



Strategic Mitigation of Methane and Nitrous Oxide Emissions from Cattle Using Tier 2 and Analytical Hierarchy Process Approaches: A Case Study in Muaro Jambi, Indonesia

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<https://doi.org/10.18280/ijdne.210215>

ABSTRACT

Received: 10 December 2025

Revised: 19 February 2026

Accepted: 26 February 2026

Available online: 28 February 2026

Keywords:

methane (CH₄) emissions, nitrous oxide (N₂O) emissions, IPCC Tier 2 methodology, Analytical Hierarchy Process, livestock greenhouse gas mitigation

This study analyzed methane (CH₄) and nitrous oxide (N₂O) emission characteristics in smallholder beef cattle production systems in Muaro Jambi Regency, Indonesia, using the IPCC Tier 2 framework and prioritized mitigation strategies using the Analytical Hierarchy Process (AHP). Primary data were collected from 150 smallholder farmers in three villages, Puduk, Tangkit, and Kademangan. The dataset included greenhouse gas (GHG) concentration monitoring conducted in cattle housing environments using an MQ-4 sensor for CH₄ detection, feed composition analysis, livestock production data, and observations of manure management practices. The monitoring results revealed spatial variation in GHG concentrations among locations, with higher concentration levels generally observed in farms with larger herd sizes, lower-quality forage, and limited manure handling practices. Feed analysis showed that farmers relied primarily on kumpai grass, which contained relatively low crude protein levels in several locations, indicating reduced feed digestibility and inefficient nitrogen utilization. These conditions are known to influence methane formation during enteric fermentation and nitrous oxide generation during manure decomposition. The emission characteristics were interpreted using the IPCC Tier 2 framework by integrating livestock parameters, feed characteristics, and manure management conditions. To identify practical mitigation options, an AHP framework was applied to evaluate three main factors: livestock production, feed and environment, and manure management. Pairwise comparison and consistency testing produced a Consistency Ratio (CR) of 0.06, indicating acceptable consistency. The prioritization results showed that improving feed quality was the most important mitigation strategy with a weight of 0.55, followed by real-time livestock monitoring with a weight of 0.24 and IoT-based manure utilization with a weight of 0.21. The combined analytical framework provides a structured approach for identifying practical strategies to reduce GHG impacts and improve sustainability in smallholder cattle production systems.

1. INTRODUCTION

Climate change mitigation requires urgent action to address major greenhouse gas (GHG) sources. Agriculture, especially the livestock sector, contributes approximately 12–14.5% of global anthropogenic GHG emissions, predominantly methane (CH₄) and nitrous oxide (N₂O) from enteric fermentation and manure management [1, 2]. Over a 100-year period, CH₄ has 28 times the global warming potential (GWP) of CO₂, whereas N₂O has approximately 270–300 times. In addition to environmental impacts, CH₄ emissions represent a 10 to 15% loss of gross energy intake (GE) in ruminants, reducing feed efficiency and productivity [3].

Indonesia is one of the world's largest livestock producers in Southeast Asia, with beef cattle production increasing to meet growing domestic demand [4]. In 2020, enteric CH₄ emissions from beef cattle were estimated at 14.5 kg/head/year,

contributing approximately 35 million tonnes of CO₂-eq annually. This condition is projected to exceed 40 million tonnes CO₂-eq by 2025 [5]. Muaro Jambi Regency in Jambi Province is among the country's major cattle production areas, yet detailed, location-specific emission inventories remain scarce. Current emission estimates largely rely on IPCC Tier 1 factors, which overlook local variations in feed quality, manure management practices, and production stages [6].

Accurate estimation of GHG emissions from livestock systems is essential for developing effective mitigation strategies. The Intergovernmental Panel on Climate Change (IPCC) provides several methodological approaches for estimating livestock emissions. Among these approaches, the Tier 2 methodology allows for more accurate emission estimation by incorporating location-specific parameters such as animal body weight, feed intake, feed composition, and manure management practices. Compared with Tier 1 methods

that rely on generalized emission factors, the Tier 2 approach provides improved accuracy because it reflects the characteristics of local livestock production systems and management conditions. In addition to emission estimation, identifying effective mitigation strategies requires decision support tools capable of evaluating multiple technical and management factors. The Analytical Hierarchy Process (AHP) is widely used in environmental management and agricultural planning as a multi-criteria decision-making method that allows systematic prioritization of mitigation strategies based on stakeholder judgments and consistency analysis.

In this study, the system boundary of the emission analysis is limited to on-farm processes associated with cattle production. Specifically, the analysis focuses on methane emissions generated from enteric fermentation in cattle and nitrous oxide emissions related to manure management practices. These two sources represent the dominant contributors to GHG emissions in smallholder cattle systems. Upstream processes such as feed cultivation, feed transportation, and other supply chain activities are not included within the scope of this research. Defining these boundaries allows the study to focus on farm-level mitigation strategies that can be directly implemented by farmers and local stakeholders.

This study addresses these gaps by focusing on smallholder beef cattle production systems, which dominate livestock farming in Muaro Jambi Regency and are typically characterized by traditional management practices, small herd sizes, and reliance on locally available forage resources. The study defines the system boundary of GHG emissions to include enteric fermentation and manure management, the two principal sources of methane (CH₄) and nitrous oxide (N₂O) in cattle production. Within this framework, the objectives of this research are to (i) quantify CH₄ and N₂O emissions from smallholder beef cattle systems in Muaro Jambi Regency using the IPCC Tier 2 methodology, (ii) identify key emission drivers related to feed quality, livestock characteristics, and manure management, and (iii) develop and prioritize mitigation strategies through the AHP. The findings provide evidence-based recommendations for reducing emissions through improved feed quality, real-time livestock population monitoring, and IoT-based manure utilization, contributing to regional climate mitigation and improved livestock system sustainability.

2. LITERATURE REVIEW

Livestock production systems are recognized as significant contributors to global GHG emissions, particularly methane (CH₄) and nitrous oxide (N₂O). Methane emissions primarily originate from enteric fermentation during the digestive process of ruminant animals, while nitrous oxide emissions are largely associated with manure management and nitrogen transformation processes. Accurate assessment of these emissions is essential for developing effective mitigation strategies and improving the sustainability of livestock production systems.

The IPCC provides standardized methodologies for estimating GHG emissions from livestock. Among these, the Tier 2 methodology offers improved accuracy compared with Tier 1 approaches because it incorporates location-specific parameters such as animal body weight, feed intake, feed composition, and manure management practices. By

considering these parameters, the Tier 2 approach allows emission estimates to better reflect the characteristics of local livestock production systems and management conditions.

In addition to emission estimation, the development of effective mitigation strategies requires decision support methods capable of evaluating multiple technical, environmental, and management factors simultaneously. The AHP is widely used as a multi-criteria decision-making method in environmental and agricultural studies. Through pairwise comparison and consistency testing, AHP enables the systematic prioritization of alternative strategies based on expert judgment and stakeholder input.

The integration of emission assessment methods, such as IPCC Tier 2, with decision support tools such as AHP provides a comprehensive framework for evaluating GHG emissions and identifying effective mitigation strategies in livestock production systems. This combined approach enables researchers and policymakers to analyze emission drivers while simultaneously prioritizing practical interventions that can reduce environmental impacts and improve production sustainability.

3. METHODS

3.1 Study area

This research was conducted from June to November 2024 in three major cattle-rearing locations in Muaro Jambi Regency, Jambi Province, Indonesia: Pudak Village (Kumpeh Ulu Subdistrict), Tangkit Village (Sungai Gelam Subdistrict), and Kademangan Village (Jambi Luar Kota Subdistrict). The study focused on smallholder beef cattle production systems, where cattle are primarily raised for meat production under traditional management practices. Farmers typically manage small herd sizes and rely on locally available forage resources as the main feed source. Within this study, the system boundary of GHG emissions includes enteric fermentation and manure management, which represent the dominant sources of methane (CH₄) and nitrous oxide (N₂O) emissions in cattle production systems.

3.2 Data collection

Methane concentration monitoring was conducted in cattle housing environments using an MQ-4 gas sensor to characterize methane presence associated with cattle activity and manure accumulation. Measurements were performed in the barn air environment at approximately 1.2–1.5 m above ground level, representing the typical breathing zone within the housing area. The sensor was positioned approximately 1–2 m from the cattle and away from direct airflow disturbances to obtain representative air concentration readings. Measurements were conducted during daytime farm activity periods when cattle were present in the housing area.

At each sampling point, the sensor was allowed to stabilize before recording measurements, and readings were repeated several times to obtain representative values. Prior to field use, the MQ-4 sensor was warmed up according to the manufacturer's operating recommendations to ensure a stable sensor response. Environmental conditions during measurement were monitored to minimize fluctuations caused by temperature and humidity variations. The MQ-4 sensor primarily responds to methane but may show cross-sensitivity

to other combustible gases such as hydrogen, carbon monoxide, and alcohol vapors. Therefore, the recorded methane values were interpreted as environmental methane concentration indicators rather than direct emission flux measurements.

A descriptive survey approach was employed, targeting smallholder farmers practicing traditional cattle management. Primary data were collected from 150 respondents (50 per village), selected purposively to represent active cattle producers. Measurements of CH₄ concentrations were performed in situ using an MQ-4 gas sensor, while N₂O emissions were estimated following the IPCC (2006) Tier 2 methodology.

Supplementary information was gathered through focus group discussions (FGDs) and key informant interviews (academics, livestock extension officers, business operators, researchers, breeders, and NGO representatives) to identify emission drivers and potential mitigation actions. Secondary data included livestock population statistics, feed availability and composition, and manure management practices. Details of data collection can be seen in Table 1.

Table 1. Factors and criteria in developing a strategy to reduce CH₄ and N₂O gas emissions

Factors	Criteria
Population and Stages of Livestock Production	Livestock population
	Livestock production stage
	Livestock reproduction
	Growth rate
Feed and Environment	Feeding management
	Composition of animal feed
	Digestion of livestock
Cattle Manure Management	Environmental conditions
	Manure as compost
	Dirt is piled up in a dense state
	Stool is spread
	Manure as biogas

3.3 Emission estimation

CH₄ emissions from enteric fermentation were estimated using the IPCC (2006) Tier 2 methodology, which incorporates site-specific livestock parameters such as animal body weight, feed intake, feed composition, growth rate, and production stage. In this study, in situ CH₄ concentration measurements obtained using an MQ-4 gas sensor were used to characterize local emission conditions and support the interpretation of emission variability among farms. These measurements were combined with feed composition data and livestock performance parameters to estimate enteric methane production following the Tier 2 calculation framework. N₂O emissions were estimated based on manure nitrogen excretion, manure management practices, and emission factors for both direct and indirect N₂O pathways. Field observations of manure handling systems, including composting, dense piling, open spreading, and biogas utilization, were incorporated to improve the accuracy of emission estimates under local management conditions.

Tier 2 emission calculation

Methane emissions from enteric fermentation were

estimated using the IPCC Tier 2 methodology, which incorporates animal performance and feed characteristics to estimate methane production. The emission factor for enteric methane was calculated as:

$$EF_{CH_4} = \frac{GE \times Ym \times 365}{55.65}$$

where, EF_{CH_4} is the emission factor for methane (kg CH₄ head⁻¹ year⁻¹); GE is gross energy intake (MJ head⁻¹ day⁻¹); Ym = methane conversion factor (% of gross energy converted to CH₄); and 55.65 = energy content of methane (MJ kg⁻¹ CH₄).

GE was estimated from dry matter intake (DMI) and feed energy content according to IPCC guidelines:

$$GE = DMI \times GE_{feed}$$

where, DMI is dry matter intake (kg head⁻¹ day⁻¹); GE_{feed} is gross energy content of feed (MJ kg⁻¹ dry matter).

Nitrous oxide emissions from manure management were estimated based on nitrogen excretion and manure management systems. Annual nitrogen excretion per animal (N_{ex}) was calculated using animal intake and retention parameters. Direct N₂O emissions from manure management were estimated using:

$$N_2O_{direct} = N_{ex} \times MS \times EF_3 \times \frac{44}{28}$$

N_{ex} is annual nitrogen excretion (kg N head⁻¹ year⁻¹); MS is fraction of manure managed in each manure management system; EF_3 is emission factor for direct N₂O emissions from manure management (kg N₂O-N per kg N); 44/28 is conversion factor from N₂O-N to N₂O; Indirect N₂O emissions were estimated using volatilization and leaching emission factors (EF_4) following IPCC guidelines.

To evaluate climate impact, methane and nitrous oxide emissions were converted into carbon dioxide equivalents (CO_{2e}) using global warming potential (GWP) factors from the IPCC:

$$CH_4 = 28 \text{ CO}_{2e}$$

$$N_2O = 265 \text{ CO}_{2e}$$

Total greenhouse gas emissions were therefore calculated as:

$$CO_{2e} = (CH_4 \times 28) + (N_2O \times 265)$$

Final results are expressed in kg CO_{2e} head⁻¹ year⁻¹.

3.4 Development of mitigation strategies

The AHP was applied to prioritize mitigation strategies. The process involved the following steps: (1) Identifying factors and criteria with three main factors were considered: (a) *Population and Stages of Livestock Production* (population, production stage, reproduction, growth rate); (b) *Feed and Environment* (feeding management, feed composition, digestibility, environmental conditions); and (c) *Cattle Manure Management* (composting, dense piling, open spreading, biogas production); (2) Pairwise comparisons – Stakeholders compared the relative importance of each factor and criterion using a nine-point scale and (3) Weighting and

consistency checking – Comparison matrices were normalized to obtain factor weights, and the consistency ratio (CR) was calculated to ensure reliability. A CR value below 0.1 was considered acceptable.

3.5 Data analysis

Gas concentration measurements of CH₄ were averaged for each location and used as inputs for emission calculations. Nitrous oxide emissions were estimated using the IPCC (2006) Tier 2 methodology based on nitrogen excretion rates and manure management system parameters. The estimation incorporated nitrogen excretion per animal (N_{ex}), manure management system fractions (MS), and emission factors for direct and indirect N₂O emissions following IPCC guidelines. Feed quality parameters, including dry matter, organic matter, crude fiber, ether extract, and crude protein, were analyzed to determine their relationship with CH₄ and N₂O emissions. To develop mitigation strategies, the AHP was applied using software called Super Decisions V3.2. The process involved

evaluating factors and criteria through pairwise comparisons, assigning weights, checking consistency, and ranking strategies. The three strategies considered were: (i) improving feed quality, (ii) implementing real-time livestock population monitoring, and (iii) applying IoT-based manure utilization.

In AHP analysis, pairwise comparisons between factors or criteria used the Saaty scale, as shown in Table 2. In addition, the standard deviation of the random index (RI) is shown in Table 3.

Table 2. Scale to compare factors in the Analytical Hierarchy Process (AHP) paired comparison

Factor i Compared to Factor j	Quantitative Value
Equally important	1
More important	3
Much more important	5
Quite more important	7
Absolutely more important	9
Intermediate values	2,4,6,8

Table 3. Standardized random index (RI) values of the mean random consistency index (CI)

Hierarchy Matrix	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.12	1.32	1.41	1.43	1.49

The AHP method for strategizing decision-making is based on the following stages:

Stage 1: Determining critical factors. The AHP can be used to make decisions, establish the sequence of criteria to be considered, and take the most reasonable decisions [7-10]. According to Akter et al. [11], the comparative value of factors will be determined based on a priority comparison scale (Table 2). Based on the scale, Table 2 shows that pairwise comparisons between equally important factors have a quantitative value of 1. The more important factor has a quantitative value of 3. The much more important factor has a quantitative value of 5. A more important factor has a quantitative value of 7. The absolutely more important factor has a quantitative value of 9. An intermediate value factor will have values of 2, 4, 6, and 8.

Stage 2: Normalize the matrix. To normalize the criterion importance matrix, divide the value of each cell in a column by the total value of that column. The weighted average (W_i) is calculated based on the sum of the weights of the X_i factor relative to X_j after normalization, divided by n . To evaluate the reliability of the weights (W_i), the Consistency Index (CI) and Consistency Ratio (CR) must be calculated. If $CR < 0.1$, the consistency of the judgments is considered acceptable. The formula for calculating CR is given by the following equations:

$$CR = \frac{CI}{RI} \text{ with } CI = \frac{\lambda - n}{n - 1}$$

$$RI = (CI_1 + CI_2 + \dots + CI_n)/n$$

$$\lambda_{max} = \frac{1}{n} \times \left[\frac{\sum_{n+1}^n W_{1n}}{W_{11}} + \frac{\sum_{n-1}^n W_{2n}}{W_{12}} + \frac{\sum_{n-1}^n W_{nn}}{W_{1n}} \right]$$

where, RI is the random index (Table 3), and λ_{max} is the eigenvalue of the matrix.

Calculation of S_i value: The total S value will be calculated according to the equation:

$$S = \sum (W_i \times X_i) \text{ with } i = 1 \dots n.$$

Stage 3: Hierarchy of total S values. Reclassification methods and regression algorithms are used to classify total S values according to their respective range of values, depending on the research content [12].

To ensure transparency in the performance evaluation process, the mathematical foundation of the AHP analysis is summarized below. The pairwise comparison matrix $A = [a_{ij}]$ expresses the relative importance of criteria i and j , where $a_{ij} = 1/a_{ji}$ and $a_{ii} = 1$. Each column of the matrix is normalized by:

$$n_{ij} = \frac{a_{ij}}{\sum_{i=1}^n a_{ij}}$$

The average of each row yields the priority vector W_i :

$$w_i = \frac{\sum_{j=1}^n n_{ij}}{n}$$

The maximum eigenvalue λ_{max} is obtained from:

$$\lambda_{max} = \frac{1}{n} \sum_{i=1}^n \frac{(AW)_i}{W_i}$$

The Consistency Index (CI) and CR are then calculated using:

$$CI = \frac{\lambda_{max} - n}{n - 1}, CR = \frac{CI}{RI}$$

where, RI is the random index (Table 3). A value of $CR < 0.1$ indicates acceptable consistency. This mathematical evaluation framework ensures that the weighting and ranking of mitigation strategies are logically coherent and statistically valid.

4. RESULT AND DISCUSSION

4.1 CH₄ and N₂O gas concentrations across study locations

Methane concentration monitoring conducted across 150 farms revealed spatial differences in CH₄ levels among the study villages. Table 4 shows a subset of observations (n = 50) from the total dataset of 150 monitored farms. Pudak Village

recorded the highest average CH₄ concentration (84.64 ppm), followed by Tangkit and Kademangan. These methane concentrations represent environmental indicators measured within cattle housing environments and reflect differences in herd size, feed quality, and manure management practices. Larger cattle populations and poor manure handling conditions can increase methane accumulation in barn air environments.

Table 4. CH₄ and CO₂ gas concentrations measured in cattle housing environments (subset of observations, n = 50 from a total of 150 farms) and estimated N₂O emissions

No.	Pudak Village			Kademangan Village			Tangkit Village		
	CH ₄ (ppm)	CO ₂ (ppm)	N ₂ O (ppb)	CH ₄ (ppm)	CO ₂ (ppm)	N ₂ O (ppb)	CH ₄ (ppm)	CO ₂ (ppm)	N ₂ O (ppb)
1	90.27	2256.75	26900.46	59.98	1499.50	17874.04	70.99	1774.75	21155.02
2	91.77	2294.25	27347.46	69.02	1725.50	20567.96	72.52	1813.00	21610.96
3	94.83	2370.75	28259.34	70.55	1763.75	21023.90	69.48	1737.00	20705.04
4	94.83	2370.75	28259.34	72.11	1802.75	21488.78	67.99	1699.75	20261.02
5	94.83	2370.75	28259.34	72.11	1802.75	21488.78	63.69	1592.25	18979.62
6	96.39	2409.75	28724.22	72.11	1802.75	21488.78	59.58	1489.50	17754.84
7	93.29	2332.25	27800.42	73.69	1842.25	21959.62	56.96	1424.00	16974.08
8	91.77	2294.25	27347.46	76.12	1903.00	22683.76	56.96	1424.00	16974.08
9	88.78	2219.50	26456.44	78.60	1965.00	23422.80	55.68	1392.00	16592.64
10	88.78	2219.50	26456.44	100.00	2500.00	29800.00	55.68	1392.00	16592.64
11	85.86	2146.50	25586.28	108.00	2700.00	32184.00	57.62	1440.50	17170.76
12	83.01	2075.25	24736.98	104.00	2600.00	30992.00	54.42	1360.50	16217.16
13	83.01	2075.25	24736.98	104.00	2600.00	30992.00	53.18	1329.50	15847.64
14	83.01	2075.25	24736.98	108.00	2700.00	32184.00	51.77	1294.25	15427.46
15	83.01	2075.25	24736.98	110.00	2750.00	32780.00	49.60	1240.00	14780.80
16	85.86	2146.50	25586.28	110.00	2750.00	32780.00	49.66	1241.50	14798.68
17	88.78	2219.50	26456.44	110.00	2750.00	32780.00	48.44	1211.00	14435.12
18	91.77	2294.25	27347.46	115.00	2875.00	34270.00	47.88	1197.00	14268.24
19	88.78	2219.50	26456.44	115.00	2875.00	34270.00	47.31	1182.75	14098.38
20	87.72	2193.00	26140.56	115.00	2875.00	34270.00	46.20	1155.00	13767.60
21	78.86	1971.50	23500.28	110.00	2750.00	32780.00	46.20	1155.00	13767.60
22	77.51	1937.75	23097.98	125.00	3125.00	37250.00	45.10	1127.50	13439.80
23	80.23	2005.75	23908.54	117.00	2925.00	34866.00	44.02	1100.50	13117.96
24	83.01	2075.25	24736.98	117.00	2925.00	34866.00	44.02	1100.50	13117.96
25	83.86	2096.50	24990.28	120.00	3000.00	35760.00	44.02	1100.50	13117.96
26	85.86	2146.50	25586.28	120.00	3000.00	35760.00	44.02	1100.50	13117.96
27	88.78	2219.50	26456.44	120.00	3000.00	35760.00	42.97	1074.25	12805.06
28	83.01	2075.25	24736.98	122.00	3050.00	36356.00	42.97	1074.25	12805.06
29	80.23	2005.75	23908.54	122.00	3050.00	36356.00	37.01	925.25	11028.98
30	77.51	1937.75	23097.98	125.00	3125.00	37250.00	37.01	925.25	11028.98
31	74.86	1871.50	22308.28	125.00	3125.00	37250.00	37.01	925.25	11028.98
32	72.27	1806.75	21536.46	122.00	3050.00	36356.00	37.01	925.25	11028.98
33	71.27	1781.75	21238.46	122.00	3050.00	36356.00	36.94	923.50	11008.12
34	71.00	1775.00	21158.00	135.00	3375.00	40230.00	35.14	878.50	10471.72
35	69.75	1743.75	20785.50	132.00	3300.00	39336.00	35.16	879.00	10477.68
36	77.51	1937.75	23097.98	130.00	3250.00	38740.00	45.15	1128.75	13454.70
37	81.23	2030.75	24206.54	117.00	2925.00	34866.00	44.02	1100.50	13117.96
38	84.86	2121.50	25288.28	108.00	2700.00	32184.00	57.62	1440.50	17170.76
39	83.07	2076.75	24754.86	103.00	2575.00	30694.00	54.45	1361.25	16226.10
40	82.01	2050.25	24438.98	104.00	2600.00	30992.00	53.25	1331.25	15868.50
41	95.83	2395.75	28557.34	72.15	1803.75	21500.70	63.71	1592.75	18985.58
42	96.49	2412.25	28754.02	72.19	1804.75	21512.62	60.58	1514.50	18052.84
43	92.29	2307.25	27502.42	73.69	1842.25	21959.62	56.98	1424.50	16980.04
44	92.77	2319.25	27645.46	74.12	1853.00	22087.76	56.96	1424.00	16974.08
45	84.01	2100.25	25034.98	104.00	2600.00	30992.00	49.59	1239.75	14777.82
46	86.86	2171.50	25884.28	106.00	2650.00	31588.00	49.65	1241.25	14795.70
47	80.25	2006.25	23914.50	114.00	2850.00	33972.00	44.02	1100.50	13117.96
48	83.09	2077.25	24760.82	116.00	2900.00	34568.00	45.03	1125.75	13418.94
49	74.88	1872.00	22314.24	123.00	3075.00	36654.00	38.02	950.50	11329.96
50	72.31	1807.75	21548.38	120.00	3000.00	35760.00	37.01	925.25	11028.98

N₂O emissions in this study were not directly measured as gas concentrations. Instead, N₂O emissions were estimated using the IPCC Tier 2 methodology based on nitrogen

excretion and manure management characteristics. The estimation incorporated nitrogen excretion rates, manure management system fractions, and emission factors for direct

and indirect N₂O emissions according to IPCC guidelines. This approach allows the evaluation of N₂O emission potential associated with manure handling practices in smallholder cattle systems.

The measured CH₄ concentrations presented in Table 4 represent field indicators of emission intensity across farms and were used to support the Tier 2 emission estimation framework. These concentration measurements were interpreted alongside livestock population data, feed nutritional characteristics, and manure management observations to estimate emissions following the IPCC Tier 2 methodology. By integrating field measurements with site-specific livestock parameters, the approach provides a more representative assessment of emission dynamics compared with default Tier 1 emission factors, which do not account for local variations in feed quality or production management. The CO₂ concentrations observed in the cattle housing environment reflect the combined effects of animal respiration and microbial decomposition of manure under limited ventilation conditions.

The nitrous oxide values presented in Table 4 are expressed in ppb. Concentrations in livestock housing environments may increase due to microbial nitrification and denitrification processes occurring in manure and bedding materials. However, these measurements represent environmental concentration levels rather than direct emission fluxes. Livestock housing environments may exhibit elevated N₂O concentrations due to microbial nitrification and denitrification processes occurring in manure and bedding materials. The observed variations among villages are associated with differences in herd size, manure management practices, and nitrogen availability in livestock waste.

It is important to note that the MQ-4 gas sensor used for methane monitoring has known cross-sensitivity to several other combustible gases, including hydrogen (H₂), carbon monoxide (CO), and alcohol vapors. In livestock housing environments, these gases may originate from microbial fermentation processes, manure decomposition, and organic

material degradation. As a result, the sensor response may be influenced by the presence of these gases in addition to methane. However, methane is typically the dominant combustible gas produced in ruminant housing environments due to enteric fermentation and manure decomposition processes. Therefore, the measurements obtained using the MQ-4 sensor are considered appropriate indicators of methane presence and relative concentration patterns across the monitored farms.

The methane monitoring in this study was primarily intended to identify spatial differences in greenhouse gas conditions within cattle housing environments rather than to provide high-precision methane quantification. Quantitative greenhouse gas emission estimates were therefore derived using the IPCC Tier 2 methodology, which relies on livestock performance parameters, feed characteristics, and manure management practices rather than sensor readings alone. Acknowledging the potential influence of sensor cross-sensitivity helps ensure that the interpretation of the monitoring results remains consistent with the methodological framework applied in this study.

Feed analysis (Table 5) indicated that all farmers rely exclusively on kumpai grass (*Hymenachne amplexicaulis*) as the primary feed source. Despite differences in location, the nutritional composition was similar across sites, with dry matter (DM) ranging from 85.51% to 87.61% and organic matter (OM) between 67.02% and 76.09%. Crude protein (CP) content was low in Puduk (4.38%) and Kademangan (4.39%), with only Tangkit showing a relatively higher CP of 9.64%. The low protein and high fiber content of kumpai grass reduces feed digestibility and rumen microbial efficiency, leading to greater hydrogen production in the rumen, which methanogens convert into CH₄. Furthermore, poor nitrogen utilization from low-quality forage results in increased nitrogen excretion in manure, creating favorable conditions for N₂O formation. This direct linkage between feed quality and both CH₄ and N₂O emissions explains why Puduk, with the lowest CP content, also exhibited the highest emission levels.

Table 5. Results of cattle feed analysis in three research villages

Village	%DM	%OM	%Ash	%CF	%EE	%CP
Tangkit	85.51	76.09	9.42	24.23	2.89	9.64
Puduk	87.61	67.02	20.59	18.95	2.87	4.38
Kademangan	86.65	73.64	12.01	19.54	3.23	4.39

Notes: DM = Dry matter, OM = Organic matter, CF = Crude fiber, EE = Extract ether, CP = Crude protein.

To translate these findings into targeted mitigation actions, the AHP framework was applied (Figure 1). Three main factor categories were evaluated: Population and Stages of Livestock Production, Feed and Environment, and Cattle Manure Management. Within this framework, three key strategies emerged as priorities: (i) improving feed quality, (ii) implementing real-time livestock population data, and (iii) utilizing IoT-based manure management systems. The AHP results align closely with the field data. Improving feed quality ranked highest due to its potential to simultaneously reduce enteric methane by enhancing feed digestibility and decrease manure nitrogen content, thereby lowering N₂O emissions. Real-time livestock population data ranked second, highlighting the importance of accurate and dynamic population monitoring for better Tier 2 emission inventories and targeted mitigation interventions. IoT-based manure utilization ranked third, addressing the need for controlled

anaerobic digestion to capture CH₄ for biogas and reduce N₂O release through optimized nitrogen management.

The integration of gas measurements, feed composition analysis, and AHP prioritization suggests that a combined mitigation approach offers the most effective pathway for reducing livestock-related CH₄ and N₂O emissions in the study area. Nutritional improvements can directly influence both gases at the source, real-time data systems can enhance management and policy responsiveness, and IoT-enabled manure systems can turn waste into a renewable energy resource while minimizing environmental impacts. Implementing these strategies concurrently can deliver synergistic benefits, including reduced greenhouse gas emissions, improved livestock productivity, enhanced farmer livelihoods, and measurable progress toward national climate change mitigation targets.

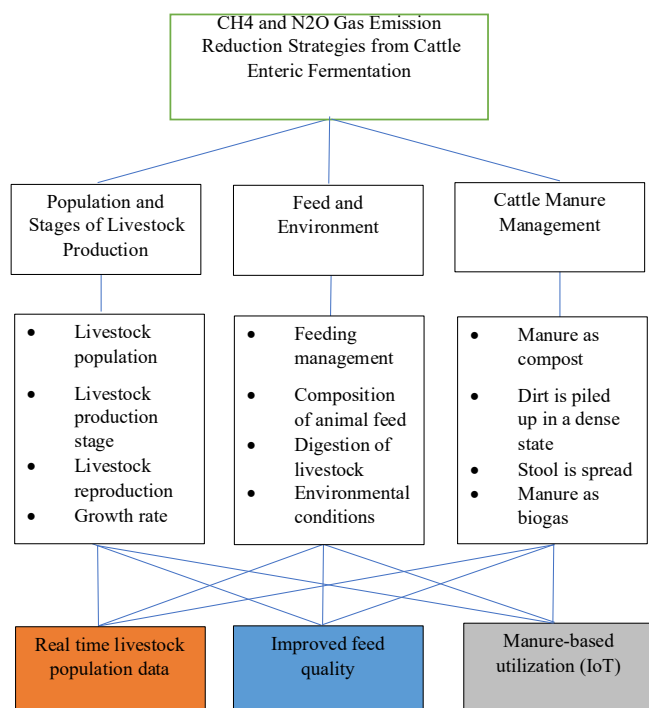


Figure 1. AHP framework for developing CH₄ and N₂O emission reduction strategies from cattle enteric fermentation

Three main factors were evaluated: (i) Population and stages of livestock production (livestock population, production stage, reproduction, growth rate), (ii) Feed and environment (feeding management, feed composition, digestion efficiency, environmental conditions), and (iii) Cattle manure management (use as compost, dense piling, open spreading, biogas production). These factors were analyzed to identify and prioritize three key strategies: real-time livestock population data, improved feed quality, and IoT-based manure utilization.

The prioritization results obtained using the AHP approach are influenced by expert judgment, which introduces a degree of subjectivity into the weighting process. Although the aggregated comparison matrix was constructed using the geometric mean of expert evaluations and the CR was within the acceptable threshold ($CR < 0.1$), differences in perspectives among stakeholder groups may influence the relative importance assigned to mitigation strategies. For example, farmers may prioritize strategies that are easy to implement and require minimal investment, while researchers and policymakers may emphasize strategies that achieve higher emission reduction potential. Future studies could further explore stakeholder-specific weighting schemes to better understand how mitigation priorities vary among different groups involved in livestock production systems.

The results of this study indicate that improving feed quality is the most important mitigation strategy for reducing greenhouse gas emissions from smallholder cattle systems. In practice, several feasible approaches can be implemented to improve feed quality under local conditions. These include the introduction of legume forages to increase crude protein content, the use of improved forage conservation techniques such as silage production, and the treatment of crop residues with urea to enhance digestibility. Mineral supplementation can also help improve rumen microbial activity and nutrient utilization. In addition, the strategic use of feed additives that reduce methane production, such as inhibitors of

methanogenesis, has been investigated in livestock systems. However, the adoption of advanced additives may depend on economic feasibility and accessibility for smallholder farmers. Therefore, locally available feed resources and low-cost feed improvement strategies are likely to provide the most practical mitigation options in the study area.

4.2 Effect of CH₄ and N₂O gas emissions to environment

CH₄ and N₂O are among the most potent and persistent GHGs influencing the global climate system. Over a 100-year time horizon, CH₄ exhibits a GWP approximately 28 times greater than carbon dioxide (CO₂), while N₂O's GWP is roughly 270 to 300 times higher. Beyond amplifying the greenhouse effect, both gases contribute to a range of atmospheric and ecological disturbances.

In the atmosphere, CH₄ participates in complex photochemical reactions that elevate tropospheric ozone (O₃) concentrations, a secondary GHG that also threatens human and animal health. Elevated CH₄ levels can lower atmospheric hydroxyl radical (OH) concentrations, which reduces the oxidative capacity of the atmosphere and prolongs the lifetime of CH₄. This feedback enhances climate forcing, increases stratospheric water vapor, and alters ozone distribution patterns, indirectly contributing to ozone depletion [13]. Historical increases in CH₄ have caused approximately a six percent rise in tropospheric O₃, particularly in the tropics and Northern Hemisphere, worsening both climate warming and air quality [14].

N₂O is not only a potent climate forcer but also the dominant ozone-depleting emission in the 21st century. With an atmospheric lifetime exceeding a century, N₂O migrates to the stratosphere, where it undergoes photolysis and catalytic reactions that destroy ozone molecules. This depletion increases ultraviolet-B (UV-B) radiation at the Earth's surface, resulting in negative impacts such as reduced crop yields, altered aquatic ecosystems, and biodiversity loss. In addition, N₂O-driven ozone depletion influences tropospheric photochemistry, indirectly affecting CH₄ levels by modifying OH concentrations. This effect can persist for more than a century [15].

From an agricultural perspective, CH₄ and N₂O emissions from cattle production create a dual environmental burden. Methane from enteric fermentation not only accelerates global warming but also represents an energy loss of approximately six to ten percent of an animal's GE, reducing feed efficiency. Similarly, N₂O emissions from manure management reflect inefficiencies in nitrogen utilization, often resulting from poor feed quality and inadequate manure handling. These inefficiencies contribute to a cycle of environmental degradation, economic loss, and reduced production sustainability. While elevated O₃ can suppress CH₄ and N₂O emissions from soils, this suppression offsets only about ten percent of the CO₂ increase caused by O₃'s negative effects on plant productivity [16]. Agriculture, through enteric fermentation and manure management, is therefore a major source of these gases, highlighting the close link between feed conversion efficiency, nitrogen management, and GHG emissions [17].

The spatial variability observed in this study, particularly the high CH₄ and N₂O concentrations in Puduk Village, illustrates how local management practices, herd size, and feed quality can shape emission profiles. High-emission zones have a disproportionate impact on regional GHG inventories,

making them priority targets for mitigation. Addressing these emissions is critical for climate change mitigation, improving air quality, protecting the ozone layer, and enhancing agricultural productivity. Interactions among climate variability, nitrogen fertilizer use, and ozone pollution further influence the spatial and temporal dynamics of CH₄ and N₂O emissions from terrestrial ecosystems [18].

4.3 Mechanism of climate change due to CH₄ and N₂O gas emissions

CH₄ and N₂O are among the most potent greenhouse gases, exerting climate impacts far greater than their atmospheric concentrations would suggest. Their high radiative efficiency and extended atmospheric lifetimes enable them to trap outgoing longwave radiation far more effectively than CO₂. Over a 100-year timescale, CH₄ has a GWP about 28 times that of CO₂, while N₂O's GWP is approximately 270–300 times greater. These factors make them disproportionately influential drivers of global warming despite being emitted in smaller absolute quantities than CO₂.

In livestock systems, CH₄ is predominantly produced through enteric fermentation in ruminants. This microbial digestive process occurs in the rumen, where carbohydrates are broken down anaerobically, generating hydrogen that methanogenic archaea convert into CH₄. The gas is expelled primarily via eructation. Once in the atmosphere, CH₄ directly contributes to the greenhouse effect by absorbing infrared radiation in the 7–8 μm and 3.3 μm bands. Indirectly, CH₄ enhances tropospheric ozone concentrations through photochemical reactions involving hydroxyl radicals (OH) and increases stratospheric water vapor through oxidation, both of which amplify radiative forcing. N₂O emissions from livestock originate mainly from nitrification and denitrification processes in manure and soils enriched with nitrogen from animal excreta. During nitrification, ammonia (NH₃) and ammonium (NH₄⁺) are oxidized to nitrate (NO₃⁻), releasing N₂O as a by-product. Under anaerobic conditions, denitrification reduces nitrate to dinitrogen (N₂), with N₂O as an intermediate. Highly stable, N₂O remains in the atmosphere for over a century. Beyond its warming potential, it migrates to the stratosphere, where photolysis and reactions with excited oxygen atoms generate nitrogen oxides (NO_x). These NO_x compounds catalytically destroy ozone molecules, thinning the ozone layer and allowing more harmful ultraviolet-B (UV-B) radiation to reach Earth's surface.

The lifecycles of CH₄ and N₂O are chemically linked. N₂O-induced ozone depletion alters ultraviolet radiation penetration and OH radical concentrations, indirectly influencing CH₄'s atmospheric lifetime [15]. This chemical coupling means that mitigation efforts targeting one gas can have cascading effects on the other, creating opportunities for integrated strategies. Within cattle production, the drivers of CH₄ and N₂O emissions are closely related. Low-quality, high-fiber feed increases hydrogen production in the rumen, promoting methanogenesis, while inefficient nitrogen utilization from protein-deficient diets increases nitrogen excretion, enhancing N₂O generation in manure. This dual pathway intensifies the total greenhouse effect of livestock systems. Global nitrous oxide (N₂O) emissions from livestock manure have risen by approximately 350%, increasing from 451 [368–556] Gg N year⁻¹ in 1890 to 2042 [1677–2514] Gg N year⁻¹ in 2020. During 2010–2019, these emissions accounted for around 30% of total global anthropogenic N₂O emissions. Cattle were the

largest contributors to this growth (60%), followed by poultry (19%), pigs (15%), and sheep and goats (6%). Since the 1990s, South Asia, Africa, and Latin America have driven most of the global emission increases. At the national level, the highest emissions in the 2010s were recorded in India (329 Gg N year⁻¹), China (267 Gg N year⁻¹), the United States (163 Gg N year⁻¹), Brazil (129 Gg N year⁻¹), and Pakistan (102 Gg N year⁻¹) [19].

Additional emission sources and dynamics complicate mitigation. Aerobic composting of manure can be a significant N₂O source, driven by microbial nitrification–denitrification processes; however, process optimization can reduce these emissions [20]. N₂O emissions from cattle urine often exceed those from dung, with emission factors varying by soil type, season, and climate, and with IPCC default values sometimes overestimating emissions in specific regions [21]. Globally, CH₄ and N₂O emissions from land ecosystems are rising due to climate change, nitrogen fertilizer use, and tropospheric ozone pollution. Livestock and rice cultivation are primary CH₄ sources, while croplands dominate N₂O increases [2]. N₂O is now the single largest ozone-depleting emission, responsible for roughly half of ozone-related health damage in 2010, with a climate impact about 27 times greater than its ozone depletion effect [22]. Mitigation strategies must therefore address CH₄ and N₂O in a coordinated way. Improving feed quality can reduce both hydrogen production and excess nitrogen excretion, thereby lowering emissions of both gases. Enhanced herd management can increase productivity and reduce per-unit emissions, while manure handling innovations such as anaerobic digestion or optimized composting can limit N₂O release. Considering the chemical coupling and shared agricultural drivers of CH₄ and N₂O is essential to developing policies and practices that maximize climate benefits while avoiding unintended trade-offs.

4.4 Alternative strategies to reduce CH₄ and N₂O gas emissions in cattle

Although global mitigation efforts often focus on CH₄, annual methane emissions have increased by approximately 61 million tonnes (20%) in the past two decades. In addition to fossil fuel use, the livestock sector is a significant source of CH₄, contributing alongside N₂O to global GHG emissions [23]. The development of mitigation strategies began with weighing each factor and criterion through paired comparisons. The three main factors: (1) Population and Stages of Livestock Production, (2) Feed and Environment, and (3) Cattle Manure Management are presented in Figure 2.

The AHP analysis indicated that among the three strategies for reducing CH₄ and N₂O emissions from cattle enteric fermentation, improved feed quality emerged as the highest priority overall, with a weight of 0.55. This strategy consistently ranked first across most decision-making factors, reflecting its substantial potential to mitigate greenhouse gas emissions while improving animal productivity [24]. Real-time livestock population data and manure-based utilization via IoT received lower overall weights of 0.24 and 0.21, respectively, suggesting their roles are more complementary than primary in emission reduction.

Across the population and stages of livestock production criteria, improved feed quality attained its strongest influence on growth rate (0.59), highlighting the critical link between nutritional optimization and reduced enteric methane production. In contrast, real-time livestock population data

scored highest for livestock population (0.53), underscoring its utility in refining emission inventories, especially in systems where herd size changes seasonally [25]. Manure-based utilization via IoT had relatively lower weights in this category, indicating a less direct impact on enteric fermentation.

In the feed and environment criteria, the advantage of improved feed quality was particularly pronounced in the digestion of livestock (0.54) and feeding management (0.53). These results support the widely recognized role of feed digestibility and optimized nutrient composition in lowering methane yields per unit of animal product [26]. Real-time livestock data contributed less in this category, while manure-based IoT utilization was more relevant for environmental conditions (0.41), suggesting its indirect role in reducing N₂O emissions through better manure handling [27].

For cattle manure management, improved feed quality again scored the highest in dirt piled in a dense state (0.54) and manure as biogas (0.55), reflecting its influence on manure characteristics and biogas production potential [28]. Real-time livestock data was most important for stool spreading (0.41),

likely due to its value in scheduling manure application, while manure-based IoT utilization reached its peak relevance for the same subfactor (0.38), indicating the potential of smart technologies to optimize manure use and reduce emissions during handling [29].

The overall synthesis of these findings shows that improving feed quality remains the most effective and immediate strategy for mitigating CH₄ and N₂O emissions in cattle systems. This is consistent with global assessments, which identify feed interventions as the most cost-effective measure for ruminant greenhouse gas reduction [24]. While technological solutions such as IoT-enabled manure management and real-time livestock population monitoring have promising long-term benefits, their current priority ranking suggests they are best applied as complementary strategies to nutritional interventions. Integrating these approaches could provide synergistic effects, enhancing both environmental sustainability and economic viability in livestock production systems.

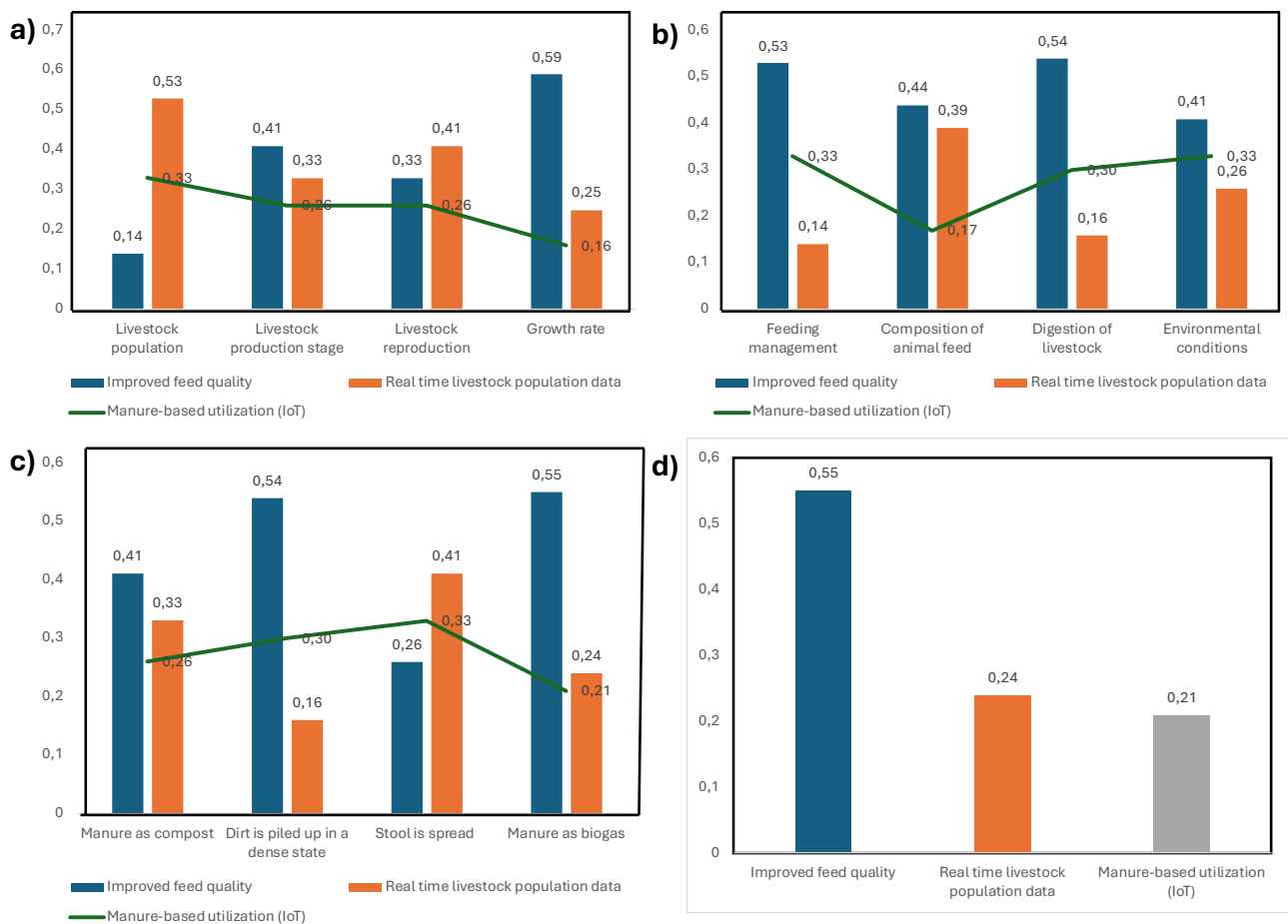


Figure 2. Analytical Hierarchy Process (AHP) results for CH₄ and N₂O emission reduction strategies from cattle enteric fermentation (a) Population and stages of livestock production, (b) Feed and environment, (c) Cattle manure management, and (d) Overall AHP priority weights

The first three subplots represent the priority weights of three alternative strategies: improved feed quality (blue bars), real-time livestock population data (orange bars), and manure-based utilization via IoT (green line) across (a) population and stages of livestock production, (b) feed and environment, and (c) cattle manure management. The last subplot (d) summarizes the overall weights of the three strategies, indicating that improved feed quality (0.55) was the most prioritized, followed by real-time livestock population data (0.24) and manure-based utilization via IoT (0.21).

4.5 Tier 2 greenhouse gas emission estimates

Greenhouse gas emissions from cattle production in the study area were estimated using the IPCC Tier 2 methodology

based on livestock population, feed intake characteristics, nitrogen excretion rates, and manure management practices. The calculated emissions include methane from enteric fermentation, methane from manure management, and nitrous

oxide emissions associated with nitrogen transformation processes in livestock waste.

The emission results were expressed both as emission factors per animal and as total emissions at the village scale.

Methane and nitrous oxide emissions were subsequently converted into CO₂e using GWP factors recommended by the IPCC (CH₄ = 28; N₂O = 265). A summary of the estimated emissions for each study village is presented in Table 6.

Table 6. Greenhouse gas emissions from smallholder cattle systems estimated using the IPCC Tier 2 method

Village	Cattle Population (head)	Enteric CH ₄ (kg/head/year)	Manure CH ₄ (kg/head/year)	N ₂ O (kg/head/year)	Total CO ₂ e (kg CO ₂ e/head/year)	Total CO ₂ e (ton/year)	Uncertainty (%)
Pudak	520	56.04	2.01	1.05	1983	1031.02	± 20
Tangkit	480	54.08	1.09	1.04	1917	920.02	± 20
Kademangan	450	53.06	1.08	1.03	1871	842	± 20

The results indicate that enteric fermentation represents the dominant source of methane emissions in the studied cattle systems, reflecting the reliance on low-quality forage with relatively low digestibility. Manure management practices also contribute to methane and nitrous oxide emissions, particularly in farms where manure is stored in open piles or unmanaged areas. The estimated uncertainty range reflects potential variability in feed intake estimation, nitrogen excretion rates, and emission factor assumptions following IPCC Tier 2 guidelines.

5. CONCLUSION

This study analyzed greenhouse gas emission characteristics in smallholder cattle production systems in Muaro Jambi Regency and identified mitigation priorities using the AHP. Environmental monitoring conducted in cattle housing environments revealed spatial differences in methane concentrations among the study villages, which were associated with variations in herd size, feed quality, and manure management practices.

The emission assessment framework applied in this study integrated livestock production data, feed characteristics, and manure management information to evaluate greenhouse gas emission conditions in the local production systems. The results indicate that feed quality and nitrogen management play important roles in influencing greenhouse gas formation in smallholder cattle farming systems.

The AHP analysis demonstrated that improving feed quality represents the most important mitigation strategy, followed by real-time livestock monitoring and improved manure management using IoT-based systems. These strategies have the potential to improve production efficiency while reducing greenhouse gas impacts.

Overall, the integrated analytical framework applied in this study provides a structured approach for identifying practical mitigation strategies to support more sustainable cattle production systems in Muaro Jambi Regency.

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