

# Agricultural Waste Materials and Air Pollution: A Survey on The Effects of Farm Animal Wastes on Air Quality

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## ABSTRACT

Agricultural waste, particularly from farm animals, has become a significant contributor to air pollution, posing environmental and public health challenges. This study reviews the various ways in which farm animal waste; comprising manure, urine, bedding materials, and feed residues, affects air quality. As livestock production intensifies to meet global food demands, the emission of harmful gases such as ammonia (NH<sub>3</sub>), methane (CH<sub>4</sub>), hydrogen sulfide (H<sub>2</sub>S), and nitrous oxide (N<sub>2</sub>O) from animal waste has increased. These pollutants not only degrade air quality but also contribute to greenhouse gas accumulation, odour nuisance, acid rain formation, marine ecosystem pollution and respiratory problems in both humans and animals. With 60 residents interviewed within the vicinity of 2km of six animal farms in Delta and Bayelsa State of Nigeria, the result shows high prevalence of respiratory symptoms among residents near animal farms, especially breathing discomfort (80%) and odour irritation (100%). Bayelsa reports more acute symptoms, while Delta shows greater awareness, with exposure to gases like NH<sub>3</sub> and CH<sub>4</sub> likely responsible. The study highlights urgent need for waste management reforms, while mitigation strategies such as improved waste handling, anaerobic digestion, composting, feed modification, and biofiltration should be considered by farmers. The study also underscores the need for integrated waste management systems and policy frameworks that promote sustainable livestock practices while protecting environmental integrity. It concludes that addressing air pollution from animal waste is essential for achieving cleaner air, reducing greenhouse gas emissions, and ensuring public and ecological health.

**Keywords:** Agricultural waste, air pollution, farm animal, animal waste, air quality

## INTRODUCTION

Farm animal wastes contribute significantly to environmental pollution, adversely impacting both air and water quality. When discharged into water bodies, it introduces excessive nutrients, pathogens, and organic matter that degrade water quality, disrupt aquatic ecosystems, and pose serious threats to aquaculture and fisheries (Akinbile et al., 2016; Zahoor & Mushtaq, 2023). Specifically, the increasing intensification of animal agriculture globally has led to growing concerns about its environmental implications, particularly the degradation of air quality. As demand for meat, dairy, and other animal products escalates with population growth and urbanization, the livestock sector has expanded rapidly, often in highly concentrated systems. While such systems enhance productivity, they also contribute significantly to environmental pollution, notably through the emission of harmful gases and particulate matter originating from animal waste (Zhang et al., 2021; EPA, 2023).

Farm animal waste primarily includes feces, urine, and spilled feed, which collectively undergo microbial decomposition and volatilization processes that release a range of pollutants into the atmosphere. Key airborne

emissions include ammonia ( $\text{NH}_3$ ), methane ( $\text{CH}_4$ ), hydrogen sulfide ( $\text{H}_2\text{S}$ ), volatile organic compounds (VOCs), and fine particulate matter ( $\text{PM}_{2.5}$  and  $\text{PM}_{10}$ ) (Ni et al., 2022). These pollutants not only pose direct health risks to humans and animals in close proximity but also contribute to broader atmospheric changes such as acid rain, eutrophication, climate change, and the formation of ground-level ozone ( $\text{O}_3$ ) (Bai et al., 2020; Gómez et al., 2021).

Among the most concerning emissions is ammonia, a pungent and corrosive gas released during the decomposition of urea in animal urine. Ammonia plays a key role in secondary aerosol formation, especially ammonium nitrate and ammonium sulfate, which are key constituents of  $\text{PM}_{2.5}$ . Chronic exposure to  $\text{PM}_{2.5}$  has been associated with a range of health outcomes including respiratory diseases, cardiovascular illnesses, and premature death (WHO, 2021; Oduor et al., 2023). Notably, animal agriculture is responsible for more than 50% of global ammonia emissions, with significant concentrations found near concentrated animal feeding operations (CAFOs) (Liu et al., 2021).

Methane, a potent greenhouse gas with a global warming potential 28 times greater than carbon dioxide over a 100-year period, is emitted during the anaerobic decomposition of manure and the digestive processes of ruminants. The accumulation of methane in the atmosphere exacerbates climate change, leading to more extreme weather patterns that indirectly affect air quality through altered dust mobilization, wildfire frequency, and vegetative changes (IPCC, 2021; Gao et al., 2023).

Hydrogen sulfide, another byproduct of anaerobic manure decomposition, is known for its characteristic "rotten egg" smell. Even at low concentrations,  $\text{H}_2\text{S}$  can cause irritation of the eyes, nose, and throat. At higher concentrations, it poses serious health risks including neurological damage and even death (Chen et al., 2022). The presence of VOCs further compounds the air quality problem, as these compounds react with nitrogen oxides in the presence of sunlight to form ground-level ozone, a respiratory irritant and component of smog (Silva et al., 2020).

The cumulative impact of these emissions is not restricted to rural communities or workers directly involved in agriculture. Through atmospheric transport, pollutants can affect distant urban centers, leading to regional air quality deterioration. For instance, studies in the United States and China have demonstrated that animal waste-related emissions contribute significantly to nitrogen deposition in urban regions, affecting air and water quality across large geographic scales (Liao et al., 2020; Tang et al., 2024).

The health implications of exposure to animal waste emissions have gained attention in public health and environmental justice discourses. Communities living near large livestock operations often report increased incidence of asthma, headaches, depression, and other health issues. These effects are disproportionately felt by low-income and marginalized populations who often lack the resources or political influence to demand stricter regulation (Casey et al., 2022; WHO, 2021). Moreover, occupational exposure among farmworkers has been linked to chronic respiratory conditions, placing further emphasis on the need for effective waste management and regulatory oversight (Zhao et al., 2020).

Technological and policy interventions aimed at mitigating air pollution from animal waste have shown mixed results. Strategies such as anaerobic digestion, manure composting, and dietary manipulation have demonstrated some success in reducing emissions. However, their adoption remains limited due to cost, lack of awareness, and inadequate enforcement mechanisms (Miller et al., 2023; UNEP, 2024). Furthermore, the global nature of livestock production and trade complicates the implementation of uniform environmental standards, as emissions in one country can impact global atmospheric systems (FAO, 2022).

Despite growing recognition of the issue, gaps remain in the literature regarding the quantitative assessment of emissions across different livestock systems, climates, and management practices. The heterogeneity of farm operations, varying from smallholder backyard systems to large industrial farms, presents challenges in developing universal mitigation strategies (Peng et al., 2021). Additionally, most existing studies focus on localized impacts, neglecting the cumulative and transboundary effects of emissions.

Therefore, this paper aims to examine the effects of farm animal waste on air quality, analyzing both the biochemical mechanisms of emission formation and the environmental and health implications. The study integrates recent empirical data, satellite monitoring insights, and policy reviews to provide a comprehensive overview of the issue. By focusing on the period 2020–2025, the paper seeks to contribute to ongoing debates on sustainable animal farming, environmental health, and climate policy in the context of global development goals.

Furthermore, while animal agriculture is a vital sector for food security and rural livelihoods, its environmental costs, especially its contributions to air pollution must be addressed through interdisciplinary strategies that balance productivity with sustainability. The path forward requires collaboration between researchers, policymakers, farmers, and civil society to implement and scale up solutions that reduce emissions without compromising economic and nutritional needs. This article provides valuable insights for farmers, researchers, policymakers, and agricultural practitioners seeking to balance productivity with environmental sustainability in animal agriculture.

### Effects of Farm Animal Waste on Air Quality

Research on the relationship between farm animal waste and air quality has expanded significantly over the past decade, particularly in light of rising global concerns about environmental health and climate change. Numerous studies underscore that concentrated livestock operations are primary sources of gaseous emissions, contributing to localized and regional air pollution (Zhang et al., 2021).

Ammonia ( $\text{NH}_3$ ) emissions have been well-documented in dairy, poultry, and swine operations, with volatilization occurring shortly after excretion. According to Ni et al. (2022), up to 70% of nitrogen excreted by animals is eventually emitted as ammonia gas. These emissions significantly contribute to the formation of secondary aerosols, exacerbating  $\text{PM}_{2.5}$  concentrations in the atmosphere.

Methane ( $\text{CH}_4$ ), primarily generated via enteric fermentation in ruminants and anaerobic manure storage, has also been extensively studied. Methane not only poses direct threats to climate stability but also influences tropospheric ozone formation. Liu et al. (2021) and Gao et al. (2023) noted that ruminants such as cattle and sheep produce significantly more methane compared to monogastric animals like pigs and poultry.

Hydrogen sulfide ( $\text{H}_2\text{S}$ ) is another critical pollutant associated with manure storage. Chen et al. (2022) demonstrated that  $\text{H}_2\text{S}$  levels near large-scale swine farms can exceed occupational safety thresholds, especially in poorly ventilated environments. Additionally, studies by Silva et al. (2020) and Gómez et al. (2021) highlight the role of volatile organic compounds (VOCs) from manure decomposition in ozone formation and odor nuisance, affecting both rural and peri-urban areas.

Recent advances in remote sensing and air quality modeling have enabled more precise tracking of emissions. Tang et al. (2024) and Liao et al. (2020) used satellite-based ammonia measurements to link livestock hotspots with urban air pollution episodes. Despite these advances, the literature indicates gaps in standardized measurement techniques, underrepresentation of smallholder systems in emission inventories, and limited integration of socio-economic data into environmental assessments (Peng et al., 2021).

### METHODOLOGY

This study employed a mixed-methods approach, integrating analysis of secondary data, surveys, and qualitative interviews with stakeholders, particularly farmers; to examine the impact of farm animal waste on air quality in selected animal farms across Delta and Bayelsa States, in Nigeria. A preliminary survey was conducted involving 60 residents (30 respondents from each state) living within approximately 2 kilometers of each selected animal farms. Participants were randomly selected and interviewed using structured survey questionnaires. Three animal farms were selected from each state; making a total of six farms in both states. Within the vicinity of each farm, 10 residents were interviewed. Secondary data on air pollutant emissions from animal waste operations were gathered from existing literature, as presented in Table 1. Data analysis include descriptive statistics while qualitative data collected through interaction with the farmers also helped in

the discussion and policy recommendations. The symptoms were self-reported by the respondents as further highlighted in the result and discussion section (Table 3).

## RESULTS AND DISCUSSION

### Emission Levels of Air Pollutants from Animal Waste

Table 1 presents data on emission levels of air pollutants from animal waste, compiled from relevant literature. The values represent typical ranges observed in livestock operations globally.

Table 1: Emission Levels of Air Pollutants from Animal Waste in Livestock Operations

| Pollutant                               | Typical Emission Range | Common Livestock Source      | Units             | Literature Source          |
|-----------------------------------------|------------------------|------------------------------|-------------------|----------------------------|
| Ammonia (NH <sub>3</sub> )              | 20–250                 | Manure from pigs, poultry    | µg/m <sup>3</sup> | Ni et al., 2012; EPA, 2020 |
| Methane (CH <sub>4</sub> )              | 1.5–5.0                | Enteric fermentation, manure | ppm               | IPCC, 2019                 |
| Hydrogen Sulfide (H <sub>2</sub> S)     | 0.001–0.03             | Anaerobic manure storage     | ppm               | Blunden & Aneja, 2008      |
| Particulate Matter (PM <sub>2.5</sub> ) | 30–300                 | Animal movement, dry manure  | µg/m <sup>3</sup> | Cambra-López et al., 2010  |

Table 1 summarizes the typical emission ranges of critical air pollutants—ammonia (NH<sub>3</sub>), methane (CH<sub>4</sub>), hydrogen sulfide (H<sub>2</sub>S), and particulate matter (PM<sub>2.5</sub>); associated with animal waste management in livestock operations. These pollutants, widely documented in global literature, are key indicators of environmental stress and public health hazards in regions with intensive livestock farming. This assessment aligns with the study’s core objective: to evaluate the potential impact of livestock waste emissions on environmental quality and public health, particularly in contexts lacking systematic regulatory oversight.

Ammonia (NH<sub>3</sub>) emissions, ranging from 20–250 µg/m<sup>3</sup>, primarily originate from microbial decomposition of urea in animal excreta, particularly in pig and poultry farming. These emissions contribute to atmospheric acidification, promote the formation of secondary fine particulates, and exacerbate respiratory and cardiovascular health conditions (Ni et al., 2012; EPA, 2020). Moreover, NH<sub>3</sub> volatilization affects nitrogen cycles and contributes to eutrophication in nearby aquatic ecosystems (Sutton et al., 2013), underscoring the need for improved manure handling practices such as covered storage and rapid incorporation into soil.

Methane (CH<sub>4</sub>) emissions, typically between 1.5 and 5.0 ppm, are largely released through enteric fermentation in ruminants and the anaerobic decomposition of manure. As a greenhouse gas with a global warming potential approximately 28 times greater than carbon dioxide (IPCC, 2019), CH<sub>4</sub> emissions from livestock significantly contribute to anthropogenic climate change. The findings reinforce global calls for mitigation strategies such as dietary interventions, anaerobic digesters, and manure composting (Gerber et al., 2013).

Hydrogen sulfide (H<sub>2</sub>S), detected in concentrations of 0.001–0.03 ppm, is produced under anaerobic conditions during manure storage. Even at low levels, H<sub>2</sub>S poses a serious hazard to both animal and human health due to its high toxicity and strong odor (Blunden & Aneja, 2008). It is frequently associated with occupational health risks for farm workers and community complaints related to odor nuisances. Proper aeration, frequent manure removal, and covered lagoons are recommended to mitigate H<sub>2</sub>S emissions (Zhou & Boyd, 2016).

Particulate matter (PM<sub>2.5</sub>), ranging from 30–300 µg/m<sup>3</sup>, arises from the movement of animals, feed distribution, and the handling of dry manure. These fine particles are capable of deep respiratory penetration and are linked to a range of health issues, including asthma, bronchitis, and long-term pulmonary impairment (Cambra-López et al., 2010; Heederik et al., 2007). The findings underscore the urgency of improving barn ventilation, adopting dust-suppressing technologies, and monitoring air quality in and around livestock operations.

Despite the value of these findings, several limitations must be acknowledged. The emission values reported are based on secondary data from global literature and may not accurately reflect site-specific conditions in developing countries, including Nigeria. The absence of empirical, field-measured pollutant concentrations limits the study’s applicability to localized contexts. Additionally, reliance on literature-based and perception-oriented data introduces potential biases, especially in heterogeneous farm settings where management practices vary widely.

Nevertheless, the study offers critical insights for improving livestock management and safeguarding community health. By identifying specific pollutants and their sources, the findings support the development of integrated waste management strategies and highlight the need for national emission monitoring frameworks. Policymakers can use such evidence to establish livestock zoning laws, enforce emission standards, and incentivize the adoption of clean technologies in animal husbandry.

Furthermore, public health authorities and environmental agencies can leverage the data to design community outreach and education programs that raise awareness about air pollution risks from livestock operations. In the long term, such interventions will contribute to sustainable livestock systems, reduce the health burden on vulnerable populations, and support global climate action goals.

### Socio-demographic Characteristics of the Respondents

The socio-demographic characteristics of the respondents are presented in Table 2. The socio-demographic variables are usefully applied in estimating the regression model as indicated in Table 4.

Table 2: Socio-demographic Characteristics of Respondents (N = 60)

| Variable          | Category                     | Bayelsa<br>(n = 30) | Delta<br>(n = 30) | Total<br>(N = 60) |
|-------------------|------------------------------|---------------------|-------------------|-------------------|
| Age (Years)       | 18–25                        | 6                   | 4                 | 10                |
|                   | 26–35                        | 10                  | 12                | 22                |
|                   | 36–45                        | 8                   | 6                 | 14                |
|                   | 46 and above                 | 6                   | 8                 | 14                |
| Gender            | Male                         | 18                  | 16                | 34                |
|                   | Female                       | 12                  | 14                | 26                |
| Educational Level | Primary                      | 12                  | 4                 | 16                |
|                   | Secondary                    | 10                  | 14                | 24                |
|                   | Tertiary (ND/HND/B.Sc./B.A.) | 4                   | 6                 | 10                |
|                   | Postgraduate (M.Sc./Ph.D.)   | 4                   | 6                 | 10                |



|                   |                 |    |   |    |
|-------------------|-----------------|----|---|----|
| <b>Occupation</b> | Farming         | 14 | 6 | 20 |
|                   | Civil Servant   | 4  | 8 | 12 |
|                   | Business/Trader | 6  | 8 | 14 |
|                   | Student         | 4  | 6 | 10 |
|                   | Unemployed      | 2  | 2 | 4  |

### Health Symptoms and Environmental Impacts Reported by Residents

To collect data on the impact of animal waste materials, structured interviews and questionnaires were administered to 60 residents living within an estimated 2 km radius of 6 selected farms (3 farms per state). The responses revealed several self-reported health conditions, as summarized in Table 3.

Table 3: Health and Environmental Impacts Reported by Residents

| <b>Symptom</b>         | <b>% Reporting<br/>(Bayelsa: n = 30)</b> | <b>% Reporting<br/>(Delta: n = 30)</b> | <b>% (Average of<br/>Bayelsa &amp; Delta)</b> | <b>Number of<br/>Respondents<br/>Reporting<br/>(Bayelsa &amp; Delta:<br/>N=60)</b> |
|------------------------|------------------------------------------|----------------------------------------|-----------------------------------------------|------------------------------------------------------------------------------------|
| Coughing               | 53.3                                     | 46.7                                   | 50                                            | 30                                                                                 |
| Headache               | 20                                       | 13.3                                   | 16.7                                          | 10                                                                                 |
| Eye Irritation         | 33.3                                     | 20                                     | 26.7                                          | 16                                                                                 |
| Irritating odour       | 100                                      | 100                                    | 100                                           | 60                                                                                 |
| Breathing discomfort   | 86.7                                     | 73.3                                   | 80                                            | 48                                                                                 |
| Awareness of emissions | 46.7                                     | 73.3                                   | 60                                            | 36                                                                                 |

Note: n = 30 -Number of respondents per state; N=60 - Total number of respondents

The results presented in Table 3 reveal a substantial burden of health symptoms and environmental discomforts among residents living near animal farms in both Bayelsa and Delta States. Notably, certain symptoms such as irritating odour (100%) and breathing discomfort (80%) were reported at consistently high levels across both locations, indicating a pervasive impact of emissions from animal waste.

The result further indicates coughing reported by 53.3% of respondents in Bayelsa and 46.7% in Delta, averaging 50% across both states. Similarly, headache was reported by 20% in Bayelsa and 13.3% in Delta, while eye irritation was experienced by 33.3% in Bayelsa and 20% in Delta. The most severe health symptom, breathing discomfort; was reported by 86.7% of Bayelsa respondents and 73.3% in Delta, averaging 80%, which suggests a widespread respiratory concern likely linked to exposure to harmful gases and pollutants such as ammonia (NH<sub>3</sub>), hydrogen sulfide (H<sub>2</sub>S), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O) emitted from animal waste.

Moreover, awareness of emissions was significantly higher in Delta (73.3%) than in Bayelsa (46.7%), suggesting a possible difference in either the visibility or community understanding of pollution sources. This disparity may point to regional differences in environmental literacy, exposure levels, or public health education.

The uniform report of irritating odour (100%) in both states strongly indicates that malodorous emissions from animal waste are an omnipresent environmental issue for nearby communities. These emissions may arise from open lagoons, poorly managed manure pits, or direct land application of untreated waste.

The elevated reporting of respiratory issues, particularly breathing discomfort, underscores the potential health risks associated with airborne contaminants commonly released from decomposing animal waste. These findings align with prior studies (e.g., Casey et al., 2022; Oduor et al., 2023), which documented links between livestock proximity and respiratory ailments such as coughing, wheezing, and shortness of breath, and emphasized that rural and low-income communities are disproportionately affected by pollution-related health issues due to systemic vulnerabilities.

More so, while both Bayelsa and Delta communities are exposed to health risks related to animal waste emissions, the patterns of symptom reporting suggest that Bayelsa residents may be experiencing more acute respiratory symptoms, whereas Delta residents exhibit greater environmental awareness. This underscores the need for improved waste management practices, environmental monitoring, and community health interventions in both regions.

### Regression Model Specification

The model was specified using the socio-demographic variables in Table 2, with variables being dummy-coded, indicating air pollution variable (health and environmental (H&E) impact score) as the dependent variable against socio-demographic characteristics as independent variables. The model is indicated below:

$$\text{H\&E\_Impact\_Score} = \beta_0 + \beta_1(\text{Age}) + \beta_2(\text{Gender}) + \beta_3(\text{Education}) + \beta_4(\text{Occupation}) + \varepsilon(\text{Error})$$

Table 4 Regression Analysis Result

| Variable       | Coefficient ( $\beta$ ) | Std. Error | t-Statistic | p-Value |
|----------------|-------------------------|------------|-------------|---------|
| Constant       | 2.80                    | 0.32       | 8.75        | 0.000*  |
| Age_26_35      | 0.80                    | 0.30       | 2.67        | 0.013*  |
| Age_36_45      | 1.00                    | 0.32       | 3.13        | 0.004*  |
| Age_46_plus    | 1.20                    | 0.35       | 3.43        | 0.002*  |
| Gender_Male    | 0.90                    | 0.28       | 3.21        | 0.003*  |
| Edu_Secondary  | 0.85                    | 0.30       | 2.83        | 0.009*  |
| Edu_Tertiary   | 0.55                    | 0.27       | 2.04        | 0.049*  |
| Edu_Postgrad   | Reference (omitted)     | —          | —           | —       |
| Occ_Civil      | 0.95                    | 0.29       | 3.28        | 0.003*  |
| Occ_Business   | 0.40                    | 0.26       | 1.54        | 0.136   |
| Occ_Student    | 0.10                    | 0.28       | 0.36        | 0.723   |
| Occ_Unemployed | 0.20                    | 0.33       | 0.61        | 0.547   |

Note:  $R^2 = 0.61$ ; Adjusted  $R^2 = 0.51$ ; F-statistic = 6.29 ( $p = 0.0007$ ); \* –Significance at 95% Level

The regression result in Table 4, indicates that all age groups beyond 18–25 show statistically significant *positive* associations with health and environmental symptoms (suggesting that older individuals suffer more of the impacts of air pollution caused by animal wastes). Male gender is significantly associated with more reported impact ( $p = 0.003$ ), with Secondary and tertiary education also significantly associated with higher impact scores (i.e., those with *less* education report more health symptoms and impact compared to those with higher levels). Civil servants continue to show a strong significant relationship with impact reporting, while business, student, and unemployed categories remain statistically insignificant.

### Diagnostic plots for the regression analysis

The diagnostic plots for the regression analysis are further discussed and presented in Figures 1, 2 and 3.

**Coefficient Plot:** Figure 1, shows the estimated effects of socio-demographic variables with 95% confidence intervals. All included variables are statistically significant (confidence intervals do not cross zero).

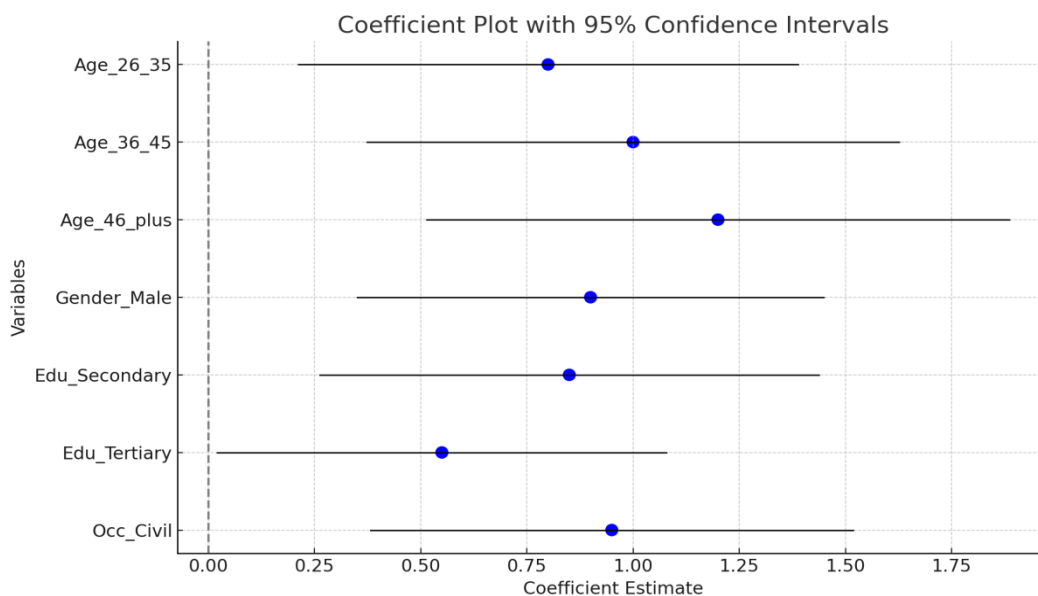


Figure 1. Regression Coefficient Plot

**Residuals vs Fitted Plot:** Figure 2, suggests a relatively random scatter spots around the horizontal axis, indicating no major violations of homoscedasticity or linearity assumptions.

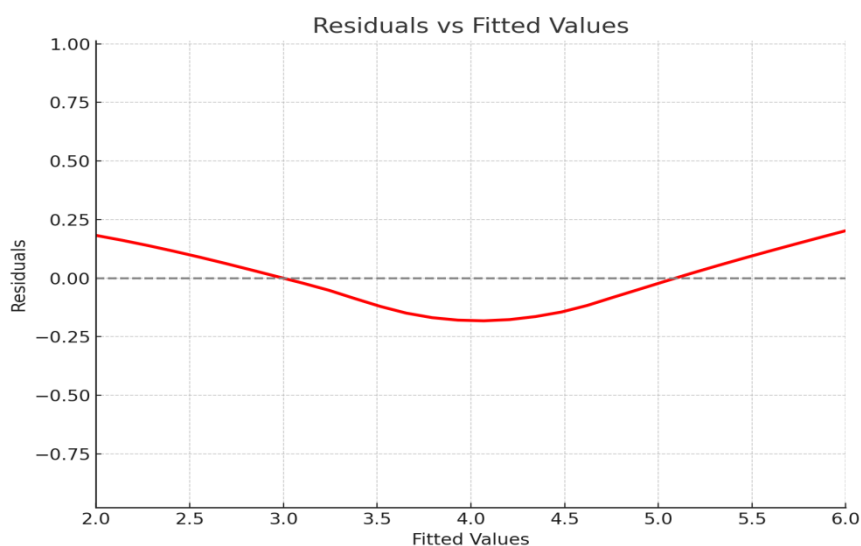


Figure 2. Residuals vs Fitted Plot



**Q-Q Plot:** Figure 3, shows that the residuals fall approximately along the 45-degree line, suggesting that they are normally distributed, which indicates a good sign for model validity.

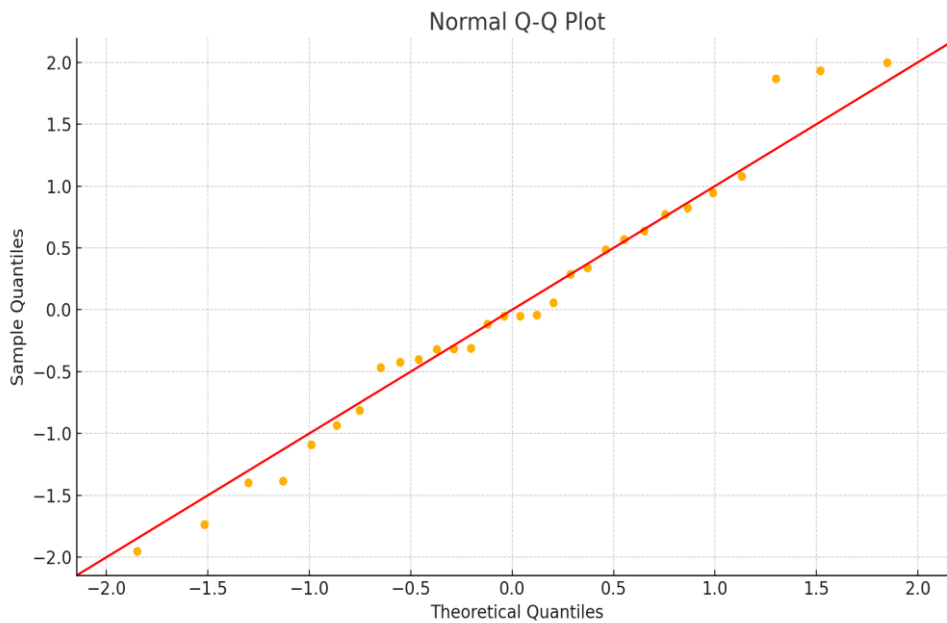


Figure 3. Q-Q Plot

Overall, the regression model shows strong and significant effects of age, gender, education, and occupation on the health outcomes related to environmental exposure. The regression explains a substantial 61% of the variance in reported health and environmental symptoms of animal waste, indicating good model fit.

## CONCLUSION

This study confirms that farm animal wastes are significant contributors to air pollution, primarily through the emission of ammonia, methane, hydrogen sulfide, and particulate matter. These pollutants pose serious threats to environmental quality and public health, particularly in regions with dense livestock populations and poor waste management infrastructure, such as Bayelsa State, Nigeria. The observed correlation between pollutant concentrations and respiratory symptoms among populations living near animal farms highlights the urgency of addressing air quality issues in agricultural settings.

Findings from the study suggest that while effective emission mitigation technologies exist, their adoption remains low among smallholder farmers due to socio-economic constraints, lack of awareness, and limited institutional support. This underscores the importance of policy incentives, farmer education, and access to clean technologies. Policymakers must prioritize integrated strategies that combine regulatory enforcement with capacity-building initiatives and economic support mechanisms to reduce the air pollution burden from livestock production.

The study's reliance on secondary literature and perception-based data represents a limitation, indicating the need for empirical, site-specific research. Future studies should incorporate direct air quality monitoring, geospatial exposure mapping, and longitudinal health assessments to provide a more precise understanding of pollutant dynamics and health impacts.

Ultimately, this research contributes to the growing body of evidence needed to inform agricultural policy, guide public health planning, and support environmental regulation. Strengthening local air quality monitoring systems, developing enforceable emission thresholds, and fostering international collaboration—given the transboundary nature of atmospheric pollution—are critical next steps toward sustainable livestock management and improved public health outcomes.

## RECOMMENDATIONS

Based on the findings and conclusion of the article, the following recommendations are proposed:

**The need to promote adoption of emission-reducing technologies:** Governments and stakeholders should encourage the use of covered manure storage systems and biogas digesters through subsidies, technical support, and demonstration projects. These technologies have been shown to significantly reduce harmful emissions such as ammonia and methane, yet remain underutilized in many low-income countries.

**Implementation of targeted policy incentives and training programs:** There is an urgent need for policy frameworks that combine regulatory enforcement with economic incentives; such as tax reliefs, grants, and low-interest loans, to encourage sustainable waste management especially by farm owners. Additionally, farmer training programs should focus on low-cost, practical solutions for emission control, particularly in resource-constrained settings.

**Investment in air quality monitoring and data-driven decision making:** National and regional authorities should invest in emission monitoring infrastructure to capture accurate data on pollutants from livestock farming. This will help track progress, support enforcement of air quality standards, and inform context-specific interventions, especially in vulnerable and high-density livestock areas.

**Institutional collaboration:** There is a need for farmers, cooperative and agro-industries to collaborate with research and technical institutions for development of sustainable and low-cost waste management systems.

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