Livestock and Animal Research
Accredited by Directorate General of Higher Education, Research, and Technology No. 152/E/KPT/2023

Open Access
Livest. Anim. Res., June 2026, 24(1): 18-29
p-ISSN 2721-5326 e-ISSN 2721-7086
https://doi.org/10.20961/lar.v22i3.84171

Original Article

Greenhouse gas emission (GHG) assessment in the livestock sector in Samin Watershed, Central Java, Indonesia

Kharisma Imam Adinata [1*], Mukh Arifin [2], Limbang Kustiawan Nuswantara [2], and Endang Purbowati [2]

1 Doctoral Program of Animal Science, Faculty of Animal and Agricultural Sciences, Diponegoro University, Semarang 50275, Indonesia.

2 Department of Animal Science, Faculty of Animal and Agricultural Sciences, Diponegoro University, Semarang 50275, Indonesia.

*Correspondence: imamliya90@gmail.com

Received: October 10th, 2025; Accepted: June 23rd, 2026 Published online: June 30th, 2026

Abstract

Objective: The livestock sector in Indonesia emits substantial greenhouse gases (GHG) through enteric fermentation and manure management. Sub-national inventories, however, remain constrained by Tier-1 default emission factors that are not sensitive to local animal characteristics. This study estimated livestock GHG emissions in the Samin Watershed, Central Java, using localized Tier-2 emission factors and compared the results with Tier-1 national defaults.
Methods: Emissions of CH_4 and N_2O from enteric fermentation and manure management were estimated following IPCC 2019 Tier-2 guidelines using physiological class-specific factors derived from local body weight and nitrogen excretion data. Livestock population data (2020 to 2024) were obtained from the Central Statistics Agency of Karanganyar and Sukoharjo regencies. Uncertainty was quantified using standard error propagation (±15 to 20%).
Results: Total GHG emissions ranged from 17.61 to 40.12 Gg CO_2-eq/year (2020 to 2024), declining sharply in 2021 before recovering steadily through 2024. Enteric fermentation dominated at approximately 66% of annual emissions, with cattle contributing 84.02% of enteric CH_4. Manure N_2O represented 25 to 32% and manure CH_4 contributed 6 to 8% of annual emissions. Tier-2 estimates were 5 to 6% lower than Tier-1 defaults for beef cattle enteric emissions.
Conclusions: The Samin Watershed livestock sector is dominated by enteric fermentation (approximately 66% of total GHG), with cattle as the primary source (84.02% of enteric CH_4) and manure N_2O as the second-largest contributor (25 to 32%). Localized Tier-2 factors improved accuracy over Tier-1 defaults, and mitigation should prioritize ruminant feed quality improvement and structured manure nitrogen management.

Keywords: Cattle; Enteric fermentation; Greenhouse gas emissions; Livestock farming; Manure management; Samin Watershed

INTRODUCTION

Livestock farming is a major source of anthropogenic greenhouse gas emissions, releasing CH_4 and N_2O primarily through enteric fermentation in ruminants and decomposition of animal manure. Both gases carry substantially higher warming potentials than CO_2: CH_4 at approximately 25 times CO_2 over a 100-year horizon, and N_2O at 298 times [1]. In Indonesia, the livestock sector particularly beef cattle, is a leading source of methane from enteric fermentation, and this contribution is expected to grow alongside national herd expansion [2].

Prior work on livestock GHG quantification in Indonesia has largely relied on the IPCC Tier-1 approach, which assigns a single national-average emission factor per species, without accounting for age class, body weight, or local management conditions. Noted that applying generic Tier-1 factors introduces systematic bias in regions where animal body weights and feeding practices diverge from national averages [3,4,5]. Despite this recognition, no watershed-scale inventory applying Tier-2 methodology across multiple species and physiological classes has been published for Central Java.

This study addresses that gap. Using livestock census data from Karanganyar and Sukoharjo regencies for 2020 to 2024, localized Tier-2 emission factors were derived from actual body weight measurements and region-specific nitrogen excretion rates for six livestock categories. The Tier-2 estimates are compared with Tier-1 national defaults to quantify the methodological difference. The findings are intended to provide a more accurate emission inventory and to support targeted mitigation planning within the Samin Watershed.

MATERIALS AND METHODS

This study applied the IPCC Tier-2 methodology to estimate GHG emissions from the livestock sector in the Samin Watershed, Central Java. Livestock population data classified by physiological category were obtained from the Central Statistics Agency (BPS) of Karanganyar and Sukoharjo regencies for 2020 to 2024 [21,22]. Emission factor values for enteric fermentation, manure CH_4, and manure N_2O were sourced from the Ministry of Agriculture and the Ministry of Environment and Forestry according to the Directorate of Greenhouse Gas Inventory [6,19,20].

Comparison between localized and national default emission factors

To represent livestock conditions in the Samin Watershed more accurately, this study applied the IPCC Tier-2 approach using region-specific parameters, including average body weight, manure nitrogen content, and physiological classes derived from local datasets (Tables 2, 4). Tier-1 estimates follow IPCC 2019 [18] defaults that assign one emission factor per species without age or physiological differentiation (e.g., 56 kg CH_4/head/year for beef cattle and buffalo; five for goats and sheep). In contrast, Tier-2 produced class-specific enteric CH_4 factors: beef cattle 18.20 to 55.89, buffalo 20.55 to 82.21, goats 2.29 to 3.27, sheep 1.31 to 5.25, pigs 0.43 to 1.28, and poultry 0.0031 to 0.0043 kg CH_4/head/year. A numerical Tier-1 vs. Tier-2 comparison is provided in Table 1.

Table 1.Numerical comparison between Tier-1 and Tier-2 livestock GHG emission estimates in the Samin Watershed

Livestock Type	Classification	Tier-1 Default EF (kg CH_4/head/year)	Tier-2 Local EF (kg CH_4/head/year)
Beef Cattle	Calf	56	18.20
	Post-weaning	56	27.20
	Heifer	56	41.78
	Adult	56	55.89
Buffalo	Calf	55	20.55
	Post-weaning	55	41.11

	Growing	55	61.66
	Adult	55	82.21
Goat	Kid	5	2.29
	Post-weaning	5	2.64
	Adult	5	3.27
Sheep	Lamb	5	1.31
	Post-weaning	5	4.33
	Adult	5	5.25
Pig	Piglet	1	0.43
	Post-weaning	1	1.03
	Adult	1	1.28
Broiler		0	0.0039
Layer		0	0.0043
Native Chicken		0	0.0031
Duck		0	0.0035

[1] IPCC (2019); [2] Agus (2019).

Table 2. Livestock population in the Samin Watershed and enteric CH_4 emission factor

Livestock Type	**Classification**	**Population (Head)[1]**					**Enteric Fermentation (kg CH_4/ head/year)**	N_2O emission factor (kg N_2O–N/kg N)
		2020	**2021**	**2022**	**2023**	**2024**		
Beef Cattle	Calf	2,453	2,431	2,331	2,082	2,072	18.20	0.78
	Post-weaning	1,471	1,458	1,398	1,249	1,243	27.20	1.62
	Heifer	5,944	5,910	5,751	5,354	5,339	41.78	3.47
	Adult	11,888	11,820	11,502	10,708	10,678	55.89	3.64
	Total	**21,756**	**21,619**	**20,982**	**19,393**	**19,332**		
Dairy	Calf	6	4	4	5	5	16.55	0.52
	Post-weaning	6	4	4	5	5	35.05	2.51
	Heifer	3	3	3	3	3	51.96	5.52
	Adult	2	2	2	1	1	77.14	12.18
	Total	**17**	**13**	**13**	**14**	**14**		
Buffalo	Calf	1	0	0	0	0	20.55	0.75
	Post-weaning	0	1	0	0	0	41.11	3.98
	Growing	0	0	1	0	0	61.66	8.97
	Adult	2	2	2	3	2	82.21	15.95
	Total	**3**	**3**	**3**	**3**	**2**		
Goat	Kid	2,898	3,120	3,125	3,176	3,230	2.29	0.02
	Post-weaning	3,711	4,137	4,191	4,237	5,867	2.64	0.02
	Adult	6,802	6,181	6,336	6,491	6,802	3.27	0.03
	Total	**13,411**	**13,438**	**13,652**	**13,904**	**15,899**		
Sheep	Lamb	4,728	5,202	5,458	6,090	4,752	1.31	0.01
	Post-weaning	5,845	3,953	4,513	5,218	3,425	4.33	0.05

	Adult	5,845	6,213	7,093	8,200	5,382	5.25	0.08
	Total	**16,418**	**15,368**	**17,064**	**19,508**	**13,559**		
Pig	Piglet	215	1,343	1,281	1,853	899	0.43	0
	Post-weaning	194	1,062	1,081	1,461	755	1.03	0.01
	Adult	755	1,137	1,084	1,559	755	1.28	0.01
	Total	**1,164**	**3,542**	**3,446**	**4,873**	**2,409**		
Broiler		4,877,111	5,749,844	6,089,944	5,488,746	4,985,195	0.0039	0.09
Layer		1,396,788	1,301,031	1,330,433	1,209,725	1,290,589	0.0043	0.043
Native Chicken		258,927	275,718	291,349	287,494	288,020	0.0031	0.0031
Duck		57,651	50,342	51,875	55,964	58,521	0.0035	0.0035

[1] BPS (2024); [2] Agus (2019).\

Nitrous oxide emissions from manure management

GHG emissions from livestock manure management, including CH_4 and N_2O, were estimated for each livestock category. Nitrogen excretion values, expressed as kg N per 1,000 kg body weight per day, were obtained from IPCC 2019 [18] for the Asia region. Average body weight data were sourced from the Ministry of Agriculture [19]. Emission factors for manure management systems, including dry manure, compost, slurry, and poultry litter, are provided in Table 3.

Table 3. N_2O emission factor for livestock manure management systems

Livestock Manure Management System	N_2O Emission Factor[1] (kg N_2O–N/kg N)
Dry Manure	0.02
Dense Manure	0.005
Spread on Surface	0
Slurry	0
Biogas	0
Compost Manure	0.01
Poultry excreta with litter	0.001
Poultry excreta without litter	0.001

[1] IPCC (2019).

Table 4. Nitrogen excretion rate and average body weight of livestock in the Samin Watershed

Livestock	Category	Nitrogen Excretion Rate[1] (kg N/1,000 kg BW/day)	Average Body Weight[2] (kg/head)
Beef Cattle	Calf	0.34	46
	Post-weaning	0.34	134.48
	Heifer	0.34	286
	Adult	0.34	400
Dairy	Calf	0.47	63
	Post-weaning	0.47	134
	Heifer	0.47	200
	Adult	0.47	250
Buffalo	Calf	0.32	100
	Post-weaning	0.32	200
	Growing	0.32	300
	Adult	0.32	400
Goat	Kid	1.37	8
	Post-weaning	1.37	20
	Adult	1.37	25
Sheep	Lamb	1.17	8
	Post-weaning	1.17	20
	Adult	1.17	25
Pig	Piglet	0.50	15
	Post-weaning	0.50	60
	Adult	0.50	80
Broiler		1.10	1.2
Layer		0.82	2
Native Chicken		0.82	1.5
Duck		0.83	1.5

[1] Agus (2019); [2] Directorate of Greenhouse Gas Inventory (2019).

GHG emission calculation method

GHG emissions from the livestock sector were estimated separately for three pathways: (1) CH_4 from enteric fermentation, (2) CH_4 from manure management, and (3) N_2O from manure management. The calculations followed the IPCC 2019 Tier-2 framework [18], which provides more differentiated emission estimates than Tier-1 by incorporating class-specific parameters such as livestock subcategory, body weight, and nitrogen excretion rate.

Enteric fermentation CH_4 emissions

Methane emissions from enteric fermentation were estimated using the following formula:

$$CH_4 \text{ emissions enteric} = EF \text{ enteric}(T) \times N(T) / 10^6$$

Where:

EF enteric(T) = methane emission factor for enteric fermentation for livestock subcategory T (kg CH_4/head/year);

N(T) = annual livestock population in subcategory T (head).

Manure management CH_4 emissions

For methane emissions from livestock manure, the following formula was applied:

$$CH_4 \text{ emissions manure} = EF \text{ manure}(T) \times N(T) / 10^6$$

Where:

EF manure(T) = methane emission factor for manure management for livestock subcategory T (kg CH_4/head/year);

N(T) = annual livestock population in subcategory T (head).

Manure management N_2O emissions

For direct nitrous oxide emissions from manure management, the following aggregate formulation was used:

$$N_2O \text{ emissions} = [\Sigma\ s\ \Sigma\ t\ (N(T) \times Nex(T) \times BW(T) \times EF_3(s))] \times (44/28) \times 365$$

Where:

N(T) = annual livestock population in subcategory T (head);

Nex(T) = nitrogen excretion rate for livestock subcategory T (kg N/1,000 kg body weight/day);

BW(T) = average body weight for livestock subcategory T (kg/head);

EF_3(s) = direct N_2O emission factor for manure management system s (kg N_2O–N/kg N);

44/28 = molecular weight ratio used to convert N_2O–N to N_2O;

365 = number of days per year.

Annual emissions from all livestock subcategories and manure management systems were then aggregated to obtain total livestock-sector GHG emissions in the Samin Watershed.

Uncertainty analysis

An uncertainty analysis was performed to evaluate the reliability of emission estimates produced by the Tier-2 method. The analysis followed the uncertainty guidance in IPCC 2019 [18], where uncertainty is represented through the combined error of activity data and emission factors. A relative uncertainty range of ±10 to 30% was applied to livestock population, emission factors, and nitrogen excretion values based on variability in field conditions and default ranges provided in the IPCC guidelines [16,18]. Total uncertainty was estimated using the following formula:

$$U \text{ total} = \sqrt{(U\ AD^2 + U\ EF^2)}$$

Where:

U total = combined uncertainty of the emission estimate;

U AD = uncertainty associated with activity data (livestock population);

U EF = uncertainty associated with emission factors.

RESULTS

Methane emissions from enteric fermentation

Enteric fermentation was the dominant GHG source in the Samin Watershed throughout the study period, contributing 60 to 69% of total livestock emissions annually. Total enteric CH_4 ranged from 10.63 Gg CO_2-eq/year in 2021 to 27.67 Gg CO_2-eq/year in 2024 (Table 5, Figure 1). The 2021 dip is discussed in the Discussion section. Cattle were responsible for 84.02% of enteric CH_4 across the study period, consistent with their numerical dominance in the herd and the higher individual emission rates relative to small ruminants and poultry. The Tier-2 class-specific factors, grounded in local body weight and feed data, support the reliability of these attribution estimates.

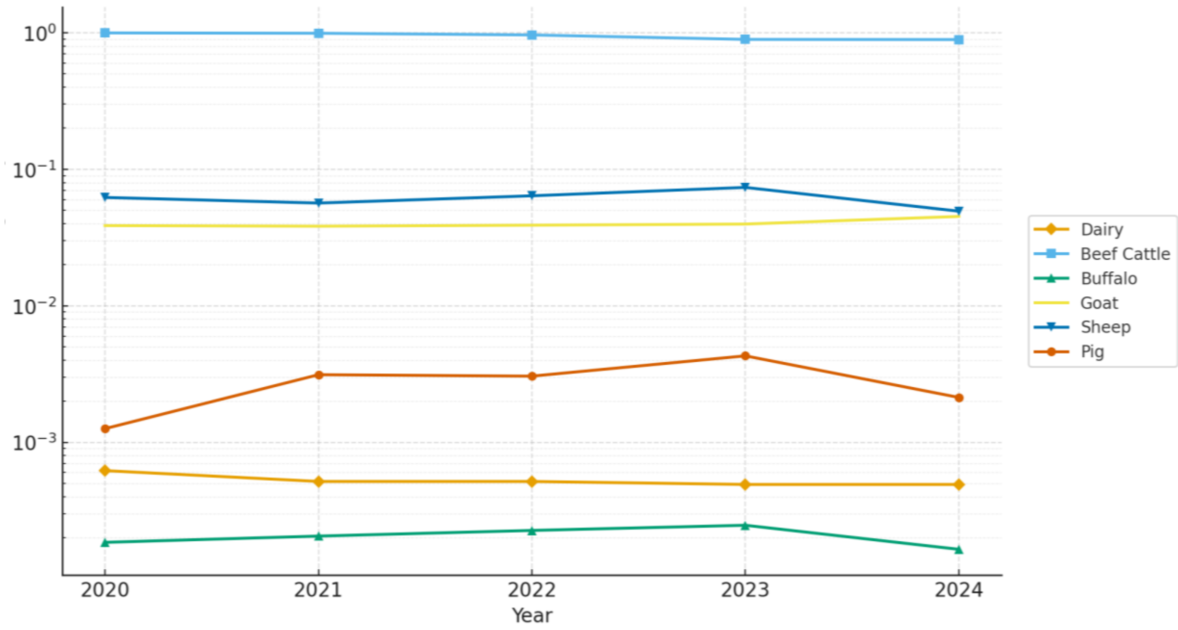

Figure 1. Methane emissions from enteric fermentation in Samin Watershed, 2020 to 2024 (Gg CO_2-eq/year).

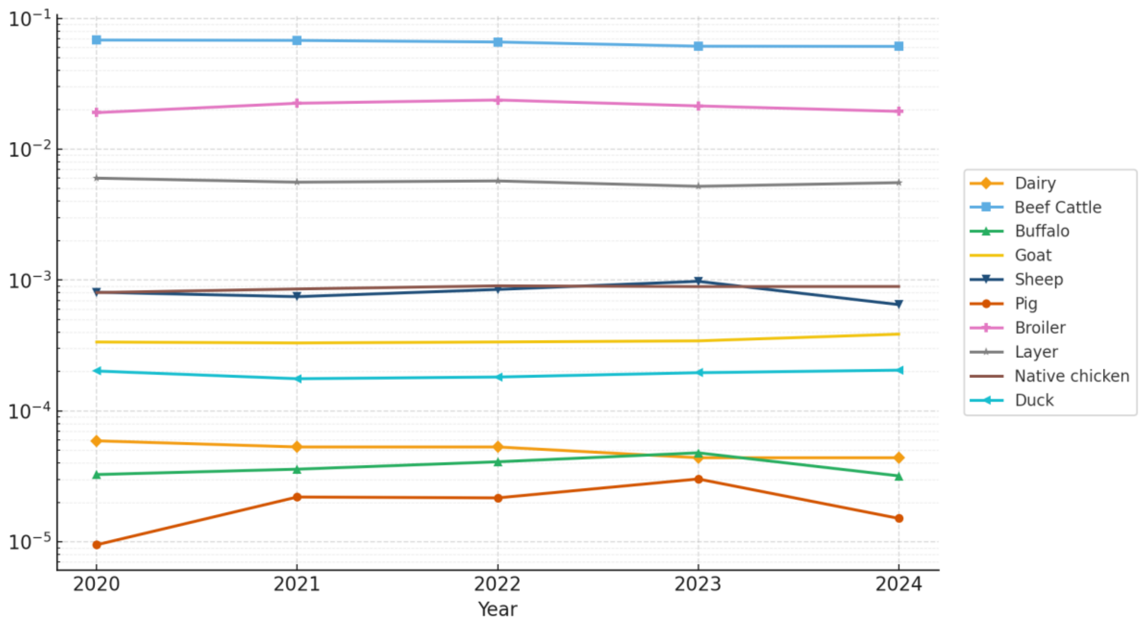

Figure 2. Methane emissions from livestock manure in Samin Watershed, 2020 to 2024 (Gg CO_2-eq/year).

Methane emissions from manure management

Methane emissions from livestock manure were quantitatively smaller than enteric emissions but showed an increasing trend over the five-year period. From 2020 to 2024, manure CH_4 emissions increased from 2.06 to 2.47 Gg CO_2-eq/year, a rise of approximately 20% (Table 5, Figure 2). Manure CH_4 accounted for approximately 6 to 8% of total livestock emissions annually. The highest relative contribution was in 2021, when total emissions were at their lowest. These results indicate that, although manure CH_4 is a secondary source relative to enteric emissions [12,15], changes in manure storage duration and management practices could still provide meaningful mitigation opportunities at the watershed scale.

Nitrous oxide emissions from manure management

N_2O from manure management was the second-largest GHG source after enteric CH_4. Annual N_2O emissions increased from 8.41 Gg CO_2-eq/year in 2020 to 9.98 Gg CO_2-eq/year in 2024, a rise of approximately 18.7% (Table 5, Figure 3). The relative contribution of manure N_2O ranged from 25 to 32% of total annual livestock emissions, with the highest proportional share observed in 2021, when enteric emissions were lowest. This pattern indicates that manure-derived N_2O becomes proportionally more prominent when enteric emissions decline, highlighting the importance of manure nitrogen management, including storage, handling, and land application, in shaping the overall GHG profile [10,17].

Table 5. Total livestock sector GHG emissions in the Samin Watershed 2020 to 2024 (Gg CO_2-eq/year)

Emission Source	2020	2021	2022	2023	2024	Total
CH_4 from enteric fermentation	22.12	10.63	21.27	19.64	27.67	101.33
CH_4 from livestock manure	2.06	1.36	2.12	1.92	2.47	9.93
N_2O from manure management	8.41	5.62	8.58	8.23	9.98	40.82
Total	**32.59**	**17.61**	**31.97**	**29.79**	**40.12**	**152.08**

Source: Analyzed Data (2025).

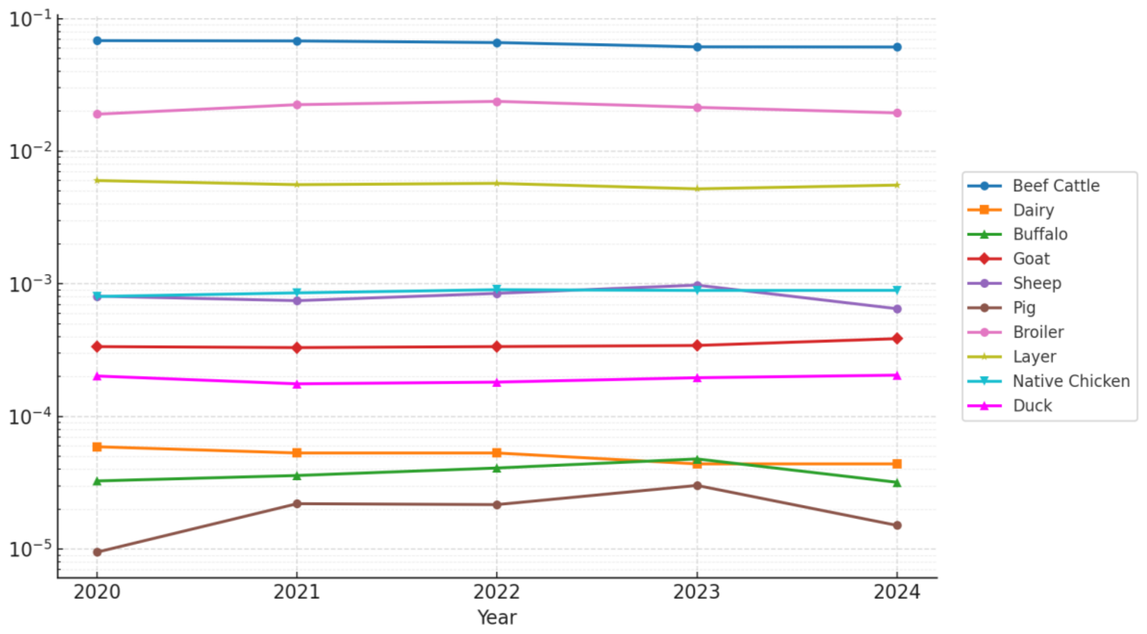

Figure 3. N_2O emissions from livestock manure management in Samin Watershed, 2020 to 2024 (Gg CO_2-eq/year).

Uncertainty and source contribution

The uncertainty analysis indicates that total GHG emissions from the Samin Watershed carry a moderate level of uncertainty because of variation in activity data and Tier-2 emission factors (±10 to 30%). Even accounting for this uncertainty, the pattern of emissions remains consistent across years: enteric CH_4 is the largest source, followed by manure N_2O and manure CH_4. This suggests that the main conclusions are robust and driven primarily by livestock population structure and feeding conditions rather than methodological uncertainty alone. The estimated combined uncertainty is approximately ±15 to 20%, which is acceptable for a regional livestock emission inventory. Although variations may occur due to changes in herd structure, feed characteristics, and manure handling practices, the Tier-2 method remains more representative of local livestock conditions than Tier-1 default emission factors, strengthening the robustness of the inventory results [16,18].

DISCUSSION

Livestock sector GHG emissions in the Samin Watershed fluctuated substantially over the study period. A sharp decrease occurred in 2021 (−45.9%), followed by a steady recovery that reached 40.12 Gg CO_2-eq/year in 2024. The 2021 decline affected all three emission components simultaneously: total emissions fell from 32.59 to 17.61 Gg CO_2-eq/year, with enteric CH_4 dropping from 22.12 to 10.63 Gg CO_2-eq/year and both manure fractions also declining. However, cattle population data show only a marginal change, from 21,756 head in 2020 to 21,619 in 2021, while most other livestock categories remained relatively stable. Because no documented culling event or major management intervention was identified for either regency in that year, the cause of the 2021 decrease cannot be determined from the available dataset alone. The 2021 annual total should therefore be interpreted cautiously. Even so, this anomaly does not alter the study's main conclusions regarding source dominance. Interannual variability of this type has also been reported in sub-national livestock inventories [7,8].

Across 2020 to 2024, enteric fermentation consistently dominated the emission profile, accounting for approximately 66% of total annual emissions. This aligns with findings by Widiawati et al. [9] and Nugrahaeningtyas et al. [1], who identified enteric fermentation as the primary GHG pathway from ruminants in Indonesian livestock systems. The Tier-2 approach captures year-to-year variation more effectively than Tier-1 because class-specific factors reflect changes in herd composition and animal body weight rather than relying on a fixed national average.

The Tier-1 versus Tier-2 comparison demonstrates the value of localized emission factors. Tier-2 generally produced lower and more differentiated estimates, particularly for enteric CH_4. In 2024, Tier-2 reduced beef cattle enteric emissions by approximately 5 to 6% relative to Tier-1, with comparable differentiation observed for goats, sheep, pigs, and buffalo, while poultry emissions remained low and showed minimal variation between approaches. These differences arise because Tier-1 assigns a single national average per species, whereas Tier-2 applies class-specific parameters including body weight and local management characteristics, producing estimates that better reflect watershed conditions [13,14].

This study extends Tier-2 assessment beyond beef cattle to include buffalo, goats, sheep, pigs, and multiple poultry categories, providing a more complete multi-species watershed inventory than has been previously published for Central Java. Prior work by Widiawati et al. [9] reported Tier-2 enteric CH_4 factors ranging from 18.18 to 55.89 kg/head/year for different cattle classes, consistent with the 18.20 to 55.89 range applied in this study. The total emission range of 17.61 to 40.12 Gg CO_2-eq/year is broadly comparable with sub-national inventories from other Indonesian provinces, including Bangka Belitung (25.54 to 33.32 Gg CO_2-eq/year during 2018 to 2022), supporting the plausibility of the watershed-scale estimates.

Source decomposition confirms that mitigation priorities should center on enteric CH_4 and manure N_2O, which together account for approximately 90 to 94% of total annual emissions. Because these two sources arise from different biological pathways, combining enteric mitigation strategies (feed additives, improved diet quality, herd management) with manure nitrogen management measures (covered storage, rapid land application, biodigestion) can generate additive emission reductions. Dietary modifications that reduce fermentable carbon and nitrogen in excreta suppress both manure CH_4 and N_2O simultaneously [11]. To effectively reduce emissions in the Samin Watershed, these interventions should be embedded within the extension programs and agricultural service networks of Karanganyar and Sukoharjo. The uncertainty analysis (±15 to 20%) confirms that the inventory is fit for regional mitigation planning, and the Tier-2 parameterization reduces the largest single source of uncertainty compared with Tier-1 defaults.

CONCLUSION

This study estimated livestock GHG emissions in the Samin Watershed, Central Java, for 2020 to 2024 using IPCC Tier-2 emission factors derived from local body weight and nitrogen excretion data. Total emissions ranged from 17.61 to 40.12 Gg CO_2-eq/year; enteric fermentation was the dominant source at approximately 66% of annual total emissions, with cattle contributing 84.02% of enteric CH_4 and manure N_2O representing 25 to 32% of annual total emissions. Localized Tier-2 factors produced estimates 5 to 6% lower than Tier-1 defaults for beef cattle enteric emissions, providing a more accurate baseline for regional mitigation planning; interventions should therefore prioritize improving ruminant feed quality and implementing structured manure nitrogen management.

CONFLICT OF INTEREST

The authors declare no conflict of interest with any financial organization regarding the material discussed in the manuscript. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

ACKNOWLEDGMENTS

The authors gratefully acknowledge support from the Ministry of Agriculture Indonesia through the student scholarship program with number 404/KPTS/Kp.320/A/08/2024.

REFERENCES

[1] Nugrahaeningtyas, E., K.-H. Park, and C. Y. Baek. 2018. Greenhouse gas emission intensity from the Indonesian livestock sector: analysis using IPCC tier 1 and tier 2 methods. J. Anim. Behav. Biometeorol. 6:109–115. Doi:10.31893/2318-1265jabb.v6n4p109-115.

[2] Suta, E., R. Soeprapto, and I. Aryana. 2022. The contribution of Indonesian livestock to global greenhouse gas emissions: inventory 2017–2021. Livest. Res. Rural Dev. 36:3649.

[3] Al Zahra, W., C. E. van Middelaar, S. J. Oosting, and I. J. M. de Boer. 2024. Nutrient imbalances of smallholder dairy farming systems in Indonesia: the relevance of manure management. Agric. Syst. 218:103961. Doi:10.1016/j.agsy.2024.103961.

[4] Apdini, T., W. Al Zahra, S. J. Oosting, I. J. M. de Boer, M. de Vries, B. Engel, and C. E. van Middelaar. 2021. Variability in estimates of greenhouse gas emissions from smallholder dairy farms in Indonesia. Int. J. Life Cycle Assess. 26:1160–1176. Doi:10.1007/s11367-021-01923-z.

[5] Sondakh, D. S. I., F. R. Tulungen, J. K. Kampilong, F. S. J. Rumondor, and E. P. Sanggelorang. 2024. Estimation of livestock greenhouse gas for impact mitigation. Glob. J. Environ. Sci. Manag. 10:857–872. Doi:10.22034/gjesm.2024.11.62.

[6] Puspito, S., B. Wardi, Haryanto, A. Suharyanto, A. Yano, A. M. Firmansyah, R. N. Hayati, Ismiarti, and N. Pratiwi. 2024. Greenhouse gas emissions estimation in the livestock sector in Bangka Belitung province using the IPCC Tier-2 method. Anim. Prod. 26:45–56. Doi:10.20884/1.jap.2024.26.1.259.

[7] Lemma, B., P. H. Evangelista, M. Stermer, N. E. Young, E. Milne, and M. Easter. 2023. Greenhouse gas mitigation potential in smallholder agroecosystems of southern Ethiopia. J. Environ. Manage. 325:116587. Doi:10.1016/j.jenvman.2022.116611.

[8] Pence, I., K. Kumaz, S. Melike, and A. Ali. 2024. Animal-based CO_2, CH_4, and N_2O emissions analysis: machine learning predictions by agricultural regions and climate dynamics in varied scenarios. Comput. Electron. Agric. 226:109423. Doi:10.1016/j.compag.2024.109423.

[9] Widiawati, Y., M. N. Rofiq, and B. Tiesnamurti. 2016. Pengaruh emisi gas metana untuk fermentasi enterik pada sapi potong menggunakan metode tier-2 IPCC di Indonesia. JITV 21:101.

[10] Weerden, T. J., A. N. Noble, I. Beltran, N. J. Hutchings, R. E. Thorman, C. A. M. de Klein, and B. Amon. 2023. Influence of key factors on ammonia and nitrous oxide emission factors for excreta deposited by livestock and land-applied manure. Sci. Total Environ. 889:164066. Doi:10.1016/j.scitotenv.2023.164066.

[11] Montes, F., R. Meinen, C. Dell, A. Rotz, A. N. Hristov, J. Oh, G. Waghorn, P. J. Gerber, B. Henderson, H. P. S. Makkar, and J. Dijkstra. 2013. Mitigation of methane and nitrous oxide emissions from animal operations: a comprehensive review of mitigation options for manure management. J. Anim. Sci. 91:5070–5094. Doi:10.2527/jas.2013-6584.

[12] Symeon, G. K., K. Akamati, V. Dotas, D. Karatosidi, I. Bizelis, and G. P. Laliotis. 2025. Manure management as a potential mitigation tool to eliminate greenhouse gas emissions in livestock systems. Sustainability 17:586. Doi:10.3390/su17020586.

[13] Ndung'u, P.W., A. Wilkes, D. Getahun, M. W. Graham, and S. M. Leitner. 2024. Comparison of Tier 1 and 2 methodologies for estimating intake and enteric methane emission factors from smallholder cattle systems in Africa: a case study from Ethiopia. Anim. Open. Space. 3:100064. Doi:10.1016/j.anopes.2024.100064

[14] Hassouna, M., T.J. van der Weerden, I. Beltran, B. Amon, M. A. Alfaro, and V. Anestis. 2023. DATAMAN: a global database of methane, nitrous oxide, and ammonia emission factors for livestock housing and outdoor storage of manure. J. Environ. Qual. 52:207-223. Doi:10.1002/jeq2.20430.

[15] Evangelista, C., M. Milanesi, D. Pietrucci, G. Chillemi, and U. Bernabucci. 2024. Enteric methane emission in the livestock sector: trends and mitigation. Animals 14:3158. Doi:10.3390/ani14213158.

[16] Solazzo, E., M. Crippa, D. Guizzardi, M. Muntean, M. Choulga, and G. Maenhout. 2021. Uncertainties in the Emissions Database for Global Atmospheric Research (EDGAR) emission inventory for greenhouse gases. Atmos. Chem. Phys. 21:5655–5683. Doi:10.5194/acp-21-5655-2021.

Hu, B., L. Zhang, C. Liang, X. Yang, Z. Shi, and C. Wang. 2024. Characterizing spatial and temporal variations in N_2O

emissions from dairy manure management in China based on IPCC methodology. Agriculture 14:753. Doi:10.3390/agriculture14050753.

[17] IPCC. 2019. 2019 refinement to the 2006 IPCC guidelines for national greenhouse gas inventories. Volume 4: Agriculture. Intergovernmental Panel on Climate Change, Geneva, Switzerland. [cited 2025 Dec 6]. Available from: https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/

[18] Agus, F. 2019. Metode penilaian adaptasi dan inventarisasi gas rumah kaca sektor pertanian [Internet]. Badan Penelitian dan Pengembangan Pertanian, Kementerian Pertanian, Jakarta, Indonesia. [cited 2025 Jul 2]. Available from: https://repository.pertanian.go.id/items/9fd3845e-a126-471f-af7e-14ea58216cc4

[19] Directorate of Greenhouse Gas Inventory. 2019. Greenhouse gas (GHG) inventory report and monitoring, reporting, and verification [Internet]. Directorate of Greenhouse Gas Inventory, Jakarta, Indonesia. [cited 2025 Dec 7]. Available from: https://unfccc.int/sites/default/files/resource/IndonesiaBUR%203_FINAL%20REPORT_2.pdf

[20] BPS Karanganyar. 2024. Populasi ternak menurut kecamatan dan jenis ternak di Kabupaten Karanganyar 2020–2024 [Internet]. Badan Pusat Statistik Kabupaten Karanganyar, Karanganyar, Indonesia. [cited 2025 Aug 2]. Available from: https://karanganyarkab.bps.go.id/id/publication

[21] BPS Sukoharjo. 2024. Populasi ternak menurut kecamatan dan jenis ternak di Kabupaten Sukoharjo 2020–2024 [Internet]. Badan Pusat Statistik Kabupaten Sukoharjo, Sukoharjo, Indonesia. [cited 2025 Aug 18]. Available from: https://sukoharjokab.bps.go.id/id/publication