



CASE STUDY

Estimation of livestock greenhouse gas for impact mitigation

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ABSTRACT

BACKGROUND AND OBJECTIVES: Anthropogenic activities in livestock sectors are responsible for emitting substantial amounts of greenhouse gases, including carbon dioxide, methane, and dinitrous oxide, into the atmosphere, thereby contributing to climate change. The impact of these gases can be reduced through effective mitigation and adaptation efforts. This study aimed to estimate the livestock greenhouse gas emissions in Minahasa District, Indonesia; identify the greenhouse gas sources and distribution; and provide feasible mitigation options.**METHODS:** This study used mixed methods to collect primary and secondary data from breeders and stakeholders in the Minahasa Regency. Interviews and questionnaires were also conducted, and the local government office provided secondary data. Breeders from various groups who lived in 25 different districts participated in this study, and the data analysis techniques used a Tier 1 model to process the data. The participants were included in focus group discussion activities for qualitative data collection to formulate potential mitigation strategies.**FINDINGS:** The livestock sector emitted 48.83 gigagrams of carbon dioxide equivalent in 2021, and this was expected to increase by 24.98 percent in 2022, resulting in a total emission of 65.09 gigagrams of carbon dioxide equivalent. The sector also experienced a steady rise in emissions since 2010, with an average annual increase of 3.17 percent. The emissions were primarily composed of methane and dinitrous oxide, which accounted for 64.68 and 0.41 gigagrams carbon dioxide equivalent, respectively. In terms of livestock greenhouse gas distribution, the Sonder District produced 13.98 percent of the emission at 8.77 gigagrams of carbon dioxide equivalent. The main emissions resulted from methane manure management and enteric fermentation at 84.53 and 15.23 percent (7.41 and 1.34 gigagrams of carbon dioxide equivalent, respectively), while the remaining was composed of dinitrous oxide gas. In Kawangkoan District, the greenhouse gas emissions were dominated by methane from enteric fermentation and manure management, which accounted for 15.23 and 20.05 percent (5.63 and 1.43 gigagrams of carbon dioxide equivalent). In addition, the total emission accounted for 11.33 percent at 7.11 gigagrams of carbon dioxide equivalent.**CONCLUSION:** The study produced an estimate of greenhouse gases from the livestock sector in the Minahasa Regency. During the studied period (2010-2022), the total greenhouse gas emissions exhibited an average annual increase of 3.17 percent. In 2022, the emissions consisted of methane and dinitrous oxide, with respective contributions of 99.38 percent per year and 0.62. Based on the spatial mapping, the Sonder District produced the largest cumulative emissions, primarily driven by emissions from animal waste management. Conversely, the Kawangkoan District dominated emissions stemming from the enteric fermentation of ruminant animals. These findings imply that all stakeholders in the Minahasa Regency should prioritize efforts to implement adaptation and mitigation programs to reduce these impacts.DOI: [10.22035/gjesm.2024.02.27](https://doi.org/10.22035/gjesm.2024.02.27)This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

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INTRODUCTION

Climate change is widely acknowledged as one of the most urgent global issues. Numerous studies have documented the global commitment to diligently address and mitigate the diverse impacts stemming from ongoing climate irregularities, such as the evaluation of various methods for climate change adaptation and mitigation (Frimawaty et al., 2023), investigation of hypothetical scenarios of climate variability (Abbas et al., 2022), development of methods to minimize the negative impacts of climate change on food systems (Aryal et al., 2020), and a review of studies on animal manure management for minimization of livestock CH₄ and N₂O emissions (Montes et al., 2018). External and internal causes have triggered an uncertain climate, such as volcanic eruptions (Robock, 1990) and variations in solar radiation (Cohen et al., 2020). Several consequences have been reported, including food insecurity (Mirzabaev et al., 2022), water scarcity (Kushawaha et al., 2020), drought (Konapala et al., 2020), and various disasters, which disproportionately affect the world's most vulnerable populations (Chu et al., 2017). Irregular temperatures and unpredictable rainy seasons have also increased food production costs due to chaotic supply chains (Godde et al., 2021) and shortages of livestock products and food crops (Rahman et al., 2022a) combined with damage caused by landslides and floods (Winter et al., 2019). Ecological changes have decreased livestock (Cheng et al., 2021) and agricultural production (Rahman et al., 2022a), including behavioral changes in various animal species and reductions in biodiversity (Rahman et al., 2022b). Greenhouse gases (GHGs) are gases that cause the greenhouse effect in the earth's atmosphere. GHGs can trap heat within the Earth's atmosphere, and the mechanism of action is related to capturing heat (Forsters et al., 2007). According to the United Nations Environment Program (UNEP, 1989), there are six types of gases classified as GHGs, namely carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), hydrofluorocarbon (HFC), perfluorocarbon (PFC), and sulfur hexafluoride (SF₆). These gases include CO₂, CH₄, and N₂O, as well as synthetic chemicals such as fluorine (F) (Anderson et al., 2016). Under normal conditions, this greenhouse effect serves to keep the Earth's temperature warm to sustain life (Kweku et al., 2018). However, the amount and concentration of GHGs have risen

significantly, impacting the severity of global warming (Ding et al., 2017). CH₄ has a concentration of 1,745 parts per billion (ppb) or approximately 0.000175 percent (%) (Forsters et al., 2007). The concentrations rise by 1% annually and contribute to 15-20% of the total GHG effect (Forsters et al., 2007). The global average temperature has increased by approximately 1 degree of Celsius (°C) since the pre-industrial era and CO₂ concentrations in the global atmosphere are currently over 408 ppm, while N₂O and CH₄ are at 331.1 ppb and 1858 ppb (Tang et al., 2022). According to recent studies, global warming caused storm surges and winds that vary greatly, including cyclone activity (Camello et al., 2022) and higher sea levels (Vousdoukas et al., 2018). The environment, economy, and health sectors have experienced many impacts (Rocha et al., 2022). The degradation of air quality resulting from forest fires and the combustion of fossil fuels have had wide-ranging adverse impacts on human health (Purohit et al., 2023). Greenhouse gas emissions affect public health and the economy through a number of mechanisms related to climate change and environmental pollution. Emissions of greenhouse gases such as CO₂, CH₄, and N₂O can result in more frequent and extreme heat waves, potentially threatening public health with risks of heat exhaustion, dehydration, and even death (Gavuvora et al., 2021). In specific regions, the onset of several diseases has become apparent due to exposure to heat waves (Arsad et al., 2022), such as respiratory, cardiovascular, and waterborne diseases (Liu et al., 2022), along with concerns related to malnutrition (Fanzo et al., 2021 and Dietz, 2019). GHG emissions are often linked to burning fossil fuels, which also produce air pollutants such as fine particulate matter (PM_{2.5}) and nitrogen oxides (NO_x) that can trigger or worsen respiratory health problems such as asthma, bronchitis, and chronic obstructive pulmonary disease (Eckelman et al., 2016). Climate change can also affect patterns of disease spread as warmer and humid climates can expand the area of distribution of disease vectors such as mosquitoes, which can increase the risk of diseases such as malaria, dengue, and Zika. Greenhouse gas emissions contribute to the effects of climate change, such as more frequent and prolonged droughts (Manisalidis et al., 2020), which can disrupt agriculture and cause food shortages, malnutrition, and hunger in various regions, which in turn, can have a negative impact on public health

(Rocha, *et al.*, 2022). Greenhouse gas emissions also have an impact on the economy. Global GHG emissions have had long-term effects on sub-Saharan Africa's economic growth. In general, there will be a concomitant decline between economic growth and environmental quality in the long term, but if CO₂ emission levels are significantly reduced in the future, there could be an increase in GDP. For such observations to be realized, the role of technology becomes very important (Adzawla *et al.*, 2019). Another study showed that the impact of GHG emissions on economic factors for China and the United States is different. China's economic factors are known to increase greenhouse gas emissions, while in America, it is precisely the opposite and there is a reduction in greenhouse gas emissions. However, we found strong evidence that renewable energy production leads to sustainable development in the US and China (Yamaka *et al.*, 2021). Human activities constantly affect the atmospheric composition, such as increased concentrations of GHGs (Chataut *et al.*, 2023). The rise in the CO₂ concentration is attributed to the burning of fossil fuels for electricity, heat, and transportation (Bradbury *et al.*, 2015), microbial

decomposition processes (Yasmin *et al.*, 2022), and unchecked land conversion (Malik *et al.*, 2023). The livestock sector emits two leading gases: CH₄ and N₂O. Enteric fermentation of ruminants and manure manufacturing, including storage, produce CH₄ emissions (San Martin Ruiz *et al.*, 2022) that can cause global warming 28 times greater than CO₂, while N₂O, which is mainly generated from the processing of animal waste, has the potential to be 265 times stronger than CO₂ (Grossi *et al.*, 2019).

Methane is a greenhouse gas commonly produced in the context of animal husbandry by the digestive process of ruminant animals, such as cows, sheep, and goats. In their digestive system, fermentation occurs which produces methane as a byproduct (Min *et al.*, 2022). The methane is then excreted through the eructation and flatulence of these animals. The methane gas released from the digestion of these animals is called enteric methane. Aside from the digestive system of ruminants, methane can also be produced from livestock waste fermented in manure and sludge (Orzuna-Orzuna *et al.*, 2021). This occurs in animal manure storage areas, such as manure barns or mud tanks, where anaerobic conditions

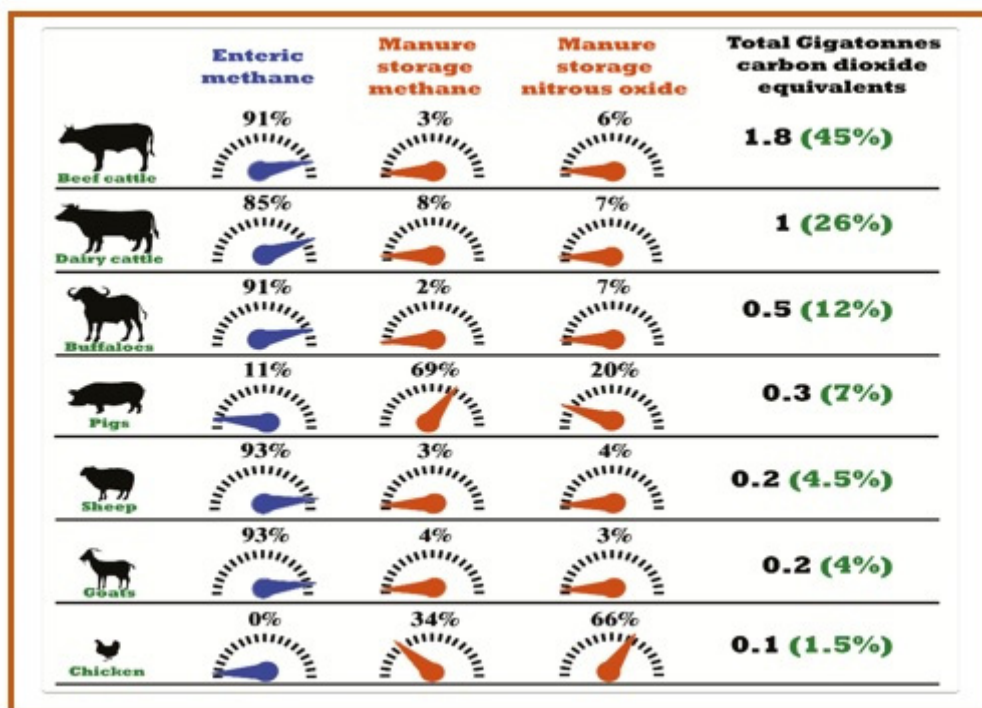


Fig. 1: GHG incidence of enteric fermentation and manure storage by animal type (Gt/CO₂-eq) (Grossi, 2019)

(without oxygen) result in methane production. Nitric oxides (N_2O) are greenhouse gases that can also be produced by livestock. One of the main sources of N_2O is synthetic fertilizers, especially nitrate fertilizers, which are used to promote the growth of animal feed crops. In addition, nitrogen oxides can also be produced from the process of nitrogen decomposition in soil and animal waste (denitrification), especially when there is an excess of nitrogen nutrients in agricultural or livestock systems (Yasmin *et al.*, 2022). The demand for livestock products is mainly triggered by increasing population growth, urbanization, and rising incomes, especially in developing countries (UN, 2017). The growing global population leads to a substantial increase in the demand for livestock meat. Projections indicate that market demand for chicken meat, eggs, and pork is expected to increase by 32%, 61%, and 39% from 2005 to 2030 (Gerber *et al.*, 2013). Still, according to Gerber, the livestock sector absorbs enough natural resources so that this sector contributes around 14.5% of the total anthropogenic GHG emissions or 7.1 gigatons carbon dioxide equivalent per year ($Gt/CO_2\text{-eq/y}$) in 2005 (Gerber *et al.*, 2013). In Indonesia, animal husbandry is a crucial sector, particularly for rural communities who depend on it for their livelihoods. The sector employs around 3.84 million workers, 3.17% of Indonesia's total workforce (BPS, 2021). Based on a report from the Ministry of the Environment's Directorate General for Climate Change, in 2020, the total GHG emission from the three primary gases (CO_2 , CH_4 , and N_2O) was 1,050,413 gigagrams carbon dioxide equivalent per year ($Gg/CO_2\text{-eq}$), with the livestock sector contributing 33,182 $Gg/CO_2\text{-eq}$ (MEFRI, 2022). This is due to the increase in the population of several types of livestock, especially poultry, which has experienced a significant increase in population. Minahasa is one of the regencies in the Indonesian region. It has an area of 121,043.31 hectare (ha), consisting of 25 districts. The leading commodity is swine farming, with a population of 174,697 heads, followed by beef cattle, with 34,267 heads (BPS, 2023). With the potential of this region, there is a need for livestock GHG estimation. However, there is a lack of regional GHG inventories. This is reinforced by the absence of an integrated mitigation program for the livestock sector of the Minahasa Regency. Some breeders carry out incidental mitigation activities, but many do not. The existence of the Presidential Regulation

of the Republic of Indonesia No. 61 of 2011 requires every regency in all regions of Indonesia to create a Regional Action Plan for GHG Mitigation, and the insufficient knowledge of breeders about greenhouse gases and their mitigation also highlights the need for this study. Many country-level GHG emission studies have been conducted, but few at the regional level. Hence, the availability of academic information on GHG emissions is minimal. This study was conducted to fill this gap by estimating livestock GHGs based on data on livestock population potential and emission factors. The uniqueness of this study is that its implementation is not only carried out by the research team but also involves farmers and local governments, from data collection to potential mitigation formulations, to increase awareness and knowledge of all parties to ultimately reduce the ongoing impact of climate change and minimize disparities in data accuracy. Thus, this study aims to estimate livestock GHG emission in the Minahasa Regency, map the GHG emission burden distribution for each district area, and provide a feasible GHG mitigation program. This study was conducted in the Minahasa Regency, North Sulawesi Province, Indonesia, in 2023 (Fig. 2).

MATERIALS AND METHODS

The study used a mixed method design, which combined quantitative and qualitative approaches in the form of analytical descriptive studies. In this study, the Tier 1 model was used as an estimation model. The Tier 1 models defined by the IPCC (Intergovernmental Panel on Climate Change) (Dong *et al.*, 2006) have varying degrees of complexity ranging from Tier 1 models based on default global or regional emission/removal factors, Tier 2 models based on local emission/removals factor; and Tier 3 models which involve more detailed modeling or inventory-based approaches. In this study, the Tier 1 model was used due to several reasons including limited activity data based on the type, age class, and local emission factor of each type of livestock and unavailability of livestock GHG inventory data (Dong *et al.*, 2006; IPCC, 2006). The Tier 1 model has a fundamental equation that multiplies information regarding human activities over a specific period (referred to as activity data, AD) with emissions factors associated with those activities (emission/absorption factors, EF). This equation is expressed as GHG

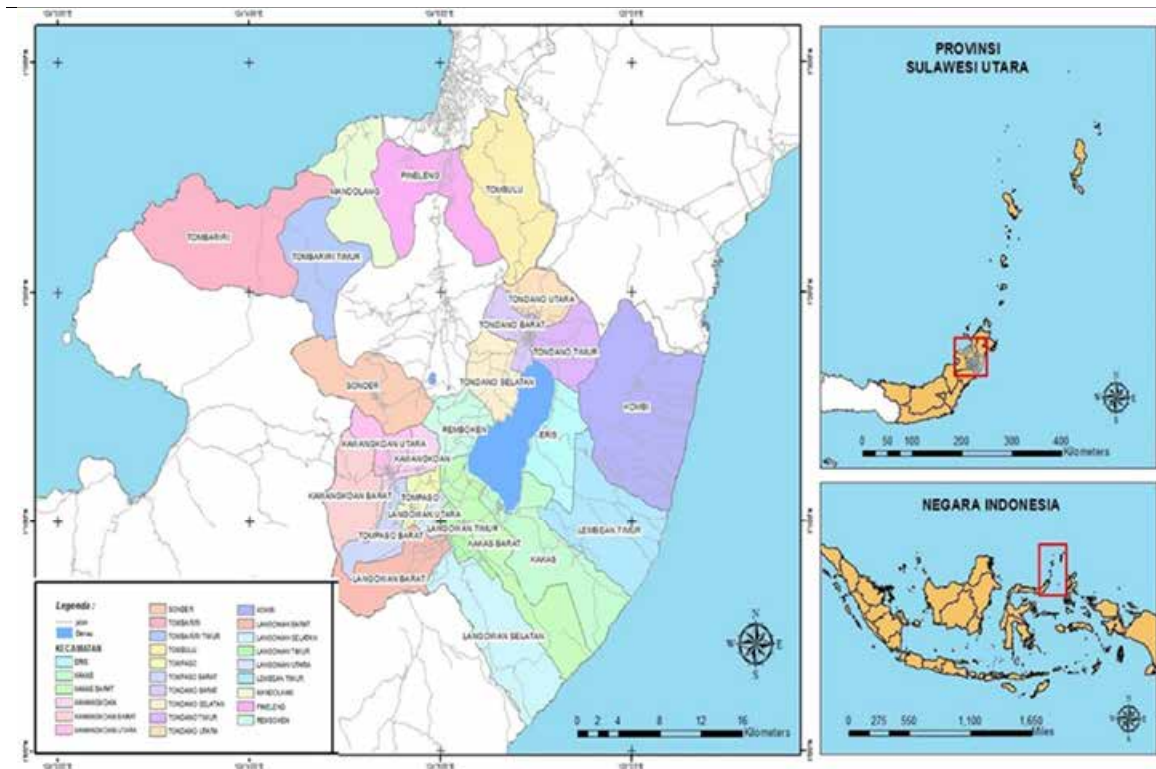


Fig. 2: Geographical location of the study area in Minahasa Regency, Indonesia. The study was conducted in 25 district locations, identified by various colors (except White color)

emissions = AD x EF, where AD is the activity data and EF denotes the emission factor. The Global Warming Potential (GWP) value was used to convert non-CO₂ GHG emission data into carbon dioxide equivalent (CO₂-eq) (CH₄= 21 and N₂O=310). To estimate livestock GHG emissions, many activity datasets will be used, as well as the assumption that GHG emissions from the livestock sector primarily arise from two sources: 1) CH₄ from enteric fermentation of ruminant (cattle beef and goats) and non-ruminant animals (swine and horse) and poultry; and 2) the emissions of N₂O that occur during the storage, processing, and natural decomposition of solid and liquid livestock manure. The study included respondents representing breeder groups who carried out their respective activities across 25 districts in the Minahasa Regency. The included breeders were those with the most livestock ownership (the top five). The livestock data included cattle, horse, swine, and poultry counts, amount of manure excreted per head of animal type, and manure management system. Secondary information,

such as animal population, was obtained from the BPS Minahasa Regency and the Office of Minahasa Regency Agriculture and Livestock. The data on the emission factors were derived from the 2006 IPCC documents. Arcmap was chosen as a geographic information system (GIS)-based application that can process, select, and display data about locations. This analysis involved determining the scale, accuracy of attributes, accuracy of data, and data structure and determining the distribution of GHG emissions in each district in the Minahasa Regency. The results are presented as a map of the distribution of GHG emissions based on all study areas of the 25 districts for the livestock sectors. In this study, breeders and the local government were involved in focus group discussion (FGD) activities to produce qualitative data and to verify the secondary data that was obtained. In this case, the breeder is not a passive participant but an expert on manure management, feeding, and other activities. This is what distinguishes this study from other case studies. The CH₄ emissions from

Table 1: Emission factor of animal type

Animal type	Enteric fermentation	Manure management
Cattle beef	47	0.02
Goat	5	0.02
Horse	18	2.19
Swine	1	7
Poultry	-	0.02

enteric fermentation were determined by multiplying activity data (e.g., population size) by an emission factor, using Eq. 1 (Dong et al., 2006).

$$\text{Emission of } CH_4 = EF_{(T)} \times N_{(T)} \times 10^{-6} \quad (1)$$

Where; CH_4 emissions = enteric fermentation CH_4 emissions (Gg/ CH_4 /y)

$EF_{(T)}$ = enteric fermentation emission factor of each animal type (kg/ CH_4 /head/y)

$N_{(T)}$ = number of animals per type.

Both primary kinds of animals are assumed to be animal units and calculated using Eq. 2 (MEFRI, 2019).

$$N_{(T)} \text{ in Animal Unit} = N_{(x)} \times K_{(T)} \quad (2)$$

Where;

$N_{(T)}$ = Total animal unit;

$N_{(x)}$ = number of farm animals (heads)

$K_{(T)}$ = correction factor: cattle 0.75

T = types of animal

The CH_4 emissions from managed manure: estimated using Eq. 3 (Dong et al., 2006).

$$\text{Emission of } CH_4 \text{ Manure Managed} = \sum_T EF_T \cdot N_{(T)} \cdot 10^{-6} \quad (3)$$

Where:

$CH_{4 \text{ Manure}}$ = CH_4 emissions from manure management (Gg/ CH_4 /y)

$EF_{(T)}$ = emission factor, kg/ CH_4 /head/y

$N_{(T)}$ = number of animal species

T = animal species.

The N_2O Emissions from manure management were estimated using Eq. 4 (Dong et al., 2006).

$$\text{Emission } N_2O_{D(mm)} = \left[\sum_S \left[\sum_T (N_{(T)} \cdot Nex_{(T)} \cdot MS_{(T,S)}) \cdot EF_{3(S)} \right] \cdot \frac{44}{28} \right] \quad (4)$$

Where:

Emission $N_2O_{(mm)}$ = direct N_2O from manure management, kg/ N_2O /y

$N_{(T)}$ = animal category T

$Nex_{(T)}$ = N animal excretion average (kg/N/animal/y), which was estimated using Eq. 5 (Dong et al., 2006).

$$NEX_{(T)} = N_{(T)} \times \frac{TAM}{1000} \times 365 \quad (5)$$

Where:

TAM = standard weight of animal for each animal type T (kg/head);

$MS_{(T,S)}$ = fraction of N excretions managed (cattle=0.2, goat=0.1, swine=0.3, horse=0.07, poultry=0.3)

$EF_{3(S)}$ = emission factor (kg/ N_2O -N/kg/N)

S = manure management system

T = Animal species

44/28 = conversion of (N_2O -N)_(mm) to $N_2O_{(mm)}$

N losses due to volatilization from manure management were estimated using Eq. 6 (Dong et al., 2006).

$$N_{\text{volatilization-MMS}} = \sum_S \left[\sum_T \left[(N_T \cdot Nex_{(T)} \cdot MS_{(T,S)}) \cdot \left(\frac{Frac_{GasMS}}{100} \right)_{(T,S)} \right] \right] \quad (6)$$

where:

$N_{\text{volatilization-MMS}}$ = nitrogen lost due to volatilization of NH_3 and NO_x (kg/N/y)

$N_{(T)}$ = animal number

$Nex_{(T)}$ = annual average N excretion (using Eq. 4)

$M.S._{(T,S)}$ = fraction N excretions managed (cattle=0.2, goat=0.1, swine=0.3, horse=0.07, poultry=0.3)

$Frac_{GasMS}$ = percent of managed manure N that volatilizes as NH_3 and NO_x (cattle 30%, swine 25%, poultry 40%, and other 30%)

The indirect N_2O emissions from volatilization of N in the forms of NH_3 and NO_x ($N_2OG_{(mm)}$) were estimated using Eq. 7 (Dong et al., 2006).

$$N_2O_{G(mm)} = [N_{\text{volatilisation-MMS}} \cdot EF_4] \cdot \frac{44}{28} \quad (7)$$

where:

$N_2O_{G(mm)}$ = indirect N_2O emissions (volatilization of N

manure management), kg/N₂O/y

EF₄ = emission factor for N₂O emissions from atmospheric nitrogen deposition on soils and water surfaces; the default value is 0.01 kg/N₂O/N (kg/NH₃-N + NO_x-N/volatilized), which was estimated using Eq. 8 (Dong et al., 2006).

The value of 44/28 is conversion of N₂O-N_(mm) to N₂O_(mm) (8)

RESULTS AND DISCUSSION

To estimate GHG emission in the livestock sector requires data on emission factors (Table 1) and

activity data in the form of livestock population data (Table 2).

Based on the estimations, the livestock sector in the Minahasa Regency in 2022 produced a total GHG emission of 65.09 Gg/CO₂-eq/y and this emission has increased by 24.98% compared to the total emission in 2021, amounting to 48.83 Gg/CO₂-eq/y. Compared with the emission in 2010 of 41.45 Gg/CO₂-eq/y, this increased by 36.31% or to 65.09 Gg/CO₂-eq in 2022. During the studied period (2010-2022), greenhouse gas emissions in the Minahasa Regency experienced a threefold increase (Fig. 3). Specifically, the periods 2011-2013 and 2016-2020 exhibited an average

Table 2: Animal population in Minahasa Regency (head)

Year	Cattle	Goat	Horse	Swine	Poultry
2010	24,709	3,025	6,054	96,725	1,231,309
2011	25,730	3,026	6,054	96,727	1,231,308
2012	28,036	3,023	5,902	108,363	1,382,515
2013	27,291	3,202	6,710	123,401	1,928,999
2014	20,559	2,682	4,379	113,757	2,226,633
2015	23,499	2,601	3,984	117,896	2,253,670
2016	19,999	2,239	4,107	124,087	1,413,596
2017	27,034	1,819	3,150	136,157	2,892,925
2018	28,400	2,127	3,201	127,400	3,099,475
2019	25,906	2,007	3,650	129,944	3,168,191
2020	24,972	2,007	3,568	128,721	3,150,330
2021	26,761	1,987	3,024	130,969	3,193,893
2022	34,267	2,143	3,025	174,697	3,541,523

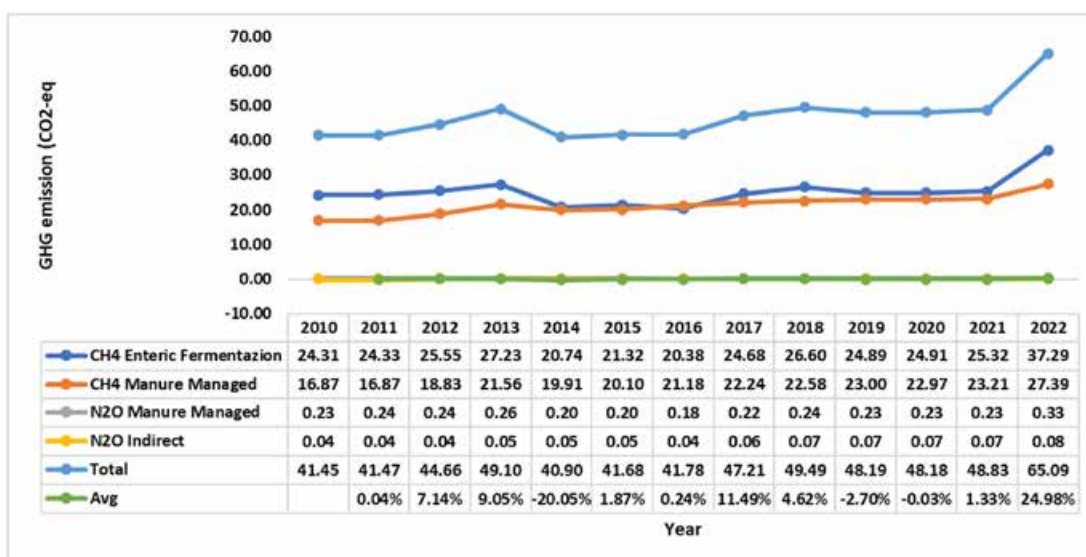


Fig. 3: Graphic of livestock GHG inventory describes fluctuations in total GHG emissions per year (2010-2022). The highest increase occurred in the period 2021-2022

Livestock greenhouse gas

increase of 8.09% and 18.11%, while the 2021-2022 period witnessed a substantial increase of 24.98%. The total greenhouse gas emissions from the livestock sector in the Minahasa Regency exhibited an average annual increase of 3.17% (Fig. 3).

This is in line with the characteristics of the Minahasa Regency area as a center for supplying livestock products for the province of North Sulawesi. The increase in GHG emissions was mostly due to the increase in the population of the two main types of livestock, namely swine and cattle, which increased, on average, by 4.39% and 1.48% per year. The marked increase in last two years (2021-2022) was attributed to the high population of animals driven by the rising demand for livestock meat due to the prevalent trend of hosting parties and celebrations in the Minahasa Regency. In 2021-2022, following the government's declaration that the COVID-19 pandemic was over, there were euphoric sentiments, including increased party activities. In Minahasan society, a party culture represents a pervasive form of social activity that is seamlessly integrated into daily life, including events such as birthday celebrations, wedding anniversaries, thanksgiving gatherings, and various other occasions. This cultural phenomenon resulted in a substantial impact on the escalating demand for livestock products. The analysis of livestock population data showed a 21.90% and 25.03% increase in the number of cattle and swine in 2021-2022. These two categories of animals are extensively consumed during these festivities, and are used to meet the daily dietary requirements of the local community. GHG emissions from livestock were primarily attributed to increased

enteric fermentation of CH_4 when categorized by gas type. According to estimation data for the year 2022, the most substantial source was the total CH_4 emissions, amounting to 64.68 Gg CO_2 -eq/y, followed by total N_2O emissions of 0.41 Gg CO_2 -eq/y. The contribution of each gas is shown in Fig. 4.

The main source of methane gas (CH_4) emissions is the digestive process of farm animals, especially in ruminants such as cows, buffaloes, goats, and sheep. Ruminants have specialized digestive systems that involve microbial fermentation in their stomachs to break down fiber—vegetables, grass, hay, and other forages—which produce methane as a byproduct of this digestive process. The methane produced in the digestive tract of these ruminant is called enteric fermentation methane (Orzuna-Orzuna *et al.*, 2021). The increase in gas production is highly dependent on the type and quality of feed consumed (Min *et al.*, 2022). High-fiber, low-energy digestible feed types resulted in higher CH_4 emissions due to increased microbes for fermentation (Guo *et al.*, 2022). Non-ruminant animals also produce CH_4 , but at much lower levels than ruminants (Chang *et al.*, 2019). The microbial populations and activity of non-ruminant animals differ from those of ruminants, leading to lower methane production (Montes *et al.*, 2018). Apart from the digestion of ruminants, livestock manure management can also contribute to methane gas emissions. Animal manure, such as feces and urine, contain ingredients that can produce methane if not managed properly, especially in anaerobic conditions (without oxygen). Managing this manure through composting can also result in

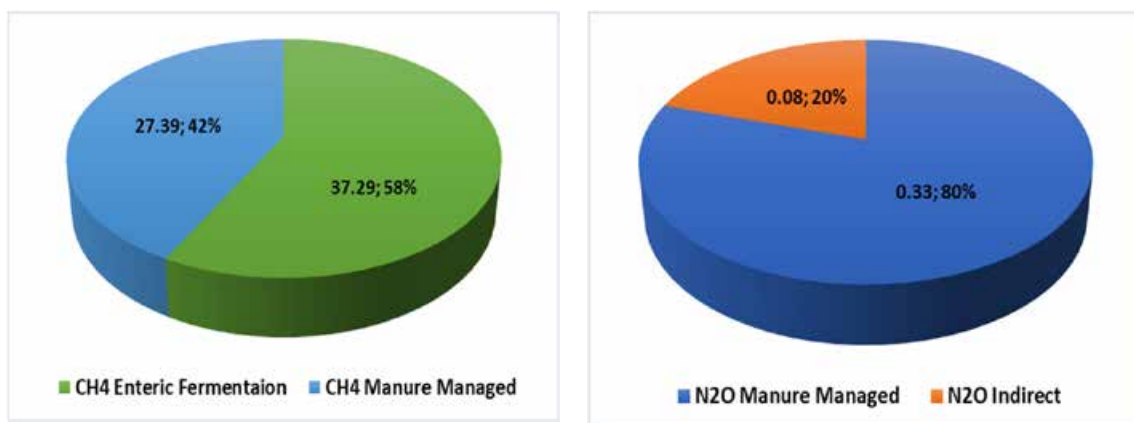


Fig. 4: Contribution of CH_4 and N_2O to total livestock GHG's

an increase in CH₄ emissions, with a simultaneous reduction in N₂O emissions, directly and indirectly, by 0.47% and 0.14%. Manure could be blended with other materials, such as straw or dry leaves, to foster aerobic conditions. This approach promotes the proliferation of aerobic microorganisms that facilitate the decomposition of organic matter and mitigate N₂O production (Yasmin *et al.*, 2022). Therefore, methane emission reductions in the livestock sector are often focused on efforts that optimize animal feed nutrition and management, as well as animal waste management to reduce the impact of waste digestion and decomposition on methane production. Based on spatial analysis, the total distribution of GHG emissions from the livestock sector across the 25 districts in the Minahasa Regency is depicted in Fig. 5. The highest emissions were observed in the Sonder District, accounting for 13.98% (8.77 Gg/CO₂-eq) of the total emissions. Furthermore, the primary contributors were CH₄ from manure management and enteric fermentation, accounting for 84.53% (7.41 Gg/CO₂-eq) and 15.23% (1.34 Gg/CO₂-eq), and the remainder was attributed to N₂O gas. In the Kawangkoan District, GHG emissions were primarily

driven by CH₄ enteric fermentation, accounting for 15.23% (5.63 Gg/CO₂-eq), and CH₄ emissions from manure management, contributing 1.43 Gg/CO₂-eq (20.05%). The total emission from the Kawangkoan District amounted to 7.11 Gg/CO₂-eq (11.33%).

These findings are consistent with several studies reporting that 14.9% of China's total GHG emissions come from the enteric fermentation of beef cattle, which produces CH₄ emissions (Guo *et al.*, 2022). In the Andean region, Southwest Colombia, the highest emissions are produced from CH₄ due to enteric fermentation (2,963 kg CO₂-eq/ha/y; 38% of total emissions) (Parra *et al.*, 2019). Approximately 70% of Australia's total agricultural emissions come from methane emissions from sheep, goats, horses, pigs, and cattle (Panchasara *et al.*, 2021). Farm animals generate a substantial amount of manure, with varying degrees of management practices in place. In Indonesia, a significant number of breeders continue to permit their livestock to graze freely within coconut plantations. Consequently, the fecal waste remains either deposited on the ground or inadequately managed. This result is in line with studies conducted by Frimawaty *et al.*, (2023) where

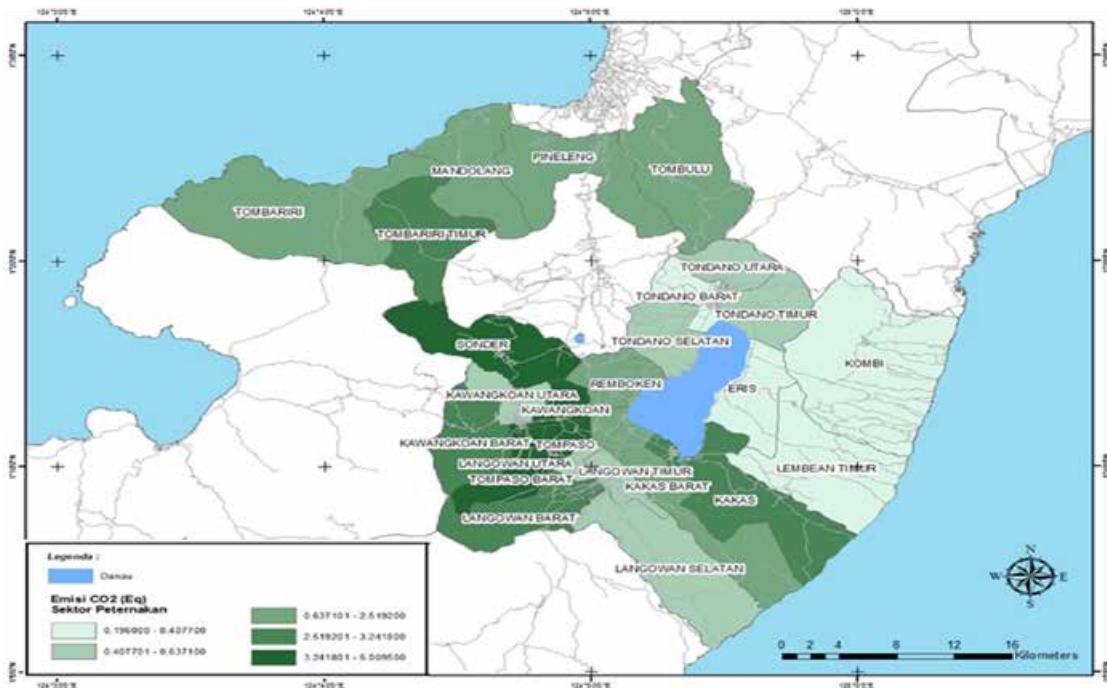


Fig. 5: Map of distribution of CH₄ gas emitted by the Livestock sector. Dark green indicates the largest CH₄ emissions spread, and pale green indicates the smallest emission

14.3% of the breeders in South Sulawesi Province, Indonesia, have already managed cattle manure in the farming. Meanwhile, 85.7% have not applied the management practices and 63.2% of manure is still left and piled up in open spaces. The GHG emissions produced will be greater than those of well-managed animal waste. As a result, these GHG emissions will produce a series of complex reactions involving the atmosphere, solar radiation, and energy flow patterns on Earth. Excessive GHG emissions will accumulate in the atmosphere, where the accumulation will form a kind of "blanket" which can capture the infrared radiation reflected by the Earth. This goes on continuously and over a long period of time, causing an increase in the average temperature of the Earth's surface, known as global warming. This increase in global temperatures has an impact on the environment and climate system, including changes in rainfall patterns, rising sea levels, increasing frequency and intensity of extreme weather events such as storms and droughts, and more extreme seasonal changes. Rising temperatures can also affect the Earth's water cycle, such as melting polar ice caps, changes in rainfall patterns, and other impacts on the hydrological cycle, threatening the availability of clean water, the sustainability of aquatic ecosystems, and the agricultural sector. Climate change can also affect ecosystems, including shifts in geographic boundaries for some species, changes in animal migration and behavior, and biodiversity loss. These mechanisms work in tandem and influence each other, resulting in observable climate change such as global warming and its diverse impacts. The effects of climate change can vary widely across regions, and can have long-term impacts on ecosystems, both socially and economically. GHG emission mitigation and adaptation to climate change are very important to maintain the sustainability of the environment and human life in the future. In predicting the GHG emissions of these farms, researchers face obstacles in obtaining data because not all data is available. This difficulty is overcome by collecting historical data on livestock operations, such as feed consumption and waste management to help in understanding trends and patterns that can help to estimate GHG emissions. This data can only be obtained by actively involving farmers and local governments, either in FGD forums or other informal forums. By using this strategy, the verification of data at the source of origin can also

be conducted directly because the data collected has been verified since the beginning. The adaptation and mitigation strategies discussed have been formulated through analysis, discussions, and interviews with breeders representing their respective groups. These strategies are also consistent with previous studies deemed suitable for implementation. The breeders' participation in the FGD was aimed at developing an effective GHG mitigation plan. Various adaptation and mitigation initiatives researched and developed by the Ministry of Agriculture of Indonesia can be utilized as inputs for their implementation. Few of the results can be implemented in the Minahasa Regency for various reasons, including incompatibility with local conditions, unavailability of evidence of the effectiveness of these measures, and lack of technical understanding regarding the standards offered. Breeders have also contemplated various potential efforts and actions for implementation. The need for practical knowledge has been implemented concerning greenhouse gases, particularly those affecting the livestock sector. Several initiatives to be conducted include extensive outreach on greenhouse gases and climate change through social media, mainstream media, or community meetings. This study is perceived as a valuable addition, specifically in enhancing the understanding and knowledge of greenhouse gases and climate change. Several conditions are still needed for the feasibility for the application of this mitigation program, such as lab tests (for tannin and seaweed use programs) and political coordination with the government for biogas programs. There are some mitigation measures that can be presented to breeders for implementation:

- 1) Using tannins in feed by mixing local feed ingredients with tannin compounds. This method has proven highly effective in significantly reducing methane gas emissions, as tannins can mitigate methane production during digestion and inhibit the growth of methanogenic bacteria (Jayanegara et al., 2009). Breeders have expressed the need for additional empirical evidence to substantiate these claims. Researcher team promised breeders that after conducted trials first in the laboratory, the results will be presented. After that stage, field trials will be carried out involving several samples. If the results are significant, it will be applied to all livestock through the Minahasa Regency Agriculture Office.

- 2) Supplying forage to livestock is essential and

the agricultural sector should not be overlooked as a contributor to methane gas production. The Agricultural Research and Development Agency of the Ministry of Agriculture has introduced green leaves, which have relatively low levels of methane gas emissions, as an alternative source of animal feed. These leaves are sourced from Leguminosa, Gliricida leucaena, and Calliandra plants known for their tannin and saponin content. Breeders can consider this approach as a viable response. Some have and are applying this type of feed to their livestock by concocting their own types of kaliandra leaves into additional feed. However, the results still need further research to obtain empirical evidence so that it is implemented by all breeders. It is also necessary to involve the Minahasa Regency Agriculture Office to carry out technical facilitation.

3) Providing animal feed with seaweed is a recent development in livestock management. Recent studies have shown that incorporating seaweed into cow feed can result in an impressive 86% reduction in methane emissions. Specifically, the supplementation of dairy cow feed with 0.25% to 0.50% *Asparagopsis taxiformis*, a red seaweed, has been reported to achieve substantial reductions in methane gas production. This reduction in methane emissions can range from 50% to 74% over a period of 147 days. The inclusion of red seaweed (*Asparagopsis taxiformis*) in the diet can reduce enteric methane gas emissions by over 80% (Roque *et al.*, 2021). Breeders may require concrete evidence of its effectiveness before implementing this approach. This also still requires further research, considering that, in this area, it is quite difficult to obtain seaweed raw materials.

4) The implementation of biogas production on farms is a viable approach for harnessing CH₄ gas, a byproduct of agriculture and livestock activities, by using microorganisms to convert agricultural and livestock waste into biogas. Biogas offers numerous benefits and advantages: a) it can serve as an alternative energy source, effectively substituting fossil fuels; b) function as a renewable energy source, ensuring long-term sustainability; c) contribute to pollution reduction through the processing of organic waste; d) provide support to the local economy by creating opportunities for economic growth; e) yield valuable solid and liquid organic fertilizers; and f) enhance environmental sanitation and hygiene standards. Breeders can initiate this approach with

financial support from the local government. Building biogas reactors is not too difficult and in some regions it has been achieved. In the Minahasa Regency, it could be implemented but it must involve the local government, especially in financing the manufacture of reactors.

CONCLUSION

In conclusion, the livestock sector in the Minahasa Regency was reported to contribute to GHG emissions primarily in the form of CH₄ and N₂O gases. In 2010, this sector emitted 48.83 Gg/CO₂-eq of GHG emissions, which increased by 24.98% to 65.09 Gg/CO₂-eq in 2022. This marked a significant rise compared to the emission of 41.45 Gg/CO₂-eq/y in 2010, experiencing a substantial increase of 36.31% by 2022. In the studied period, GHG emissions experienced three distinct periods of increase in 2011-2013, 2016-2018, and 2021-2022 with an average increase of 8.09%, 18.11%, and 24.98%. The cause was attributed to the growth of the animal population, driven by the demand for livestock meat. This demand was a direct consequence of numerous social activities, such as parties and celebrations, which are deeply embedded in the culture of the Minahasa tribe. The 2021-2022 period coincided with the government's declaration of the end of the emergency status in response to the COVID-19 pandemic. This declaration was met with enthusiasm by the public, leading to an increase in the hosting of various parties. This phenomenon was underscored by a substantial increase in the cattle and swine populations by 21.90% and 25.03% during the 2021-2022 period. Based on the type of gas emitted, the livestock sector primarily released CH₄ and N₂O. The predominant source was CH₄ emissions, amounting to 64.68 Gg/CO₂-eq, followed by N₂O emissions at 0.41 Gg/CO₂-eq. The substantial methane gas emissions were also primarily attributed to the sizable population of ruminant animals, such as cows and goats. These animals produced more methane gas due to the digestive process. In contrast, non-ruminant animals also emitted methane, but the emissions were considerably lower. Concerning the distribution of livestock greenhouse gas emissions, the Sonder District accounted for emissions of 8.77 Gg/CO₂-eq (13.98%), where the most significant contributor was CH₄ from manure management and enteric fermentation, amounting to 7.41 Gg/CO₂-

eq (84.53%) and 1.34 Gg/CO₂-eq (15.23%), and the remainder was attributed to N₂O gas. In contrast to the Sonder District, in the Kawangkoan District, GHG emissions were primarily dominated by CH₄ from enteric fermentation and manure management, amounting to 5.63 Gg/CO₂-eq (15.23%) and 1.43 Gg/CO₂-eq (20.05%), with a total emission of 7.11 Gg/CO₂-eq (11.33%). The knowledge derived from these findings implies that climate change and its various phenomena were a reality, necessitating concrete actions for mitigation and adaptation. These actions could be undertaken collaboratively at the global, regional, and national levels. Breeders, in collaboration with the government and other stakeholders, also implemented various adaptation and mitigation measures. These measures included conducting a climate change assessment to minimize its adverse impact on the livestock sector, undertaking a range of actions to adapt natural and social systems to cope with the effects of climate change, and making efforts to reduce emissions sources while enhancing greenhouse gas absorbers. The efforts were accomplished through various mitigation strategies, such as mixing local feed ingredients with tannin compounds, providing forage to livestock, supplementing animal feed with seaweed, and implementing biogas production on farms. The role of the Minahasa Regency Agriculture Office is necessary, especially in facilitating both technical and non-technical aspects, such as program financing. The results of this study are expected to benefit other researchers, especially for climate change science and GHG estimation so that more and more varied GHG mitigation approaches can be developed according to the characteristics of the region and source. For breeders, it is expected to increase awareness to carry out various GHG mitigation efforts to reduce the impact of climate change. In this study, there are several limitations such as not using statistical analyses, estimates of GHGs were only based on emissions from animals, and there was no discussion of the socioeconomic feasibility of the mitigation programs. These limitations are directions for future studies including by other researchers.

AUTHOR CONTRIBUTIONS

D.S.I. Sondakh, as the first and corresponding author, has contributed to preparing, writing, and

finishing the manuscript, F.S.J. Rumondor conducted the FGD and handled research administration, J.K. Kampilong calculated all the raw data and interpreted the results, Y.S. Kawuwung prepared all the maps and tables, F.R. Tulungen analyzed the data, and E.P. Sanggelorang responsible in interviewing to the breeders.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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ABBREVIATIONS

%	Percent	$Kg/CH_4/head/y$	Kilograms CH_4 per head per year
$^{\circ}C$	Degree of Celsius	$Kg/N/animal/y$	Kilograms nitrogen per animal per year
44/28	The value describes change in the emission value of $N_2O-N_{(mm)}$ to value $N_2O_{(mm)}$	$Kg/N_2O/y$	Kilograms N_2O per year
13 th	Thirteenth	$K_{(T)}$	Correction factor (by animal type)
AD	Activity data	$MS_{(T,S)}$	Fraction of N excreted per animal type (T) based on manure management system (S)
Arcmap	geographic information software	N	Nitrogen
BPS	Central bureau of statistics	N_2O	Dinitrous oxide
CH_4	Methane gas	$N_2O_{(mm)}$	Direct N_2O from manure management
CO_2	Carbon dioxide	$N_2O_{G(mm)}$	Indirect emissions of N_2O resulting from evaporation of N manure management
COP	Conferences of parties	$Nex_{(T)}$	Annual average N excretion
COVID-19	Corona virus disease	$N_{volatilization-}$	The amount of manure lost due to volatilization NH_3 and NO_x
EF or Ef	Emission factor	$N_{(T)}$	Animal number by type/species
EF4	Emission factor for N_2O emissions from atmospheric nitrogen deposition	Ppb	Parts per billion
FGD	Focus Group Discussion	T	Animal type/species number
$Frac_{Gasm}$	Percentage of managed manure N that volatilises as NH_3 dan NO_x	Tier-1	Method of GHG emission estimation (one of three methods from IPCC)
F	Flourine	$Tg/CO_2-eq/y$	Tetagrams CO_2 equivalent per year
GDP	Gross domestic products	UN	United Nations
GHGs	Greenhouse gases	UNFCCC	United Nations Frameworks Convention on Climate Change
Gg/y	Gigagram per year		
$Gg/CH_4/y$	Gigagram methane per year		
$Gg/CO_2-eq/y$	Gigagram carbón dioxide equivalent per year		
GIS	Geographic Information System		
$Gt/CO_2-eq/y$	gigatons carbón dioxide equivalent per year		
ha	Hectare		
IPCC	Intergovernmental Panel on Climate Change		
MEFRI	The Ministry of Environment and Forest of the Republic of Indonesia		
Kg/day	Kilograms per day		
$Kg/ha/day$	Kilograms per hectare per day		
$Kg/head/y$	Kilograms per head per year		

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