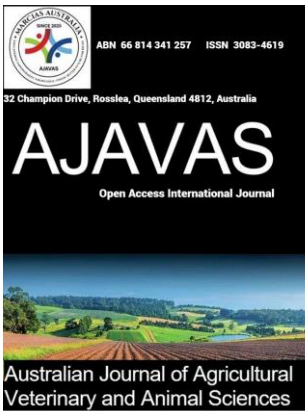

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Original Full Length Research Article

An inventory analysis of temporal trends in ruminant greenhouse gas emissions using Tier 1a methodology

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ABSTRACT: *The objective of the study was to estimate greenhouse gas emissions from ruminants using the Intergovernmental Panel on Climate Change (IPCC) Tier 1a Protocol. Primary data were collected from 360 respondents across livestock producing regions of Nigeria via structured questionnaires, complemented by secondary data from Food and Agricultural Organisation, National Agricultural Extension and Research Liaison Services and National Bureau of Statistics. Primary and secondary data on enteric and manure methane (CH_4) and nitrous oxide (N_2O) emissions were computed, analysed and validated for reliability following IPCC guidelines. Results showed that between 1998 and 2022, cattle, sheep and goat populations increased by 34, 134 and 135%, respectively. Similarly, total enteric methane and manure emissions increased by 64 and 62%, respectively, corresponding to CO_2- equivalent of 65%. It was also evident that N_2O from manure also increased by 69%, a CO_2-equivalent of 66%. Cattle contributed the largest proportion of emissions, followed by goats and sheep, respectively. Low and high productivity systems accounted for >70 and 30% of total emissions, respectively. A significant increase in ruminant greenhouse gas emissions over the 25-year period with enteric CH_4 as the largest emission source was evident. There is the urgent need for targeted interventions like improved feeding strategies, improvements in genetics and manure management through composting, anaerobic digestion and vermicomposting, to mitigate greenhouse gas emissions and optimise nutrient utilisation. Our findings provide critical insights for national climate strategies and sustainable livestock development in Nigeria.*

Keywords: Greenhouse gas emission; Tier 1a; methane; nitrous oxide; temporal trends, IPCC guidelines

Highlights

- Small ruminants in low productivity livestock systems account for 70% of greenhouse gas emissions
- The Tier 1a methodology is an advanced analytical model approach in the IPCC framework
- An increase in Nigeria's ruminant population resulted in an increase in greenhouse gas emissions

1.0 Introduction

Livestock production is a vital component of global agricultural systems, contributing substantially to food security, income generation, employment, and the livelihoods of millions of rural households, particularly in developing countries (Martínez-Ramón et al., 2026). Despite its socio-economic importance, the livestock sector is a significant contributor to anthropogenic greenhouse gas (GHG) emissions. Livestock production systems emit methane (CH_4), and nitrous oxide (N_2O) through enteric fermentation, manure management, feed production, and land-use changes associated with animal agriculture (Nugrahaeningtyas et al., 2025; Manono, 2026). Globally, livestock supply chains account for approximately 14.5% of total anthropogenic greenhouse gas emissions, making the sector one of the major contributors to climate change (Gerber et al., 2013; Grossi et al., 2022). The quantity of emission is influenced by animal species, manure management systems, climatic conditions, and management practices (Kowalska et al., 2025). Cattle are the dominant contributors to livestock-related emissions because of their large population size, greater feed intake, and higher methane production during ruminal fermentation (Grossi et al., 2022).

To derive emissions from livestock, the Intergovernmental Panel on Climate Change (IPCC) Guidelines on National Greenhouse Gas Inventories recommend methods using three tiers of increasing complexity: Tier 1, Tier 1a, Tier 2, and Tier 3 (IPCC, 2019). The Tier 1a methodology represents an advanced Tier 1 approach within the IPCC framework, specifically designed for countries with differentiated production systems. It is particularly relevant for countries where agricultural production systems transition from low productivity subsistence systems to high productivity systems, or where low and high productivity systems coexist. Unlike the default Tier 1 approach that uses uniform emission factors for broad livestock categories, Tier 1a allows inventory compilers to better track transitions and changes in productivity and related emissions over time (IPCC, 2019).

The Tier 1a methodology is particularly relevant for Nigeria because its livestock sector encompasses vastly different production systems, ranging from extensive Fulani pastoralism to intensive commercial dairy operations (Adeyemi and Akinfala, 2021). The Tier 1a approach allows recognition of this diversity through productivity based classification, potentially providing more accurate emission estimates than uniform default factors. The methodology enables tracking of emission changes related to productivity improvements and system transitions, which is critical for monitoring progress toward national climate goals and measuring the effectiveness of development in-terventions. Tier 1a methodologies satisfy international reporting obligations under the United Nations Framework Convention on Climate Change and support Nigeria's commitments under the Paris Agreement while providing a pathway for gradual improvement toward higher-tier approaches. The primary objective of this study was to estimate greenhouse gasses emission from ruminant animals in Nigeria using IPCC's Tier 1a Protocol.

2.0 Materials and methods

2.1 Study area

The study conducted in Nigeria, primary data were collected from six major livestock-producing states including; Yobe, Kano, Adamawa, Kogi, Plateau, and Katsina. These states were selected because they represent important ruminant production zones and reflect variation in livestock management practices. The area therefore provided a suitable basis for classifying livestock into category and productivity groups, which the critical steps of assessing emission trends using Tier 1a guidelines**.**

2.2 Data sources

Two categories of data were used in the study. The first consisted of primary data obtained through structured questionnaires administered to 360 respondents, with 60 respondents selected from each state. The second consisted of secondary data on cattle, sheep, and goat populations from 1998 to 2022, obtained from Food and Agricultural Organization Corporate Statistical Database (FAOSTAT, 2022), the National Bureau of Statistics (NBS, 2022), and the National Agricultural Extension and Research Liaison Services (NAERLS, 2022). These data sources were compared and validated before emission estimation.

2.3 Sampling and distribution

Respondents were selected using purposive and stratified sampling. Purposive sampling ensured the inclusion of livestock farmers, extension officers, industrial expert and other targeted. Stratified sampling was used to capture both low-productivity and high-productivity livestock systems within the study area. The questionnaire collected information on herd composition, production purpose, feeding systems, and manure management practices, which are needed for classification under the Tier 1a framework.

2.4 Validation of livestock population data

To improve reliability, livestock population figures were compared across multiple sources, including FAOSTAT, the National Bureau of Statistics, NAERLS, and other reputable sources. Where differences occurred, the most consistent and complete dataset was retained for analysis. This validation step was necessary because the accuracy of Tier 1a emission estimates depends on dependable population data and proper classification of livestock into productivity system.

2.5 Data analysis

Questionnaire responses dataset was coded and analyzed using Statistical Package for the Social Sciences (SPSS). Descriptive statistics such as frequencies and percentages were used for categorical data. For continuous variables, measures of central tendency (mean, median) and dispersion (standard deviation, range) were used.

2.6 Estimation of emissions

The study followed the 2019 IPCC refinement for estimating methane from enteric fermentation and methane and nitrous oxide from manure management using Tier 1a. Livestock were first grouped by species and production system. Emission factors were then applied to each category, and the resulting emissions were summed to obtain species-level and total emissions. Emission estimates were calculated separately for cattle, sheep, and goats and then aggregated across the study period from 1998 to 2022. Results were presented in tables and figures. Total emissions were then converted to CO_2-equivalent using standard global warming potential values (CH_4 = 28, N_2O = 265).

Calculation of enteric fermentation emissions from livestock

$$E_T = \sum_{(P)} EF_{(T,P)} \bullet \left(\frac{N_{(T,P)}}{10^6} \right)$$

where: E_T = methane emissions from Enteric Fermentation in animal category T, Gg CH_4 yr^{-1}.

$EF_{(T,P)}$ = emission factor for the defined livestock population T and the productivity system P, in kg CH_4 $head^{-1}$ yr^{-1}.

$N_{(T,P)}$ = the number of head of livestock species / category T in the country classified as productivity system P.

T = species/category of livestock.

P = productivity system, either high or low productivity for use in advanced Tier 1a.

Total Emissions from Livestock Enteric Fermentation

$$Total\ CH_{4\ Enteric} = \sum_{i,P} E_{i,P}$$

where: Total $CH_{4\ Enteric}$ = total methane emissions from Enteric Fermentation, Gg CH_4 yr^{-1}

$E_{i,P}$ = is the emissions for the i^{th} livestock categories and subcategories based on production systems (P), (IPCC, 2019).

Calculation of methane and nitrous oxide from manure management

$$CH_{4(mm)} = \left[\sum_{T,S,P} \left(N_{(T,P)} \bullet VS_{(T,P)} \bullet AWMS_{(T,S,P)} \bullet EF_{T,S,P} \right) / 1000 \right]$$

where:

$CH_{4\ (mm)}$ = CH_4 emissions from manure management in the country, kg CH_4 yr^{-1}

$N_{(T,P)}$ = number of head of livestock species/category T in the country, for productivity system P.

$VS_{(T,P)}$ = annual average VS excretion per head of species/category T, for productivity system P, in kg VS $animal^{-1}$ yr^{-1}.

$AMWS_{(T,S,P)}$ = fraction of total annual VS for each livestock species/category T that is managed in manure management system S in the country, for productivity system P.

$EF_{(T,S,P)}$ = emission factor for direct CH_4 emissions from manure management system S, by animal species/category T, in manure management system S, for productivity system P, g CH_4 kg VS^{-1}

S = manure management system

T = species/category of livestock

P = high productivity system or low productivity system for use in advanced Tier 1a.

Calculation of N_2O from manure management

$$N_2O_{D(mm)} = \left[\sum_{S} \left[\sum_{T,P} \left(\left(N_{(T,P)} \bullet Nex_{(T,P)} \right) \bullet AWMS_{(T,S,P)} \right) + N_{cdg(s)} \right] \bullet EF_{3(S)} \right] \bullet \frac{44}{28}$$

where:

$N_2O_{D\ (mm)}$ =direct N_2O emissions from Manure Management in the country, kg N_2O yr^{-1}

$N_{(T,P)}$ = number of head of livestock species/category T in the country, for productivity system P.
$Nex_{(T,P)}$ = annual average N excretion per head of species/category T in the country, for productivity system P, in kg N animal^{-1} yr^{-1}
$N_{cdg(S)}$ = annual nitrogen input via co-digestate in the country, kg N yr^{-1}, where the system (s) refers exclusively to anaerobic digestion
$AWMS_{(T,S,P)}$ = fraction of total annual nitrogen excretion for each livestock species/category T that is managed in manure management system S in the country, dimensionless; to consider productivity class P.
$EF_{3(s)}$ = emission factor for direct N_2O emissions from manure management system S in the country, kg N_2O-N/kg N in manure management system S
S = manure management system
T = species/category of livestock
P = productivity class, high or low.

44/28 = conversion of N_2O-N(mm) emissions to N_2O(mm) emissions.

$$Nex_{(T,P)} = N_{rate(T,P)} \bullet \frac{TAM_{(T,P)}}{1000} \bullet 365$$

where:
$Nex_{(T,P)}$ = annual N excretion for livestock category T, kg N animal^{-1} yr^{-1} (production level P)
$Nrate_{(T,P)}$ = default N excretion rate, kg N (1000 kg animal mass) $^{-1}$ day-1 for animal category T and production level P.
$TAM_{(T,P)}$ = typical animal mass for livestock category T, kg animal^{-1}
P = productivity class, high or low.

3.0 Results

The data in Table 1 show a steady increase in cattle numbers from 15 million in 1998 to 21 million in 2022. Similarly, sheep increased from 22 million to 50 million, and goats from 38 million to 88 million over the period (Table 1).

Figure 1 shows that cattle contributed the largest share of greenhouse gas emissions. In 1998, cattle emitted 866 Gg of methane from enteric fermentation and 135 Gg of methane plus 15 Gg of nitrous oxide from manure management, increasing by 2022 to 1,200 Gg of methane from enteric fermentation and 187 Gg of methane plus 20 Gg of nitrous oxide from manure management. Over the same period, total CO_2-equivalent emissions from cattle rose from 32 Mt to 44 Mt. Sheep also showed a marked increase in emissions. Enteric methane rose from 125 Gg in 1998 to 292 Gg in 2022, while manure management emissions increased from 21 Gg to 49 Gg of methane and from 1.8 Gg to 4 Gg of nitrous oxide. Corresponding CO_2-equivalent emissions increased from 4.5 Mt to 10.6 Mt over the study period. Goats recorded a similar upward trend. Enteric methane increased from 212 Gg in 1998 to 497 Gg in 2022, while manure management methane and nitrous oxide increased from 23 Gg to 53 Gg and from 5. Gg to 12 Gg, respectively. The CO_2-equivalent emissions of goats rose from 8 Mt to 19 Mt between 1998 and 2022.

Table 1. Distribution of ruminant livestock in Nigeria from 1998 – 2022

Year	Cattle	Sheep	Goat
1998	15,088,100	21,500,000	37,500,000
1999	15,103,200	24,000,000	40,000,000
2000	15,118,300	26,000,000	42,500,000
2001	15,133,400	28,692,600	45,260,400
2002	15,148,600	29,400,000	46,400,000
2003	15,163,700	30,086,400	47,551,700
2004	15,700,000	30,800,000	48,700,000
2005	15,875,266	31,547,900	49,959,000
2006	16,013,382	32,305,000	51,208,220
2007	16,152,700	33,080,400	52,488,200
2008	16,293,200	33,874,300	53,800,400
2009	16,434,978	34,687,264	55,145,440
2010	16,577,962	35,519,760	56,524,076
2011	19,041,270	38,376,024	67,292,536
2012	19,206,928	39,335,424	68,974,848
2013	19,374,029	40,318,809	70,699,218
2014	19,753,249	41,284,022	71,958,213
2015	20,184,763	41,632,158	72,527,691
2016	19,884,104	43,418,947	76,135,326
2017	20,057,095	44,504,420	78,038,709
2018	20,240,605	45,609,634	79,893,060
2019	20,402,276	46,767,182	81,875,539
2020	20,585,153	47,926,393	84,039,154
2021	20,764,244	49,124,553	86,140,133
2022	20,901,100	50,304,116	88,070,668

Source: FAOSTAT (2023)

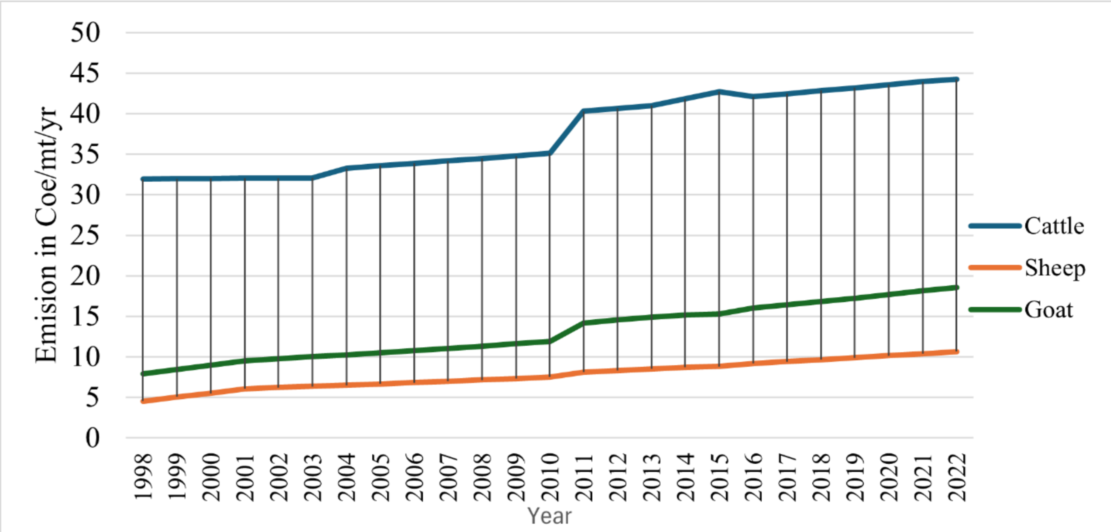

Fig. 1. Estimated greenhouse gas emissions from Nigerian ruminant livestock in CO_2-Equivalent.

The combined emissions from all ruminants also increased substantially. Total enteric methane rose from 1,202 Gg in 1998 to 1,988 Gg in 2022, while methane and nitrous oxide from manure management increased from 179 Gg and 22 Gg to 289 Gg and 36 Gg, respectively. In CO_2-equivalent, total emissions increased from 44 Mt to 73 Mt, as shown in Figure 2.

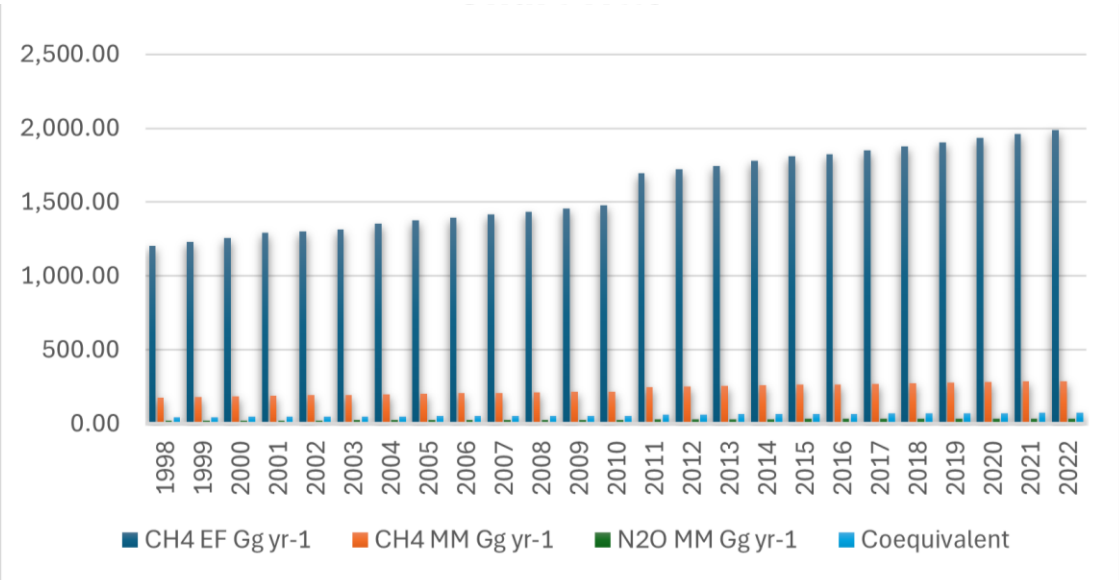

Fig. 2. Estimated total emitted greenhouse gasses of Nigerian ruminant livestock

4.0 Discussion

4.1. Trends in ruminant population growth

The observed increase in cattle, sheep, and goat populations between 1998 and 2022 reflects the growing demand for animal source foods driven by population growth, urbanization, and changing dietary preferences in Nigeria. Livestock ownership also remains an important livelihood strategy among rural households, particularly in northern Nigeria, where cattle, sheep, and goats serve as sources of income, food security, social status, and financial resilience during periods of economic uncertainty. These factors have contributed to the continuous expansion of ruminant populations over the study period. The relatively higher growth rates observed in sheep and goat populations compared with cattle may be attributed to their shorter reproductive cycles, higher reproductive efficiency, lower production costs, and greater adaptability to harsh environmental conditions goat in particular. Small ruminants are generally preferred by poor households because they require lower capital investment and can utilize a wider range of feed resources than cattle. Similar trends have been reported across sub-Saharan Africa, where small ruminant populations have expanded more rapidly than cattle populations due to their adaptability and economic importance to smallholder farming systems (Svinurai and Wilkes, 2026). The continued increase in livestock populations has important implications for greenhouse gas emissions because larger animal populations inevitably increase feed consumption, enteric fermentation, manure production, and overall emission. Consequently, population growth remains one of the principal drivers of livestock-related greenhouse gas emissions globally and in developing countries where productivity gains have not always kept pace with herd expansion (Fischer and Herrero, 2026).

4.2 Enteric methane emission trends

The substantial increase in enteric methane emissions observed during the study period is consistent with the growth in ruminant populations and the predominance of extensive production systems in Nigeria. Enteric methane is generated as a natural by-product of microbial fermentation in the rumen, where methanogenic microorganisms utilize hydrogen produced during feed digestion to form methane. Consequently, increases in animal numbers directly translate into higher methane emissions when management and feeding practices remain largely unchanged. Another important factor contributing to elevated methane emissions is the reliance on low-quality fibrous feeds and natural grazing resources, which dominate many ruminant production systems in Nigeria. Diets with high fiber content generally promote greater methane production because they favor fermentation pathways that generate larger quantities of hydrogen within the rumen. Improved feeding strategies, including higher-quality forages and balanced supplementation, have been shown to reduce methane emissions per unit of animal product by improving feed conversion efficiency and animal productivity (Roques et al., 2024). The findings agree with recent studies reporting that enteric fermentation remains the largest source of greenhouse gas emissions from livestock systems worldwide. Similar increases in enteric methane emissions have been reported in African and Mediterranean livestock systems where population growth and extensive production systems remain dominant drivers of emissions (Chebli et al., 2026; Svinurai & Wilkes, 2026).

4.3 Methane emissions from manure management

Methane emissions from manure management increased considerably throughout the study period, largely reflecting the increase in livestock populations and the corresponding rise in manure production. As animal numbers increase, greater quantities of manure are generated and become potential sources of methane emissions during storage, accumulation, and decomposition. The magnitude of methane emissions from manure is strongly influenced by manure handling practices, storage conditions, temperature, and moisture content. In many traditional livestock systems, manure is often deposited directly on grazing lands or accumulated under conditions that facilitate anaerobic decomposition, thereby increasing methane production. Although manure-related methane emissions were lower than emissions from enteric fermentation, they nevertheless represent an important component of the overall greenhouse gas inventory and should not be overlooked in mitigation planning. Recent studies have highlighted the potential of improved manure management practices such as composting, anaerobic digestion, manure drying, and biogas production to reduce methane emissions while simultaneously improving nutrient recycling and energy recovery (Kowalska et al., 2025).

4.4 Nitrous oxide emissions from manure management

The increase in nitrous oxide emissions observed in this study was primarily associated with increased manure production resulting from growing livestock populations. Nitrous oxide is produced through microbial nitrification and denitrification processes that occur when nitrogen contained in animal excreta is transformed under suitable environmental conditions. Consequently, larger livestock populations increase nitrogen excretion rates and subsequently increase the potential for nitrous oxide emissions. The relatively high global warming potential of nitrous oxide makes it a particularly important greenhouse gas despite being emitted in smaller quantities than methane. Effective manure management strategies that improve nitrogen utilization and reduce nitrogen losses can therefore contribute significantly to climate change mitigation within livestock production systems. Similar relationships between livestock population growth and nitrous oxide emissions have been reported in recent greenhouse gas inventory studies conducted in both developed and developing countries (Nugrahaeningtyas et al., 2025; Chebli et al., 2026).

4.5 Contributions of cattle, sheep and goats to greenhouse gas emissions

Cattle contributed the largest proportion of total greenhouse gas emissions. This finding is expected because cattle possess greater body weights, consume larger quantities of feed, produce more manure, and exhibit higher methane emission factors than sheep and goats. The larger rumen capacity of cattle also supports greater microbial fermentation activity, resulting in higher methane production per animal. Although sheep and goats contributed smaller proportions of total emissions, their rapidly growing populations indicate that their contribution to national greenhouse gas emissions may continue to increase in the future. The findings are consistent with global livestock emission inventories, which consistently identify cattle as the dominant source of livestock-related greenhouse gas emissions because of their biological characteristics and population size (Fischer & Herrero, 2026; Manono, 2026). Low-productivity systems accounted for the majority of greenhouse gas emissions from Nigerian ruminants. This finding reflects the dominance of extensive production systems characterized by low-quality feed resources, limited supplementation, lower animal performance, and poor feed conversion efficiency. Under such conditions, animals require longer periods to reach market weight or achieve productive performance, resulting in higher greenhouse gas emissions per unit of output.

Conversely, high-productivity systems contributed a smaller proportion of emissions because improved feeding practices, better genetics, and enhanced management increase production efficiency and reduce emission intensity. While total emissions may still occur in high-productivity systems, the amount of greenhouse gas emitted per unit of milk or meat produced is generally lower than in low-productivity systems. Similar observations have been reported in recent studies emphasizing the importance of productivity improvement as a key strategy for reducing livestock emission intensity while maintaining food production (Fischer and Herrero, 2026; Svinurai and Wilkes, 2026). A key implication of these findings is that climate mitigation in the livestock sector should focus on improving productivity rather than simply reducing herd numbers. The Tier 1a approach is particularly useful because it distinguishes between low- and high-productivity systems and can therefore better represent emission trends in heterogeneous production environments such as Nigeria. This makes tier 1a more informative than a default Tier 1 factor when livestock systems vary widely in feeding, breeding, and management intensity (IPCC, 2019).

5.0 Limitations of the study

This study relied on Tier 1a default emission factors, which improves estimation relative to a simple Tier 1 approach but still does not fully capture local variation in diet composition, animal performance, and management intensity. The estimation also depended on secondary livestock population datasets and survey-based classification of category and production systems, which may introduce uncertainty where records were incomplete or where management practices changed over time. Despite these limitations, the study provides a valuable baseline for understanding long-term ruminant emission trends in Nigeria.

6.0 Conclusion

The study shows that greenhouse gas emissions from ruminant livestock in Nigeria increased substantially between 1998 and 2022. Cattle contributed the largest share of emissions, followed by goats and sheep, while enteric fermentation remained the dominant emission source. The results indicate that population growth, low feed quality, and extensive management systems were the main drivers of the observed trends. The Tier 1a approach provided a useful framework for capturing differences between low and high productivity systems and offers a practical basis for improving national livestock emission estimates.

7.0 Recommendations

The following recommendations were made; awareness and training to farmers through extension services on climate-smart livestock practices, including efficient grazing systems, feed supplementation, and manure recycling, to reduce emissions and accelerate animal growth. Development and maintenance of a robust national livestock data system to support future GHG inventory upgrades to Tier 2 or 3 methodologies. Facilitate construction of composting units, biogas digesters, and stabilization ponds to lower CH_4 and N_2O emissions while producing renewable energy or biofertilizer. Integrate livestock emission inventories into Nigeria's Nationally Determined Contributions (NDCs) to ensure alignment with global climate targets and access to international support mechanisms.

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