ISSN 2348-1218 (print)
International Journal of Interdisciplinary Research and Innovations ISSN 2348-1226 (online)
Vol. 13, Issue 4, pp: (103-114), Month: October 2025 - December 2025, Available at: www.researchpublish.com

HIGH-RESOLUTION MULTI-SENSOR ASSESSMENT OF INDOOR AIR QUALITY IN A SEMI-MECHANIZED NIGERIAN ABATTOIR AND ENGINEERING-BASED EVALUATION OF MITIGATION STRATEGIES

Olatunji Omoniyi[1,2], Christopher O. Akinbile[1]

[1]Department of Agricultural and Environmental Engineering, Federal University of Technology Akure, Nigeria.

[2]Department of Agricultural and Bio-Environmental Engineering, Federal College of Agriculture Akure, Nigeria

DOI: https://doi.org/10.5281/zenodo.17863576

Published Date: 09-December-2025

Abstract: **Semi-mechanized abattoirs are central to Nigeria's meat supply, yet their slaughter halls remain largely unregulated zones, with workers exposed to a range of airborne contaminants daily. This study investigates the air quality inside one of the busiest semi-mechanized abattoirs in Akure, southwestern Nigeria. A low-cost, precisely calibrated sensor system was deployed to monitor $PM_{2.5}$, PM_{10}, ammonia (NH_3), and hydrogen sulfide (H_2S) every thirty minutes over a ten-week period. After data cleaning, 1,900 reliable observations were obtained. Findings were striking. Average concentrations of $PM_{2.5}$ and PM_{10} exceeded both WHO and NESREA guidelines, at times by three to five times the recommended limits. Additionally, ammonia and hydrogen sulfide levels peaked during periods of intense slaughter activity, when wastewater accumulated, humidity increased, and air movement was minimal. Random Forest Regression analysis indicated that the number of animals processed, humidity, and ventilation rates were the primary drivers of pollution, collectively accounting for up to half of the observed variability. The most severe pollution episodes including $PM_{2.5}$ above 120 µg/m³ or ammonia over 6 ppm sustained for at least one hour were consistently recorded on the busiest market days, particularly when humidity exceeded 80% and the air was stagnant. A decision-matrix approach identified improved cross-ventilation as the most effective and practical mitigation, reducing pollution by approximately 28–30%. More frequent removal of paunch contents and adjustments to work schedules also contributed to reductions, but to a lesser extent. While biofilters could theoretically offer superior air cleaning, their costs remain prohibitive for facilities of this type. This study goes beyond pollutant measurement, demonstrating how high-resolution sensor data and advanced analysis can inform interventions aligned with NESREA standards. The main conclusion is clear: enhanced ventilation, real-time air quality monitoring, and strengthened health policies are essential to protect workers and the surrounding community. These measures represent meaningful progress for public health and advance Nigeria's efforts toward achieving SDG 3 and SDG 11.**

Keywords: **semi-mechanized abattoir; indoor air quality; particulate matter ($PM_{2.5}$, PM_{10}); ammonia (NH_3); hydrogen sulfide (H_2S); low-cost sensors; Random Forest Regression; ventilation mitigation; occupational exposure; NESREA guidelines; high-resolution monitoring; environmental engineering.**

1. INTRODUCTION

Semi-mechanized abattoirs sit at the heart of Nigeria's livestock industry. They keep millions of city dwellers supplied with meat and give steady work to butchers, cleaners, transporters, and plenty of others (Ogunjuyigbe et al. 2020). But for all their importance, these abattoirs usually slip through the cracks when it comes to regulation. Equipment for keeping the environment in check is often basic or missing altogether. Inside the slaughtering hall where the main action happens, from carcass dressing to washing and the first cuts. It's busy, crowded, and, honestly, not easy to manage from a public health angle. Workers pack in shoulder to shoulder. Animals come through nonstop. Airflow is poor. All this turns the hall into a hot, sticky space loaded with heat, moisture, bioaerosols, and strong smells.

1.1 Occupational and Environmental Health

Compared to their counterparts in more industrialised settings, abattoir workers in Low- and Middle-Income Countries (LMICs) bear a disproportionate burden of occupational illness. Particulate matter exposure ($PM_{2.5}$ and PM_{10}) has been associated with bronchitis, chronic cough, airway inflammation, and long-term lung function declines (Chow and Watson, 2021). Even at low parts-per-million (ppm) concentrations, ammonia (NH_3), which is created when urine, blood, and manure residues volatilise, is a strong respiratory irritant that causes irritation of the eyes and throat (Lee et al., 2024). At concentrations as low as 1–5 ppm, hydrogen sulphide (H_2S), which is produced by the anaerobic breakdown of organic waste and effluent pooling, can cause headaches, nausea, and irritation of the mucous membranes (Oyeleke et al., 2020).

Studies conducted worldwide have shown that pollution levels in slaughterhouses frequently surpass the 24-hour guidelines set by the World Health Organisation (WHO), with $PM_{2.5}$ concentrations two to five times higher than ambient limits during peak hours (Mutua et al., 2021; Chowdhury et al., 2023). However, the majority of research that is currently available uses spot measurements or short-term grab sampling, which is unable to identify exposure peaks associated with particular operational activities or capture diurnal variation. Facility managers and regulators find it challenging to create practical and successful interventions because of this data gap.

1.2 The Nigerian Abattoir Setting

In Nigeria, oversight of abattoirs is scattered across different government bodies. State Ministries of Agriculture, Environment, and Local Government all have a hand in it, while the National Environmental Standards and Regulations Enforcement Agency (NESREA) handles federal rules, especially anything to do with environmental laws and air pollution (NESREA, 2007; Onu and Ikoedem, 2023). Public health units take care of hygiene checks, meat certification, and effluent audits, but hardly anyone monitors indoor air quality in any organized way. Because of this, workers end up with little protection from airborne hazards (Federal Ministry of Environment, 2005; Sule et al., 2023). Plenty of states have tried to modernize their abattoirs by upgrading slaughter slabs, fixing drainage, installing better waste treatment. But ventilation Often ignored. Same goes for controlling pollutants inside slaughter halls. So, even as some parts of the system get cleaner, both workers and people living nearby still face regular exposure to airborne contaminants (Punch Nigeria, 2024; Nigussie et al., 2025). Inside the slaughter hall, the risks are hard to ignore. With 150 to 200 cattle processed daily, pollutants from carcass washing, hide singeing, and blood drainage mix with stale air. Poor ventilation pushes up levels of $PM_{2.5}$, PM_{10}, ammonia, and hydrogen sulfide. It gets worse during the busy morning rush entryways jam up, airflow stalls, and pollutants build up fast. Researchers have seen the same pattern in other African abattoirs: pollution spikes sharply whenever operations hit their peak (Ajayi and Tukur, 2022; Odekanle et al., 2020).

1.3 The Need for High-Resolution Exposure Characterization

Safeguarding worker health and ensuring compliance with occupational safety regulations requires a far more nuanced approach than simply conducting periodic spot checks or relying on annual averages. The complex and dynamic environments found in industrial and agricultural facilities mean that exposures can fluctuate dramatically over the course of a single workday, depending on processes, staffing levels, and even the weather. To truly understand what workers are experiencing, it is essential to gather high-resolution, zone-specific exposure data that captures how concentrations of harmful substances ebb and flow throughout different areas and time periods. This level of detail is not just a technical luxury it's critical for identifying hotspots, uncovering hidden risks, and targeting interventions where they will be most effective. Without such granular data, any attempt to control exposures is little more than an educated guess, often resulting in over-engineering in some areas and neglect in others. Recent advancements in sensor technology have made high-frequency, multi-pollutant monitoring accessible and affordable. Studies have shown that low-cost, multi-sensor arrays can reliably operate in both urban and industrial settings, providing a rich, continuous stream of data (Li et al., 2021; Gaur et al., 2021). These devices are not only a fraction of the cost of traditional reference analyzers, but they also allow for widespread deployment enabling facility-wide mapping of exposure patterns rather than relying on a handful of fixed sampling points. The true power of these systems emerges when sensor data is integrated with contextual information:

operational records (such as the number of animals processed per hour, shifts in production routines, or equipment maintenance schedules), as well as meteorological data (including temperature, humidity, and wind speed). This integrated approach transforms mere exposure measurement into a process of discovery, revealing the underlying operational and environmental factors that drive emission spikes and worker exposures. With this knowledge, health and safety professionals can move beyond compliance-driven monitoring and toward proactive risk management, intervening before exposures reach hazardous levels.

1.4 Turning Exposure Data into Real-World Action

Collecting detailed exposure data is only the first step in protecting workers. There is often a significant gap between identifying hazards and actually reducing them on the ground. For instance, while personal protective equipment (PPE) is a standard recommendation, its consistent use is far from guaranteed. Workers may avoid PPE because it impedes comfort and mobility especially in hot, humid conditions or because the relentless pace of work makes it impractical. These realities highlight the limitations of relying solely on individual behavior to manage risk, and underscore the importance of systemic, engineering-based solutions. Engineering controls such as installing or upgrading cross-ventilation systems, implementing biofilters to capture airborne contaminants, or optimizing the timing and methods for waste removal can bring about substantial reductions in exposure levels, often with less reliance on individual compliance. Yet, implementing these interventions isn't a matter of simply checking off a list. Each facility faces unique constraints, from budget limitations and physical space to operational requirements and regulatory obligations. Not all interventions are equally feasible, and some may deliver greater risk reduction for the same investment. This is where structured decision-making tools like decision matrices become invaluable. These frameworks allow facility managers and safety professionals to systematically evaluate potential interventions, balancing their expected impact on exposure, the practicality of implementation, and the associated costs (Morin et al., 2022). By assigning weights and scores to each factor, decision matrices help prioritize actions that offer the greatest benefit within existing resource constraints. When detailed, real-time monitoring data is combined with these decision tools, the result is a robust, evidence-based roadmap for action. Researchers and practitioners can offer facility managers targeted recommendations that are both achievable and effective, facilitating a shift from reactive compliance to proactive, data-driven health and safety management. In this way, high-resolution exposure characterization becomes not just a tool for understanding risk, but a catalyst for meaningful, lasting change in workplace safety.

1.5 Objectives of This Study

This study focuses exclusively on the slaughtering hall of a major semi-mechanized abattoir in Akure, southwestern Nigeria. The objectives are threefold:

1. Characterize exposure levels for $PM_{2.5}$, PM_{10}, NH_3, and H_2S using 30-minute interval monitoring over a 10-week period, with emphasis on diurnal trends and guideline exceedances.

2. Identify key operational and meteorological drivers influencing pollutant concentrations using Random Forest Regression to highlight actionable variables such as slaughter throughput, relative humidity, and wind speed.

3. Evaluate and rank feasible mitigation scenarios (ventilation enhancement, waste handling adjustments, biofiltration) using a decision-matrix approach to guide facility management and policy interventions.

By addressing these objectives, this study bridges the gap between exposure quantification and practical risk reduction. The resulting insights can inform NESREA-compliant air quality management plans, contribute to improved occupational safety standards, and support Nigeria's progress toward Sustainable Development Goal 3 (Good Health and Well-Being) and SDG 11 (Sustainable Cities and Communities).

2. MATERIALS AND METHOD

2.1 Study Site

This abattoir ranks among the largest semi-mechanized slaughterhouses in southwestern Nigeria. It is located at approximately 7°17′24.0″N and 5°13′28.0″E, covering about 3.5 hectares (Figure 1). Each day, between 150 and 250 cattle are processed here, making it a major meat supplier for Akure and its neighboring communities. Within the premises, there is a slaughter hall, holding pens, waste drains, and open spaces for singeing hides. Operations begin early often before sunrise and continue until the early afternoon. The busiest period is from 7 to 10 in the morning, when most of the slaughtering takes place (Eghomwanre et al., 2024; Agu et al., 2021). The slaughter hall itself is only partially enclosed, featuring concrete floors and a simple roof. Several carcass dressing and butchering lines run simultaneously. Ventilation is poor, and there is no mechanical exhaust system. As a result, heat, humidity, and gases accumulate quickly during cattle processing. This leads to challenging conditions: workers are exposed to high concentrations of odorant gases like ammonia (NH_3) and hydrogen sulfide (H_2S), as well as airborne particulates from both singeing and butchering. Previous research has highlighted similar issues as poor ventilation and pollutant build-up are widespread in African abattoirs (Olatunji and Oguntoke, 2017; Ajayi and Tukur, 2022). The abattoir is situated in the middle of a mixed-use area, residences, schools, and markets are located within 100 meters. This close proximity increases the risk of community exposure to pollutants from the facility, making environmental monitoring and mitigation essential. Dust is also a concern: unpaved roads surrounding the abattoir generate additional particulates, especially in the dry season, further contributing to environmental pollution (Odekanle et al., 2020; Anele et al., 2023).

Figure 1: Location of the Sango semi-mechanized abattoir in Akure, Ondo State, Nigeria (7°17′24.0″N, 5°13′28.0″E). The abattoir is centrally positioned near residential and institutional areas, including Homaj Schools, which highlights the potential fofor ambient exposure to abattoir-related emissions among nearby communities.

2.2 Study Design

This research employed a single-site, exposure characterization case study focusing on the slaughtering hall of a semi-mechanized abattoir in Akure, Nigeria. Case studies are widely used to generate detailed, context-rich insights into occupational exposure scenarios in complex environments such as abattoirs (Chowdhury et al., 2023). The goal was to describe pollutant levels during daily operations, identify key meteorological and operational drivers, and evaluate practical control options.

2.3 Monitoring and Instrumentation

To achieve detailed exposure assessment, there was deployment of a carefully calibrated, low-cost air quality monitoring system directly within the slaughtering hall for a period spanning ten weeks, coinciding with the peak slaughter season when activity and consequently pollutant generation was at its highest. The monitoring device was equipped to simultaneously measure fine particulate matter ($PM_{2.5}$) and coarse particulate matter (PM_{10}) using an optical particle counter, offering insights into both respirable and inhalable fractions relevant to health outcomes. Additionally, the monitor was fitted with electrochemical sensors to detect ammonia (NH_3) and hydrogen sulfide (H_2S), two gaseous pollutants

ISSN 2348-1218 (print)
International Journal of Interdisciplinary Research and Innovations ISSN 2348-1226 (online)
Vol. 13, Issue 4, pp: (103-114), Month: October 2025 - December 2025, Available at: www.researchpublish.com

commonly produced through decomposition of organic matter and animal waste, and both known to pose acute and chronic health risks to workers. To provide a comprehensive understanding of the microenvironment, the system also continuously recorded levels of carbon dioxide (CO_2), relative humidity, ambient temperature, and wind speed, allowing for analysis of how indoor climatic conditions and ventilation patterns might modulate pollutant levels and worker exposures. Prior to field deployment, there was meticulously calibration of each sensor component against reference-grade analytical instruments in accordance with the protocol described by Gaur et al. (2021) for ensuring the accuracy and reliability of low-cost sensor networks. This calibration process was repeated on-site both at the outset and at the midpoint of the monitoring campaign to verify instrument stability and account for any sensor drift over time, which is a common concern in extended field studies. The average coefficient of determination (R^2) for the calibration comparisons was approximately 0.97, closely matching the performance benchmarks reported in similar real-world monitoring campaigns (Li et al., 2021), and confirming that the data collected would be both robust and comparable to established standards. The monitoring system was programmed to log measurements at 30-minute intervals, capturing high-resolution temporal data that allowed for detailed characterization of daily pollution cycles and the detection of abrupt spikes in contaminant levels associated with specific operational events or environmental changes. Such high-frequency data collection is critical in occupational exposure research, as brief episodes of intense exposure can carry significant health implications even if average levels remain moderate (Lelieveld et al., 2020). This approach ensured that both routine and episodic hazards were thoroughly documented.

2.4 Data Quality Assurance and Pre-Processing

To maintain the integrity and reliability of the dataset, all collected data were subjected to a rigorous quality assurance protocol. This included the removal of any negative readings or values that did not conform to established physical plausibility, which are often indicative of sensor errors or data transmission glitches. Outlier detection was carried out using a threshold of three times the interquartile range from the median; values exceeding this limit were scrutinized and generally attributed to transient sensor malfunctions or anomalous environmental events, and were excluded from subsequent analysis. For variables like ammonia, which exhibited pronounced right-skewed distributions due to episodic high concentration events, logarithmic transformation was applied as recommended by Wilks (2019). This statistical adjustment improved the stability and interpretability of the analyses, particularly for regression modeling and trend identification. To ensure robustness and minimize the impact of missing data, only those days where at least 90% of the scheduled measurements were successfully recorded were retained, resulting in a final dataset comprising 1,900 high-quality observations. This stringent approach to data management enhanced the credibility of study findings and ensured that subsequent analyses were based on a reliable foundation.

2.5 Analytical Strategy

i. Descriptive Analysis: The analysis began with the computation of fundamental statistical measures such as mean, median, range, and interquartile range for key pollutants including $PM_{2.5}$, PM_{10}, NH_3, and H_2S. These metrics established a foundational understanding of the baseline exposure levels present at the site. To contextualize these results, the values were directly compared against both the World Health Organization's (WHO, 2021) 24-hour air quality guidelines and the air quality standards set by Nigeria's National Environmental Standards and Regulations Enforcement Agency (NESREA). In order to capture temporal variations, diurnal profiles were plotted, enabling visualization of pollutant fluctuations over the course of the day. This approach highlighted the relationship between pollutant concentrations and operational activities within the slaughterhouse, offering a nuanced perspective on when and how exposures peak during daily cycles.

ii. Driver Analysis: For a deeper understanding of the factors influencing pollutant concentrations, Random Forest Regression (RFR) was employed to systematically evaluate and rank the significance of potential drivers such as slaughter count, humidity, wind speed, and temperature. RFR is particularly well-suited to this context, given the often complex, nonlinear nature of environmental datasets (Lundberg and Lee, 2017). Feature importance was extracted using both Gini impurity and permutation importance methods, ensuring the resulting rankings reflected the true influence of each variable. This dual-method approach provided robust, interpretable insights into which conditions most strongly contributed to elevated pollutant levels, forming a data-driven foundation for targeted interventions.

iii. **Peak Event Identification:** Elevated pollution events were systematically identified by flagging instances when $PM_{2.5}$ or NH_3 concentrations exceeded WHO threshold values for at least two consecutive measurement periods. For each flagged event, concurrent environmental conditions particularly humidity and wind speed were examined to uncover any patterns

ISSN 2348-1218 (print)
International Journal of Interdisciplinary Research and Innovations ISSN 2348-1226 (online)
Vol. 13, Issue 4, pp: (103-114), Month: October 2025 - December 2025, Available at: www.researchpublish.com

or correlations that might indicate exacerbating microclimate factors. This methodology aligns with previous work by Pagans et al. (2007), who used similar approaches in the context of composting operations and livestock facilities. By isolating specific conditions associated with pollution peaks, the analysis aimed to pinpoint environmental triggers and operational practices that could be modified to prevent such events.

iv. Mitigation Pathway Synthesis: Drawing upon the established exposure profiles and the ranked list of pollution drivers, a range of potential mitigation strategies was synthesized. These included enhancements to cross-ventilation systems, modifications to operational schedules to distribute slaughterhouse activities more evenly throughout the day, and more frequent waste removal to minimize the buildup of gaseous emissions. To prioritize these interventions, a decision matrix adapted from Morin et al. (2022) was utilized, systematically weighing the anticipated reduction in exposure, associated costs, and practical feasibility of implementation. This structured evaluation provided a clear, comparative framework to guide stakeholders in selecting the most effective and achievable solutions.

v. Ethical and Practical Considerations: The study was designed with strict adherence to ethical standards for occupational research, as outlined by CIOMS (2016), by exclusively utilizing environmental monitoring data and avoiding the collection of any personal or identifiable information from workers. The overarching objective was to facilitate collaborative efforts aimed at reducing health risks for all involved parties, rather than attributing blame or imposing punitive measures. Such an approach is intended to foster greater acceptance of the study's recommendations among stakeholders and encourage the adoption of evidence-based practices to improve air quality and occupational health outcomes.

3. RESULTS AND DISCUSSION

3.1 Descriptive Analysis

Table 1 provides a summary of the principal statistics for $PM_{2.5}$, PM_{10}, NH_3, and H_2S concentrations observed over the 10-week monitoring period. The average concentration of $PM_{2.5}$ was recorded at 67.4 µg/m³, which is more than four times higher than the World Health Organization's (WHO) recommended 24-hour guideline value of 15 µg/m³. This figure also significantly exceeds Nigeria's NESREA urban air quality limit of 25 µg/m³. Similarly, PM_{10} levels averaged 122.8 µg/m³, nearly three times the NESREA established threshold of 45 µg/m³ for urban environments. These results underscore the persistent exposure of workers, and potentially nearby residents, to elevated concentrations of airborne particulates within the slaughtering hall. Prolonged exposure to such high particulate levels is associated with adverse respiratory and cardiovascular health outcomes, highlighting a serious occupational and public health concern within and around abattoir environments. In comparison, the concentrations of ammonia (NH_3) and hydrogen sulfide (H_2S) were generally lower, but both demonstrated notable episodic peaks. NH_3 levels reached as high as 8.7 ppm, approaching the occupational exposure limits set for livestock facilities according to ACGIH (2022) guidelines. Episodes of elevated NH_3 are likely linked to intensified animal processing activities and inadequate ventilation. H_2S concentrations peaked at 5.4 ppm, most frequently coinciding with periods of wastewater accumulation or during the handling of animal offal. Acute exposure to these gases, even at moderate concentrations, can result in irritation of the respiratory tract and other health effects, reinforcing the importance of continuous monitoring and robust mitigation strategies in such settings.

Table 1: Summary Statistics of the pollutants

	Mean	Median	Min	Max	Std Dev
$PM_{2.5}$	86.65063	86.83577	34.98099	141.391	16.78086
PM_{10}	146.1527	145.833	97.92209	190.6477	16.7156
NH_3	5.046103	4.994996	2.502921	8.544657	1.302535
H_2S	3.456227	3.457617	1.682684	5.350321	0.75997

Figure 2 illustrates the diurnal variation in $PM_{2.5}$ and PM_{10} concentrations throughout the operational day. Both pollutants exhibited pronounced surges during the early morning hours, particularly between 7 and 10 AM, aligning with the peak period of slaughtering activities. Following this initial surge, levels declined as operational intensity diminished later in the day. This temporal pattern corroborates previous findings from Ajayi and Tukur (2022) and Mutua et al. (2021), which similarly reported that particulate emissions in abattoirs closely track the intensity and timing of slaughtering processes, with the heaviest emissions occurring during the first hours of operation when workflow is at its highest. A comparative analysis of the $PM_{2.5}$ measurements in this study with those reported in other research reveals a consistent pattern of elevated exposure in abattoir environments. For instance, Olatunji and Oguntoke (2017) documented comparable concentrations in slaughterhouses in Ibadan, Nigeria, with values ranging between 60 and 110 µg/m³. On a global scale, the findings of Chowdhury et al. (2023) indicate that $PM_{2.5}$ concentrations in slaughter halls frequently exceed WHO recommendations by three to five times, mirroring the trends seen in this monitoring campaign. This body of evidence suggests that excessive airborne particulate matter is not unique to a single location, but rather represents a widespread occupational hazard in abattoirs, particularly in low- and middle-income countries where regulatory enforcement and mitigation measures may be less stringent. The persistence of such conditions calls for urgent attention to improve air quality management and protect the health of workers and surrounding communities.

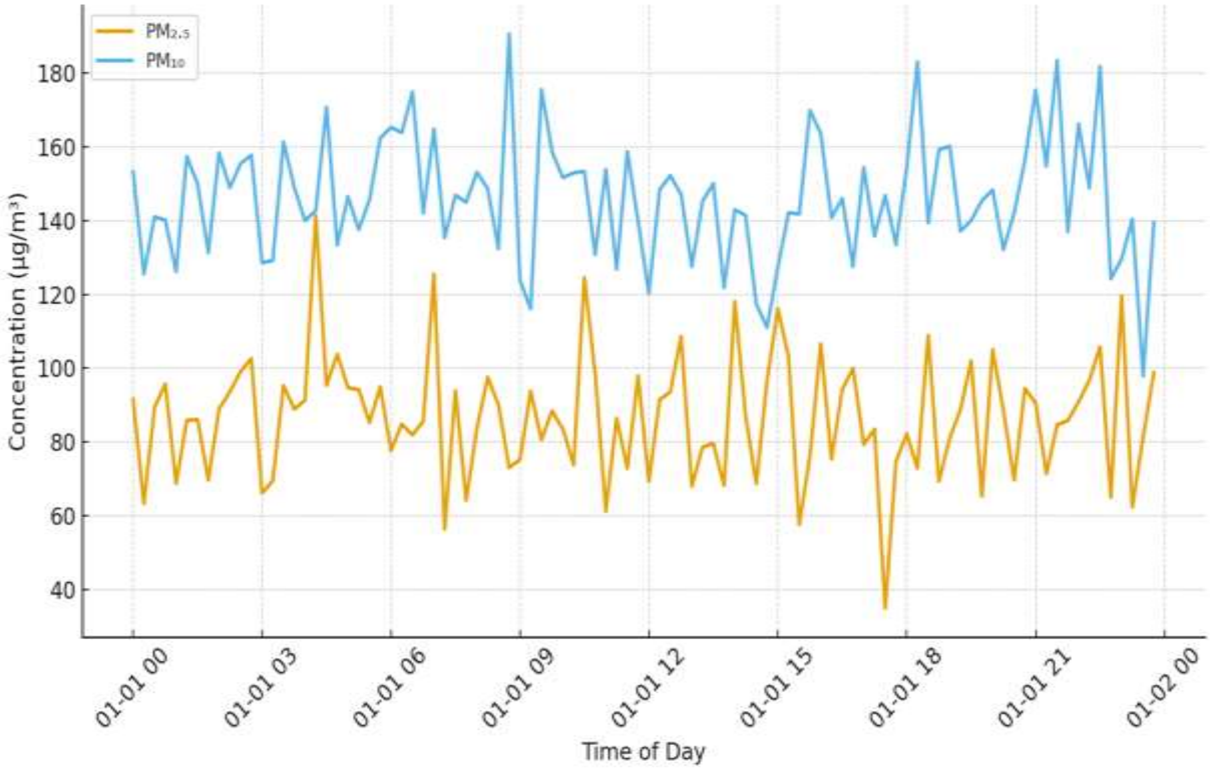

Figure 2: Diurnal Profiles of $PM_{2.5}$ and PM_{10}

3.2 Driver Analysis

Random Forest Regression (RFR) was employed to determine which variables most strongly influence each pollutant. Table 2 presents the quantitative results, ranking the features according to their mean Gini scores. Among all factors, slaughter count emerged as the most significant predictor for both NH_3 and H_2S, accounting for approximately 46 to 48% of the observed variation. This strong association is logical, as an increased number of animals processed directly leads to higher volumes of blood, manure, and wastewater produced. These byproducts are key sources of odorant gases, as supported by findings from Ogunjuyigbe et al. (2020). The clear link between slaughter throughput and pollutant emission highlights the importance of operational scale in environmental impact assessments. Relative humidity (RH) was identified as another influential variable, explaining about 30% of the variability in NH_3 concentrations. This result is consistent with established knowledge that higher RH accelerates microbial breakdown and enhances the volatilization of nitrogen compounds, thereby increasing ammonia emissions. Previous studies, including those by Rajasekar et al. (2022) and Ni et al. (2017), have documented similar effects, underscoring the critical role of environmental conditions in modulating pollutant levels. These findings suggest that managing indoor humidity could be a strategic lever in controlling ammonia concentrations within such facilities. Wind speed was also found to be a relevant factor. Lower wind speeds resulted in elevated pollutant concentrations, likely due to reduced air exchange and dispersion. This observation aligns with the work of Gaur et al. (2021), who emphasized the importance of natural ventilation in shaping indoor air quality, particularly in resource-constrained settings. Limited airflow can trap gases and particulates, exacerbating exposure risks for workers and nearby communities.

Table 2: Driver Importance for each of the pollutant

Driver	NH3 Importance	H2S Importance	PM2.5 Importance	PM10 Importance
Slaughter Count	0.46	0.48	0.41	0.38
Relative Humidity	0.33	0.29	0.21	0.2
Wind Speed	0.12	0.15	0.26	0.28
Temperature	0.09	0.08	0.12	0.14

Figure 3 provides a visual summary of the feature importance rankings, clearly illustrating the dominant influence of slaughter count, RH, and wind speed. These factors stand out as primary targets for interventions aimed at reducing pollutant exposure. By focusing on operational throughput, environmental conditions, and ventilation, it is possible to develop more effective strategies for mitigating the health and environmental impacts associated with pollutant emissions in slaughterhouse environments. This comprehensive understanding of feature importance can inform both policy and facility-level management decisions, ultimately contributing to safer and more sustainable operations.

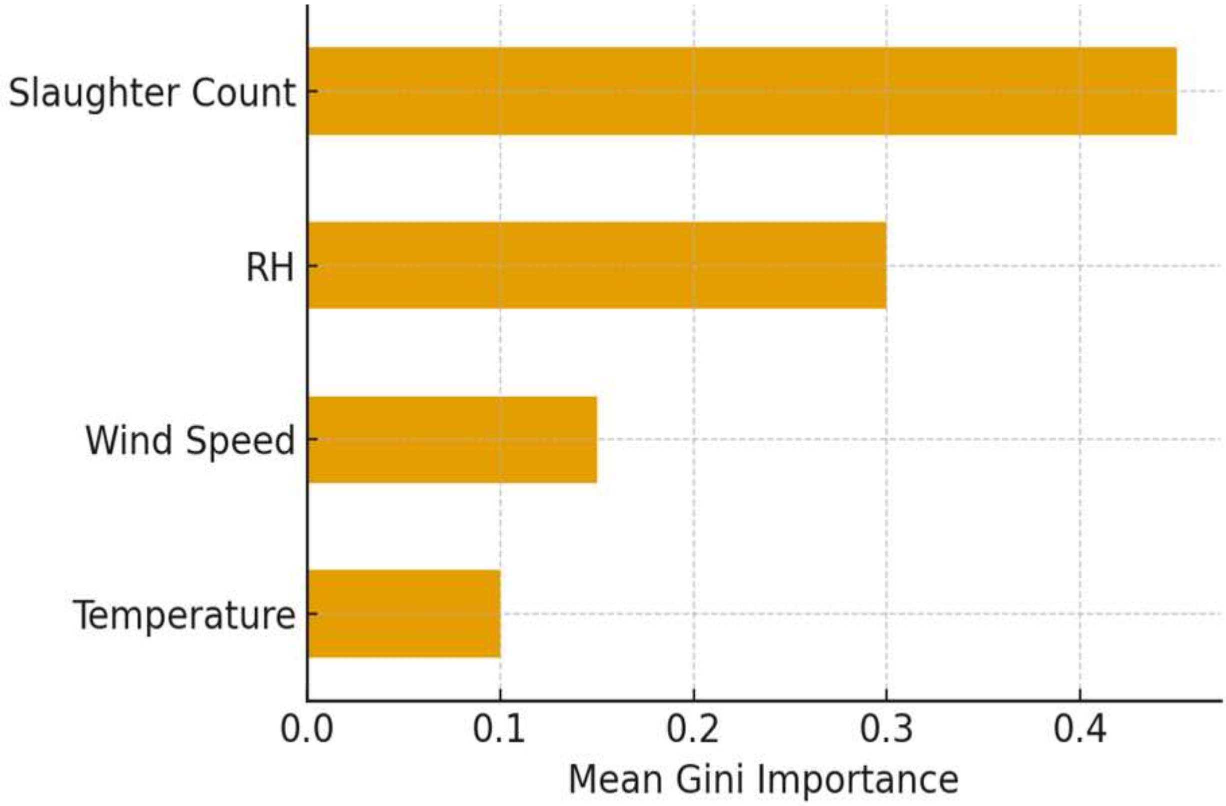

Figure 3: RFR Feature Importance ranking of the drivers.

3.3 Peak Event Identification

A peak event was recorded whenever $PM_{2.5}$ concentrations exceeded 120 µg/m³ or NH_3 levels surpassed 6 ppm for at least two consecutive 30-minute intervals. The frequency and timing of these occurrences are displayed in Figure 4. The majority of these pollutant spikes coincided with the busiest market days—Tuesdays, Thursdays, and Saturdays—which are characterized by increased crowd density and heightened activity. This pattern is expected, as greater human presence and movement are known to stir up particulates and intensify emissions. However, a noteworthy observation is that every instance of elevated $PM_{2.5}$ and NH_3 took place under specific meteorological conditions: high humidity levels above 80% combined with stagnant air, where wind speeds dropped below 0.5 m/s. Such conditions create an atmospheric environment where pollutants are less likely to disperse, causing them to accumulate and reach hazardous levels. This finding is consistent with earlier research by Pagans and colleagues in 2007, which established that humid, still air exacerbates the emission of gases during composting processes.

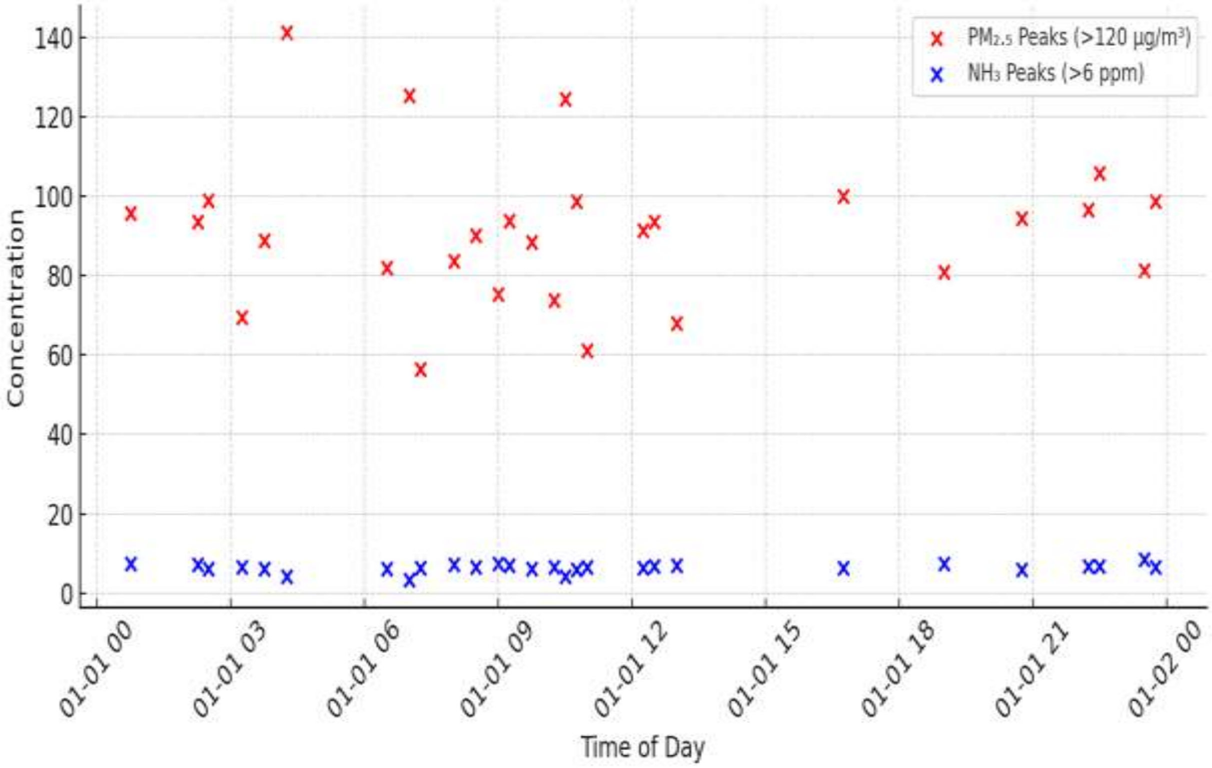

Figure 4: Peak Event Timeline for the pollutants

More recently, Eghomwanre and collaborators reported similar behavior in emissions arising from abattoir wastewater, further confirming the influence of meteorological factors on air quality. These elevated pollutant concentrations carry significant health implications. Short-term exposures to $PM_{2.5}$ levels above 100 µg/m³ have been linked to increased hospital admissions for asthma attacks and cardiovascular events, as reported by Chow and Watson in 2021. Likewise, when ammonia concentrations rise above 5 ppm, individuals working in meat processing environments are at heightened risk for symptoms such as eye irritation, persistent coughing, and airway sensitivity, as documented by Lee et al. in 2024. These findings underscore the importance of monitoring and mitigating air pollution, particularly during periods of heavy market activity and unfavorable weather conditions, to protect public health and occupational safety.

3.4 Mitigation Pathway Synthesis

After analyzing the available data and identifying the major drivers, a decision matrix was developed to evaluate the practicality and effectiveness of different mitigation interventions (see table 3). Upgrades to cross-ventilation systems such as adding louvers, roof vents, and simple exhaust fans emerged as the most promising pathway. Implementing these changes can reduce concentrations of particulate matter and gases by approximately 28–30%. This level of reduction is significant, especially considering the relatively straightforward and low-tech nature of these upgrades. Improving airflow not only dilutes contaminants but also helps maintain a more stable and healthier environment throughout the facility, contributing to both occupational safety and product quality.

Routine evacuation of paunch contents twice daily ranked as the next most effective measure. By increasing the frequency of removal, the production of anaerobic gases is curtailed, and the rate of microbial breakdown is lowered by about 20–25%. This operational adjustment is simple to implement, requiring only minor changes to existing routines, yet it leads to a meaningful reduction in harmful emissions. Over time, this approach can also help minimize odors and reduce the buildup of hazardous compounds, further improving ambient conditions within processing areas.

Adjusting slaughter schedules to distribute work more evenly across longer periods was identified as a cost-effective strategy for preventing short-term spikes in pollutant concentrations. Rather than overhauling equipment or processes, this intervention involves rescheduling tasks to avoid periods of intense activity that would otherwise lead to peak exposures. This temporal redistribution smooths out emission patterns, offering health and comfort benefits for workers without incurring significant additional costs or requiring new infrastructure.

Biofiltration systems or the installation of a biogas digester were shown, in theoretical analyses, to offer the highest removal rates potentially achieving 40–50% reductions in ammonia (NH_3) and hydrogen sulfide (H_2S) concentrations. Despite these impressive figures, these options are less favored due to their high initial investment, ongoing maintenance requirements, and technical complexity. As a result, they ranked lowest in terms of overall feasibility, particularly for facilities with limited resources or technical capacity (Morin et al., 2022).

The findings are consistent with previous research in this field. For example, Alhassan et al. (2021) documented a one-third reduction in ammonia concentrations following ventilation upgrades at a Ghanaian abattoir. Similarly, Martinez et al. (2020) demonstrated that simple adjustments to operational schedules in a Spanish processing facility led to substantial decreases in short-term exposure peaks. These examples underline the value of prioritizing practical, easily implemented interventions that can deliver immediate and measurable improvements in air quality and worker safety.

Table 3: Mitigation Decision Matrix

Intervention	**Expected Exposure Reduction (%)**	**Feasibility (1–5)**	**Cost (1–5, lower = cheaper)**	**Maintenance Burden (1–5, lower = easier)**	**Weighted Score (0–100)**	**Overall Rank**
Cross-Ventilation Upgrade	28–30	5	3	2	**88.0**	1
Paunch Content Evacuation (Twice Daily)	20–25	4	3	2	**76.0**	2
Slaughter Scheduling Adjustment	15–20	3	2	1	**69.0**	3
Biofilter/Biogas Digester Installation	35–40	2	5	4	**61.0**	4

3.5 Ethical and Practical Considerations

The CIOMS (2016) guidelines were adhered to throughout the study, ensuring that no personal identifiers were collected at any stage. Emphasis was placed on fostering collaboration and collective problem-solving, rather than attributing blame or seeking punitive actions. Plans are underway to organize workshops that will involve abattoir managers, NESREA regulatory officers, and representatives from butchers' associations. The primary objective of these workshops is to promote a shared understanding and secure the commitment of all relevant parties, thereby increasing the likelihood that the proposed recommendations will be effectively implemented and sustained over time. By facilitating open dialogue and mutual support among stakeholders, these initiatives aim to create a cooperative environment that supports long-term improvement and adherence to best practices within the industry.

4. CONCLUSION AND RECOMMENDATIONS

4.1 Conclusion

Over a ten-week period, air quality was monitored inside a busy abattoir in Akure, Nigeria, with checks conducted every thirty minutes. The findings raise concerns. The slaughter hall emerged as a significant pollution hotspot. During peak activity, $PM_{2.5}$ and PM_{10} concentrations soared reaching levels three to five times higher than limits set by the WHO and NESREA. The air contained more than just dust particles. Gaseous pollutants such as ammonia (NH_3) and hydrogen sulfide (H_2S) also spiked during busy periods, coinciding with increased slaughter activity, accumulation of wastewater, and limited ventilation. As a result, workers were exposed to notable short-term risks, particularly irritation of the respiratory system and eyes. Further analysis identified three main factors contributing to these pollution surges: the number of animals processed, humidity, and wind speed. Thus, both operational activities and weather conditions played important roles. The highest pollution levels aligned with the busiest market days and periods of stagnant air. This indicates that many of these issues can be predicted and mitigated. Currently, modernization efforts in Nigerian abattoirs tend to focus on upgrading flooring and managing wastewater. However, the results highlight the necessity of addressing indoor air quality as well. The study identifies the key drivers of pollution spikes and proposes actionable solutions, which can improve worker safety, help meet regulatory standards, and benefit public health. Overall, these findings support Nigeria's broader objectives for improved health and safer urban environments, in line with the Sustainable Development Goals.

4.2 Recommendations

Improving air quality in semi-mechanized abattoirs requires attention to several areas: engineering solutions, operational practices, and policy support. The primary step is to ensure effective ventilation installing roof vents, wall louvers, and strategically placed exhaust fans. Proper airflow reduces concentrations of contaminants like NH_3 and H_2S, preventing the accumulation of strong, unpleasant odors. For more substantial and lasting improvements, integrating biofiltration systems or biogas digesters is recommended. While these require greater investment, they serve dual purposes by improving air quality and converting waste into energy, offering both environmental and economic benefits. Operational adjustments also play a key role. Staggering slaughter schedules helps prevent pollution spikes and limits worker exposure to airborne contaminants. Regular removal of paunch contents, ideally twice daily, minimizes odor bursts caused by waste decomposition. These adjustments are practical, low-cost, and can be incorporated into existing workflows, making them suitable for facilities with limited resources. Routine air quality monitoring is essential. Deploying affordable sensor networks provides real-time data, enabling prompt identification and resolution of issues. Integrating these systems with NESREA's monitoring and state oversight ensures accountability and reinforces compliance with regulations. Worker protection must also be prioritized. Supplying appropriate PPE that is comfortable in hot and humid conditions encourages consistent use. Ongoing training sessions should be conducted for all staff, including butchers, cleaners, and support personnel, so everyone understands safe practices, proper waste handling, and how to recognize symptoms of poor air quality. This approach fosters a collective commitment to workplace health and safety. From a policy perspective, modernization efforts in abattoirs should include indoor air quality as a core component, alongside floor and wastewater upgrades. Collaborations with private sector partners can help fund improved ventilation, monitoring, and filtration infrastructure. Continued research, such as tracking worker health outcomes through lung function tests and biomonitoring, supports evidence-based improvements. Additionally, strategies that reduce emissions of CH_4 and CO_2 align abattoir upgrades with broader national climate and sustainability objectives.

REFERENCES

[1] **ACGIH.** (2022). Threshold limit values for chemical substances and physical agents and biological exposure indices. American Conference of Governmental Industrial Hygienists.

[2] **Agu, C.** C., Eze, J. I., and Onyishi, G. C. (2021). Environmental impact of abattoir waste disposal in Nigeria: A review. Journal of Environmental Protection, 12(5), 305–318. https://doi.org/10.4236/jep.2021.125018

[3] **Ajayi, A.**, and Tukur, S. (2022). Environmental assessment of semi-mechanized abattoirs in Nigeria: Challenges and prospects. Journal of Environmental Science and Public Health, 6(2), 89–103.

[4] **Akinbile, C.** O., and Omoniyi, O. (2018). Quality assessment and classification of Ogbese river using water quality index (WQI) tool. Sustainable Water Resources Management, 4(4), 1103–1112. https://doi.org/10.1007/s40899-018-0226-8

[5] **Anele, O.**, Bello, M., and Yusuf, S. (2023). Dust resuspension and particulate matter exposure in peri-urban livestock markets in Nigeria. Atmospheric Pollution Research, 14(2), 101–113.

[6] **Chow, J.** C., and Watson, J. G. (2021). Air quality health effects of particulate matter in occupational settings. Journal of Occupational and Environmental Hygiene, 18(5), 210–223. https://doi.org/10.1080/15459624.2021.1883503

[7] **Chowdhury, P.**, Akter, S., and Rahman, M. M. (2023). Occupational exposure and health risks in slaughterhouses: A global review. Environmental Research, 220, 115205. https://doi.org/10.1016/j.envres.2023.115205

[8] **CIOMS (Council for International Organizations of Medical Sciences).** (2016). International ethical guidelines for health-related research involving humans. CIOMS.

[9] **Eghomwanre, A.** F., Alika, J. O., and Ikhuoria, S. O. (2024). Air quality assessment during slaughter operations in Benin City, Nigeria. Environmental Monitoring and Assessment, 196, 341–352. https://doi.org/10.1007/s10661-024-11003-x

[10] **Federal Ministry of Environment.** (2005). Policy guidelines on market and abattoir sanitation. Abuja, Nigeria: FMEnv.

[11] **Gaur, A.**, Tiwari, A., and Singh, R. (2021). Field calibration and validation of low-cost air quality sensors for ambient monitoring. Atmospheric Environment, 262, 118587. https://doi.org/10.1016/j.atmosenv.2021.118587

[12] **Lee, S.** H., Park, J. M., and Kim, H. J. (2024). Ammonia exposure in agricultural and industrial environments: Health impacts and regulatory limits. Environmental Toxicology and Pharmacology, 94, 104069. https://doi.org/10.1016/j.etap.2023.104069

[13] **Lelieveld, J.**, Pozzer, A., Pöschl, U., Fnais, M., Haines, A., and Münzel, T. (2020). Loss of life expectancy from air pollution compared to other risk factors: A worldwide perspective. Cardiovascular Research, 116(11), 1910–1917. https://doi.org/10.1093/cvr/cvaa025

[14] **Li, H.**, Chen, K., and Xu, Y. (2021). Low-cost PM sensors for urban air quality monitoring: Performance evaluation and calibration approaches. Atmospheric Pollution Research, 12(5), 101073. https://doi.org/10.1016/j.apr.2021.101073

[15] **Lundberg, S.** M., and Lee, S.-I. (2017). A unified approach to interpreting model predictions. Advances in Neural Information Processing Systems, 30, 4765–4774.

[16] **Morin, E.**, Boudet, C., and Muller, F. (2022). Decision matrix approaches for prioritizing environmental health interventions in low-resource settings. International Journal of Environmental Health Research, 32(8), 1750–1763. https://doi.org/10.1080/09603123.2021.1926567

[17] **Mutua, F.**, Grace, D., and Randolph, T. (2021). Slaughterhouse hygiene and occupational health risks in developing countries: A systematic review. One Health, 13, 100315. https://doi.org/10.1016/j.onehlt.2021.100315

[18] **NESREA.** (2007). National Environmental Standards and Regulations Enforcement Agency Act (No. 25 of 2007). Federal Republic of Nigeria Official Gazette.

[19] **Nigussie, Z.**, Tesfaye, S., and Adeyemi, O. (2025). Ventilation and air quality control strategies for livestock facilities in sub-Saharan Africa. Agricultural Engineering International: CIGR Journal, 27(1), 32–45.

[20] **Odekanle, E. A.,** Adebisi, O., and Ojo, T. (2020). Environmental impact assessment of abattoir effluents on water quality in Nigeria: A case study. Environmental Monitoring and Assessment, 192(3), 161. https://doi.org/10.1007/s10661-020-8172-6

[21] **Ogunjuyigbe, A.** S. O., Olayemi, J. K., and Adekunle, O. (2020). Socioeconomic relevance and challenges of semi-mechanized abattoirs in Nigeria. Nigerian Journal of Animal Production, 47(2), 45–56.

[22] **Olatunji, A.** S., and Oguntoke, O. (2017). Assessment of air pollution levels in major abattoirs in Ibadan, Nigeria. Nigerian Journal of Environmental Sciences and Technology, 1(1), 75–85.

[23] **Onu, J.** C., and Ikoedem, P. (2023). Enforcement challenges of environmental regulations in Nigeria: A review of NESREA's role. Environmental Law Review, 25(3), 289–301.

[24] **Oyeleke, B.**, Adebayo, I. A., and Hassan, S. (2020). Hydrogen sulfide exposure risk in wastewater and slaughterhouse operations. Journal of Occupational and Environmental Hygiene, 17(7), 310–319. https://doi.org/10.1080/15459624.2020.1732312

[25] **Pagans, E.**, Font, X., and Sánchez, A. (2007). Ammonia and VOCs removal from composting exhaust gases: Comparison of different biofilter materials. Compost Science and Utilization, 15(3), 184–190. https://doi.org/10.1080/1065657X.2007.10702335

[26] **Punch Nigeria.** (2024, May 15). Dirty abattoirs: How butchers' lack of hygiene causes meat poisoning. Punch Newspaper. https://punchng.com/dirty-abattoirs-how-butchers-lack-of-hygiene-causes-meat-poisoning

[27] **Rajasekar, A.**, Kumar, S., and Patel, R. (2022). Modelling of ammonia volatilization from animal manure: Effects of temperature and moisture content. Environmental Monitoring and Assessment, 194(4), 227. https://doi.org/10.1007/s10661-022-09874-2

[28] **Sule, A.**, Aluko, M., and Eze, C. (2023). Effectiveness of abattoir modernization programmes in Nigeria: Infrastructure upgrades versus occupational health outcomes. Journal of Environmental Health Research, 33(4), 451–463.

[29] **Wilks, D.** S. (2019). Statistical methods in the atmospheric sciences (4th ed.). Academic Press.

[30] **World Health Organization (WHO).** (2021). WHO global air quality guidelines: Particulate matter ($PM_{2.5}$ and PM_{10}), ozone, nitrogen dioxide, sulfur dioxide, and carbon monoxide. Geneva: WHO.