi abattoir was greater than that of the Ipata abattoir.

According to USEPA standards, the incremental lifetime cancer risk (ILCR) classifies values below $1\times10^{-6}$ as non-carcinogenic and values above $1\times10^{-4}$ as carcinogenic [34]. The value of ILCR at the Sobi abattoir was $3.319\times10^{-7}$, and that at the Ipata abattoir was $5.01\times10^{-7}$..Both are well within safe limits, and no significant cancer risk is associated with the exposure pathway or scenario analyzed.

HQ values greater than1 are considered anadverse non-cancer health effect of concern, while HQ ≤ 1 are considered acceptable or at safe level [35]. The HQ value at the Sobi abattoir was greater than unity [27], indicating that exposure to the particulate bound aromatic hydrocarbon compounds at Sobi abattoir has the potential to cause non-carcinogenic effects to the workers, traders, and nearby residents. In contrast, at the Ipata abattoir, no adverse health effects are expected under current exposure conditions.

### *4.4. Proposed Strategies for Mitigating and Controlling Particulate Aromatic Hydrocarbon emissions from Nigerian Abattoirs*

The process of singeing meat is a fundamental and widely practiced stage in meat processing, primarily aimed at the complete removal of hair from animal carcasses while preparing the skin for subsequent butchering. However, this practice results in the release of particulate-bound polycyclic aromatic hydrocarbons (PAHs) into the atmosphere, contributing to significant environmental and health hazards. Shortand long-term exposure to these pollutants degrades air quality and negatively impacts both human health and the ecosystem.

Given the detrimental effects associated with biomass and fuel combustion during the singeing process, the adoption of scaldingas an alternative method is strongly recommended. Scalding involves the application of hot water to the carcass, followed by mechanical or manual friction to facilitate hair removal. This process heats the skin within a controlled temperature range, ensuring the dermal extracellular matrix remains intact while effectively loosening the hairs. Hair removal can then be achieved through mechanical means, such as paddle washers or cylindrical rollers, or manually using a scraping knife. This method is significantly more environmentally sustainable, as it eliminates the emission of airborne pollutants [33].

The hot water required for the scalding process can be generated through solar water heating systemsor, alternatively, by utilizing biogasproduced from the anaerobic digestion of animal dung collected during the butchering process. This approach not only mitigates PAH emissions but also promotes sustainable energy use within abattoirs, thereby reducing their overall environmental footprint.

## 5. Conclusions

This study investigated the composition and concentration of particulate-bound polycyclic aromatic hydrocarbons (PAHs) within the broader spectrum of aromatic hydrocarbons emitted from two selected Nigerian abattoirs in Kwara state: Sobi and Ipata.

The toxicity potentials of the detected particulate-bound PAHs were evaluated. The findings indicated that particulate-bound PAHs exceeded permissible thresholds, suggesting that the routine operational practices at these abattoirs substantially contribute to environmental degradation and contamination, thereby posing notable risks to public health. In addition, the carcinogenic potential of the identified particulate-bound PAHs at the selected abattoirs was assessed. The findings indicated that the routine operations at these abattoirs do not pose a significant carcinogenic threat to individuals upon exposure but suggests a high potential for adverse non-carcinogenic health effects To mitigate these risks, the study recommends the adoption of alternative scalding techniques, specifically those utilizing solar-heated or biogas-heated water, as sustainable and environmentally sound alternatives to the traditional open-flame singeing practices currently employed in Nigerian abattoirs.

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