REVIEW

J Anim Sci Technol 2024;66(6):1083-1098
https://doi.org/10.5187/jast.2024.e86

JAST
Journal of Animal Science and Technology
pISSN 2672-0191 eISSN 2055-0391

Greenhouse gas emissions from livestock: sources, estimation, and mitigation

Eska Nugrahaeningtyas, Jong-Sik Lee, Kyu-Hyun Park*

Department of Animal Industry Convergence, College of Animal Life Sciences, Kangwon National University, Chuncheon 24341, Korea

Check for updates

Received: Feb 19, 2024
Revised: Aug 26, 2024
Accepted: Sep 11, 2024

***Corresponding author**
Kyu-Hyun Park
Department of Animal Industry Convergence, College of Animal Life Sciences, Kangwon National University, Chuncheon 24341, Korea.
Tel: +82-33-250-8621
E-mail: kpark74@kangwon.ac.kr

ORCID
Eska Nugrahaeningtyas
https://orcid.org/0000-0002-4931-7952
Jong-Sik Lee
https://orcid.org/0000-0002-9101-6811
Kyu-Hyun Park
https://orcid.org/0000-0002-6390-5478

Competing interests
No potential conflict of interest relevant to this article was reported.

Funding sources
This work was funded by the Cooperative Research Program for Agriculture Science & Technology Development (RS-2023-00231663), Rural Development Administration, Korea.

Acknowledgements
Not applicable.

Abstract

The increase in greenhouse gas (GHG) emissions has resulted in climate change and global warming. Human activities in many sectors, including agriculture, contribute to approximately 9.2% of total GHG emissions from Annex I countries. An argument on issues of livestock being the highest contributor to GHG emissions has grown since FAO's 2006 report Livestock's Long Shadow. The issue has continued growing, conflicting the importance of the industry in terms of food security and livelihoods, thus, monitoring GHG emission from this sector is vital. The most commonly used methods for calculating GHG emissions from the livestock sector are life cycle assessment (LCA) and the GHG inventory. Although the LCA presents information on the impacts of the livestock industry on the environment, the GHG inventory is the main tool used internationally for GHG reporting. This review comprehensively discusses the source of GHG emissions from the livestock industry and its estimation methodology, as well as the current strategies for mitigating these emissions.

Keywords: Greenhouse gas (GHG) inventory, Livestock, Intergovernmental Panel on Climate Change (IPCC) guidelines, 2019 Refinement

INTRODUCTION

Since the pre-industrial era, the observed mean land surface air temperature has increased considerably compared to the global mean surface temperature. For 2006–2015, the average temperature over land was 1.53℃ higher than that for 1850–1900 [1]. This change in the Earth's average surface temperature since the Industrial Revolution, primarily due to greenhouse gas (GHG) emissions from human-induced activity, is referred to as global warming [2,3], which is the result of the ability of GHG to absorb sunlight. Because the GHG effect becomes stronger, more heat is trapped than required [4]. Climate change refers to the long-lasting changes in the Earth's climate, characterized by alterations in temperature, precipitation, and wind patterns, which can persist for several decades or even longer [3]. The Earth's climate system has evolved over millions of years and is influenced by major natural factors; however, due to overwhelming anthropogenic carbon dioxide (CO_2) emissions, the climate system is rapidly changing [2].

GHG emissions originate from four main sectors: energy; industrial processes and product use; agriculture, forestry, and other land use; and waste [5]. The six GHGs specified in the Kyoto Protocol

Availability of data and material
Upon reasonable request, the datasets of this study can be available from the corresponding author.

Authors' contributions
Conceptualization: Park KH.
Data curation: Nugrahaeningtyas E.
Methodology: Nugrahaeningtyas E, Park KH.
Validation: Lee JS, Park KH.
Investigation: Nugrahaeningtyas E.
Writing - original draft: Nugrahaeningtyas E.
Writing - review & editing: Nugrahaeningtyas E, Lee JS, Park KH.

Ethics approval and consent to participate
This article does not require IRB/IACUC approval because there are no human and animal participants.

are CO_2, methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride, with CO_2, CH_4, and N_2O accounting for nearly 90% of the total GHG emissions [6,7].

According to United Nation Framework on Climate Change GHG profiles of Annex I countries in 2021, agricultural sector contributed 9.2% of the total GHG emissions without land-use and land-use and change forestry [8]. Livestock accounted for 4.91% of the total anthropogenic GHG emissions on a CO_2 equivalent basis. The key sources of livestock sector emissions are enteric fermentation (CH_4) and manure management (CH_4 and N_2O). The livestock sector accounts for approximately 32% of total anthropogenic CH_4 emissions [9].

The expanding population with higher disposable income, coupled with the rising demand for meat, will result in an upsurge in emissions from enteric fermentation and manure management, which is primarily attributed to the increasing number of livestock [9]. However, with a technically feasible reduction, emissions in 2050 will be 40% below the 2015 baseline level, specifically from the livestock sector, which could apply a feasible mitigation that can reduce emissions by up to 14% [10]. Livestock production plays a crucial role in mitigating and adapting to climate change by promoting a circular bioeconomy. This is achieved by utilizing the livestock as a renewable energy source with its waste, as well as contributing to global food security and nutrition [11].

Although many mitigation proposals have mainly focused on CO_2, there has been a growing interest in CH_4 in recent times. It is important to note that CH_4 has a higher global warming potential (GWP) than CO_2, particularly 84 times higher on a 20-year timescale, and 28 times higher on a 100-year timescale [12]. In addition, CH_4 has a shorter lifespan (12 years) in the atmosphere. This means that CH_4 accounts for approximately 40% of the GHG contribution to short-term global warming, which makes it an obvious candidate for targeting rapid climate change mitigation by 2050 [13]. According to Intergovernmental Panel on Climate Change (IPCC) [14], CH_4 and CO_2 are expected to have comparable effects on global warming in the next 10 to 20 years, as indicated by their GWP and temperature increase potential (global temperature change potential). Therefore, reducing CH_4 emissions will possibly reduce the total emissions; thus, the goal of limiting the temperature to 2℃ will be achieved. Methane is not directly harmful to humans; however, recent studies have found evidence that its consequences on health and agricultural damage are greater than previously believed [15]. The Coalition [9] reported that 95% of global CH_4 emissions stem from human activities, of which 40% are from agricultural activities. By 2019, the largest growth in absolute emissions occurred for CO_2 from fossil fuels and industry, followed by CH_4 [16]. Under current business-as-usual conditions, by 2050, anthropogenic CH_4 emissions are expected to increase by > 30% over the 2015 level [10].

Two common tools to assess GHG emissions from the livestock sector are life cycle assessment (LCA) and the GHG inventory (Table 1). LCA is a technique used to address the environmental aspects and potential environmental impacts associated with the entire process of a product, from raw materials through production, use, end-of-life treatment, recycling, and final disposal [17,18]. LCA is useful for determining the most available life cycles; thus, it helps industries select important indicators of environmental behavior. However, LCA is a large and complex method with many variations. Certain or standard boundaries are unavailable, making it flexible to apply, but impossible to use as a comparison, even for the same end product. The LCA approach accounting all GHG emissions associated with commodity production includes direct emissions from animals and indirect emissions arising from the production of inputs, such as nitrogenous fertilizer and feed, even if the emissions associated with the production of these imported products were generated in other jurisdictions [19]. The LCA approach helps the sector understand the sources of impact, identify areas for improvement, and assess the impact of best practices on GHG emissions. This

 https://doi.org/10.5187/jast.2024.e86

Table 1. Main differences between life cycle assessment (LCA) and GHG inventory as GHG reporting tool

Elements	LCA	GHG Inventory
Purpose	Evaluate potential environmental impacts across the full life cycle of product	Evaluate the amount of GHG from the main emission sources
Focus	Life cycle perspective (e.g., cradle-to-gate, cradle-to-grave)	Sectoral (e.g., waste, agriculture, transportation)
Procedure and methodology	ISO 14040 series (ISO 14040, ISO 14044) in accordance with other documents	IPCC Guidelines (1996 GL, 2006 GL, 2019 Refinement) in accordance with other supplementations published by IPCC
Coverage	Broad range of environmental impacts (greenhouse gases, acidification, water depletion, etc.)	Greenhouse gases
Expressed unit	Functional unit (e.g., kg CO_2-eq/kg meat)	CO_2-eq/year
Typical use	Product level, with current increase for organizational level	Regional level, national level

GHG, greenhouse gas.

approach provides a baseline against which improvements could be measured over time [19].

The GHG inventory refers to the gases emitted and removed within a country's (including territories under administration) territorial boundaries and offshore regions where the country has jurisdiction [20]. Many countries have committed to reporting their national GHG emissions using the GHG inventory to monitor trends in GHG emissions. The GHG inventory covers sources and sinks of direct GHGs such as CO_2, CH_4, N_2O, and other gases. The Paris Agreement in 2015 marked a commitment to reduce the global increase in temperature by 2℃ since the pre-industrial industry, in addition to a further reduction of 1.5℃. Nationally determined contribution, as the core of the Paris Agreement, communicates the country's efforts to mitigate and adapt actions to climate change [21]. The GHG inventory is crucial because it guides the strategies that governments may employ to meet their emissions reduction goals and thus limit the projected temperature increase. In addition, the GHG inventory plays a critical role in facilitating international policy negotiations and domestic policy interventions aimed at promoting climate action by offering accurate and reliable information on emissions. Furthermore, GHG inventory could be beneficial for evaluating the overall conditions of the livestock sector in relation to GHG emissions and their impact, for instance, milk production [22] or emission intensity that displays livestock production efficiency [23]. Information presented in a GHG inventory can help corporations strategize and prioritize actions to reduce emissions and to provide benchmarks for measuring the success of these activities.

SOURCES OF GHG EMISSIONS FROM LIVESTOCK

Enteric fermentation: source of CH_4 emission

Emissions from enteric fermentation originate from ruminant eructation. It is estimated to account for approximately 33% of global anthropogenic CH4 emissions [24]. Enteric fermentation in ruminants is responsible for 66.6% of the annual regional CH_4 emissions in the EU, 97.6% of agricultural CH_4 emissions, and 85.6% of all anthropogenic CH_4 discharges in New Zealand [24]. Enteric CH_4 from developing countries (Latin America, Asia, and Africa) contributes 69.9% to the global CH_4 from ruminants, among which Asia is responsible for approximately 30.3% [25].

Methane is a byproduct of animal digestive processes through microbial fermentation [19]. This process occurs when ingested food is broken down in the digestive tract by enzymes and microbes in the rumen at the beginning of the tract as a 'fermentation vat,' expediting carbohydrate digestion [26]. CH_4 formation in the rumen is the predominant method of hydrogen elimination, and methanogens, the microbes responsible for this process, use hydrogen as their energy source. Hydrogen is then transferred to methanogens to degrade cell wall carbohydrates. Methane production in the rumen depends on the molar percentage of volatile fatty acids (VFAs) produced during this process. Acetate and butyrate promote CH_4 production, whereas propionate formation is a competitive pathway for hydrogen use in the rumen, resulting in less production of CH_4. However, dietary management influences ruminal pH and alters VFA production. The drop of pH level to a non-physiological value of less than 5.3 result in the accumulation of hydrogen and a significant decrease in propionate. Conversely, acetate levels increases, indicating that the microbial ecosystem responsible for propionate formation changed with different dietary conditions [27].

The amount of CH_4 produced is determined by the digestive system of the animal [19] and by digestible organic matter or energy, residence time in the rumen, level of intake, and carbon source and structure [27]. This implies that management practices and feeding strategies may have substantial effects on CH_4 discharge. For instance, cattle fed high-quality forage have a negative relationship with CH_4 production [28], whereas those fed low-quality forage increase enteric CH_4 yield, and severe intake restriction increases CH_4 production by up to 10% [29]. This difference is potentially because >50% of digestible organic matter occurs in the rumen, indicating that CH_4 emissions are closely related to the amount of fermented organic matter (FOM) [27].

Different types of feed and their characteristics affect the digestion period in the rumen, which eventually influences CH_4 production. Decreasing the residence time of feed in the rumen is expected to result in a reduction of CH_4 production, as ruminal digestion decreases and the methanogenic bacteria are less able to compete under such conditions. [27]. In addition, dietary characteristics have significant effects on CH_4 production because the proportion of individual VFAs is influenced by the composition of organic matter in the diet. Diets rich in starch that favor propionate production affect ruminal pH and decrease the methane/FOM ratio in the rumen. Roughage-based diets and those high in maize starch can provide substantial amounts of digestible organic material to the hindgut. In this regard, approximately 10% to 30% of the digestible organic material can be broken down and utilized [27].

Manure management: source of CH_4 and N_2O emissions

Livestock manure comprises animal feces and urine and may contain livestock bedding, additional water, and wasted feed. It contains organic matter and a broad range of nutrients (i.e., nitrogen, phosphorus, and potassium) and micronutrients (i.e., copper, manganese, and zinc) [30]. Urine contains urinary nitrogen (urinary N), which is in contact with urease in feces and soil and transforms into NH_3. In addition, urinary N is an important source of N_2O emissions from manure [31]. Nutrient excretion from manure is strongly associated with feed digestibility. Organic matter in animal manure undergoes aerobic or anaerobic breakdown once excreted [32].

CH_4 from manure is a product of the decomposition of organic materials by bacteria under anaerobic conditions [33]. The conversion of VFAs to CH_4 and CO_2 varies depending on the storage conditions [32]. Manure management systems, such as ponds, tanks, or pits, promote more anaerobic conditions than when manure is handled as a solid [33], resulting in more CH_4 than that of other manure management systems that promote aerobic conditions. In addition to the manure management system, the CH_4 emitted from manure is also affected by ambient temperature, moisture, manure storage, and residence time [33]. These factors influence the growth of the methanogens responsible for CH_4 formation. In addition, other factors, such as animal diet, growth rate, and digestive system, also affect CH_4 production [33].

Nitrous oxide is generated both directly and indirectly throughout the storage and treatment of manure and urine. Direct emissions result from the processes of nitrification and denitrification, while indirect emissions are caused by volatilization, leaching, and runoff [34,35]. Nitrite (NO_2^-) is oxidized to nitrate (NO_3^-). In the process of nitrification, nitric oxide (NO) and N_2O may be released as gaseous intermediates from incomplete reactions. Furthermore, during denitrification,

 https://doi.org/10.5187/jast.2024.e86

where NO_3^- is reduced to nitrogen (N_2), a series of sequential enzymes, including dissimilatory NO_3^- reductase, dissimilatory NO_2^- reductase, NO reductase, and N_2O reductase, is involved [36]. The production and emission of N_2O from manure are influenced by factors such as animal feed digestibility and composition, manure management practices, the length of waste management, and environmental conditions such as low pH level, elevated temperature, enhanced aeration, and reduced moisture content [37,38]. High levels of N_2O emissions are typically associated with high feed intake and high nitrogen concentrations. The release of N_2O from manure depends on the amount of oxygen and moisture present in it. Manure stored for extended periods of time can lead to increased N_2O emissions due to the nitrification process that occurs in stored animal manure, provided that there is sufficient oxygen [39].

ESTIMATING GHG EMISSIONS USING IPCC GUIDELINES

1996 GL, 2006 GL, and 2019 Refinement

As the main instrument for reporting emissions, the GHG inventory should be transparent, accurate, complete, comparable, and consistent [40]. IPCC Guidelines (GL) as the standard method of calculating inventories has made it easier to compare nations and regions [41]; thus, decisions based on GHG Inventory calculated with IPCC GL can be made both regionally and globally. The IPCC GL were first published as the Revised 1996 GL, which aimed to set a standard for GHG estimation. This ensures the transparency, consistency, and comparability of inventory. A new version of the IPCC GL was issued in 2006, with important suggestions for improving and restructuring source categories to make the guidance clearer, more accurate (updated methods, improved default values), and more complete (more sources and sinks, more gases) [39]. A refinement of the IPCC 2006 (2019 Refinement), published in 2019, contains updates, supplements, and further elaborates on the 2006 IPCC GL for use in conjunction with them [5].

The main differences among the guidelines are changes in default values, regions, and climatic characteristics. Changes in default values affect the estimated emissions. These changes are attributed to additional and updated data related to the values used in each guideline. Factors such as the feeding management, average weight gain per day, and average body weight are used to determine the emissions factor (EF) [39]. Enhancements in the genetic qualities and modifications in feeding procedures can also impact the production of CH_4 [42]. Manure biodegradability or the ultimate CH_4 production is an important value for calculating the EF, similar to the daily volatile solids (VS) excreted for livestock and the methane conversion factor for a particular manure management system [43].

In 2019, the GL introduced two new productivity categories: low productivity and high productivity. These classifications are based on factors such as usage, production level, typical feed, and manure management [5]. The intake of feed varies depending on the type of animal and the specific management practices used for each animal type, which in turn influences the EF [44].

In the 1996 GL, the climate characteristics described typical climate conditions in a certain range of average annual temperatures, whereas in the 2006 GL, using the same climate classification, a more specific average annual temperature was added (Table 2). However, in the 2019 Refinement, climate characteristics were classified based on mean annual temperature, mean annual precipitation, and potential evapotranspiration, which determine humidity.

The principal calculation of CH_4 emissions using the IPCC GL is multiplying the EF, which represents the amount of GHGs emitted per head per year and the total population of the livestock category. However, the calculation of CH_4 emissions from manure management in the 2019 Refinement had a different approach, using the same principle of calculation with modification.

Table 2. Changes in main elements in IPCC guidelines

Elements	1996 GL	2006 GL	2019 Refinement
Characteristic			
Regional characteristic	· Regional only (i.e., North America, Asia, Latin America, Africa, and Middle East)	· Regional only (i.e., North America, Asia, Latin America, Africa, and Middle East)	· Regional only (i.e., North America, Asia, Latin America, Africa, and Middle East) · Productivity based (low productivity, high productivity)
Climate characteristic	· Only based on mean annual temperature (cool, temperate, warm)	· Based on mean annual temperature (cool, temperate, warm) · Able to choose specific annual temperature	· Based on mean annual temperature (cool, temperate, warm) · Based on the elevation, MAP, MAP:PET ratio (i.e., temperate moist, boreal moist, tropical wet)
Equation			
CH_4 enteric fermentation	Population × EF	Population × EF	Population × EF
CH_4 manure management	Population × EF	Population × EF	$\frac{\text{Population} \times \text{VS} \times \text{AWMS} \times \text{EF}}{1000}$
N_2O manure management	Population × N_{ex} × AWMS × EF_3 × 44/28	Population × N_{ex} × AWMS × EF_3 x 44/28	Population × N_{ex} × AWMS × EF_3 × 44/28
Unit of default value			
Emission factors CH_4 enteric	Kilogram CH_4 per head per year	Kilogram CH_4 per head per year	Kilogram CH_4 per head per year
Emission factors CH_4 manure	Kilogram CH_4 per head per year	Kilogram CH_4 per head per year	Gram CH_4 per kg VS per animal per year
Nitrogen excretion	Kilogram nitrogen per head per year	Kilogram nitrogen per head per year	Kilogram nitrogen per head per year
EF_3	Kilogram N_2O-N per kilogram nitrogen	Kilogram N_2O-N per kilogram nitrogen	Kilogram N_2O-N per kilogram nitrogen

IPCC, Intergovernmental Panel on Climate Change; MAP, mean annual precipitation; PET, potential evapotranspiration; EF, emission factor; VS, volatile solid; AWMS, animal waste management systems; N_{ex}, nitrogen excretion.

EF was expressed as the amount of CH_4 emitted per kg volatile solid (g CH_4/kg VS), and VS was an independent factor. In addition, the animal waste management systems (AWMS), as one of the factors determining EF in the 1996 and 2006 GL, has also become an independent factor. Therefore, EF, VS, and AWMS had the same influence on the total emissions.

Tier 1 vs Tier 2

The IPCC GL provide three methods for calculating the national inventory of GHG emissions: Tier 1, Tier 2, and Tier 3. Tier 1 is the simplest method and uses the default values available in the guidelines. Tier 2 is a more detailed approach requiring country-specific information regarding livestock and manure management [39]. Tier 3 enables countries to perform sophisticated analyses and modeling. This has the potential advantage of providing a more accurate account and discovering real and demonstrable mitigation opportunities that are less disruptive to agricultural practices and, therefore, easier to implement. However, because Tier 3 is an advanced and complex method, its application is challenging. Therefore, the use of the Tier 2 method is encouraged. As of 2017, 63 countries had used Tier 2 for one or more types of livestock [45].

Most countries without country-specific data used Tier 1. The availability of livestock data to perform baseline analyses and the GHG inventory are common challenges and barriers to climate change in the livestock sector [46]. Nevertheless, to calculate GHG emissions from manure management, the typical manure treatment used in the country should be obtained from national data or statistics. However, Tier 2 requires country-specific data, particularly substantial data, for some factors (Table 3). Feeding management, feed quality, grass type, and grass quality vary among countries depending on climate. Consequently, countries in the same region with the same climatic conditions may produce different amounts of emissions. Therefore, using country-specific data is

 https://doi.org/10.5187/jast.2024.e86

Table 3. Type of country-specific data necessary for the Tier 2 method of IPCC GL

Source of emissions		Necessary data
Enteric fermentation	CH_4	Gross energy intake (GE), methane conversion factor (MCF), percent of growth energy in feed converted to methane (Y_m)
Manure management	CH_4	Maximum methane production (B_0), methane conversion factor (MCF), average body weight (ABW), volatile solid excretion (VS)
	Direct N_2O	Average body weight (ABW), nitrogen excretion (N_{ex})

IPCC GL, Intergovernmental Panel on Climate Change Guidelines.

favorable. However, even if the level of detail in Tier 2 cannot be applied and only portions of the variables are available, the calculation of country-specific emission factors is still encouraged [5].

Considerable time and effort are required to build country-specific data. Country-specific data should ideally be obtained from peer-reviewed papers, official government publications, and national statistics. However, these documents are not available for some countries. As an alternative, the IPCC allows the use of gray literature such as non-peer-reviewed papers and theses. Using data from gray literature, Nugrahaeningtyas et al. [47] showed that country-specific data remain preferable, because they show more actual emissions from a country that uses Tier 1 or default data from the IPCC.

Methane emissions from enteric fermentation increased as the default EF increased in each guideline, whereas N_2O emissions from manure management decreased as nitrogen excretion decreased. However, CH_4 emissions from manure management increased when using the 2006 GL from the 1996 GL but decreased during the 2019 Refinement. This is possibly due to changes in the calculation method used for the 2019 Refinement. Nonetheless, the result implied that separating several factors in the calculation affected the total estimated emissions. Additionally, the decrease in total emissions using the 2019 Refinement indicates that independent factors in estimating GHG emissions from manure management are important. Mitigation of manure management systems is more likely to be feasible than mitigation of enteric fermentation.

A comparison of Tier 1 and Tier 2 calculation methods indicated the importance of country-specific data. Regardless of the guideline used, the difference between the total emissions using Tier 1 and Tier 2 is clear, indicating that country-specific data are required. Won et al. [48] highlighted that country-specific direct GHG measurements were higher than the Tier 1 values used in the Korean National Inventory Report (NIR). This indicates that using Tier 1 results in either overestimation or underestimation of emissions; thus, mitigation may be less effective than expected. There is no defined threshold indicating the amount of country-specific information required for Tier 2. Moreover, by representing local production characteristics, the increased use of country-specific information improves emissions estimates [5]. Therefore, the partial use of country-specific data is still encouraged, because reflecting the actual emissions in the NIR will accommodate decision-making in emissions reduction, emission mitigation, or other measures related to GHG emissions. Moreover, a similar trend in the 1996 GL and the 2019 Refinement shows that these guidelines are more comparable and closer to each other than those of the 2006 GL.

Implication of GHG inventory for mitigation measures

Developing a GHG inventory is essential for undertaking future mitigation actions, including climate considerations in sustainable development planning and the development of domestic climate policies [49]. In addition, the GHG inventory provides a comprehensive scheme for prioritizing sectoral mitigation, and directly and indirectly affects progress monitoring. The GHG inventory can help identify the distinct trajectories and features of different types of GHGs generated from various sources as the basis for policy-related insights into feasible yet flexible mitigation countermeasures [50]. For instance, the emissions from energy, agriculture, and waste in Pakistan increased faster than the industrial processes and land use and change forestry sectors from 1994 to 2012, where energy contributed 27% of the national GHG emissions; thus, the mitigation effort and climate policy could be focused primarily on this point source [51].

In the livestock sector, a GHG inventory may reflect which mitigation measures should be taken and in which areas. This is unusually relevant in developing countries, although they are not major emitters contributing substantially to global GHG emissions from agriculture, particularly through enteric fermentation and manure management [52].

MITIGATION MEASURES FOR LIVESTOCK SECTOR

Source elimination

The elimination of these sources may be the best mitigation strategy. The rationale is that when there is no source of emissions, no emissions occur. In livestock, the emitted gases mainly come from biological processes that occur naturally, either inside the body (enteric fermentation) or outside the body (manure). In this context, the elimination of sources results in the death of the animal; thus, this mitigation is nonviable.

Livestock provides valuable nutritional benefits and supports livelihoods and the resilience of families and communities [53]. Livestock is the key to food security. Meat, milk, and eggs provide 34% of the protein consumed globally, as well as essential micronutrients such as vitamins B12 and A, iron, zinc, calcium, and riboflavin [54]. Owing to the nutritional benefits of livestock products, the importance of livestock in food security is because ruminants can convert feeds that are unsuitable and unpalatable to humans into milk and meat. A study in North America showed that feeding leftover human edible foods or non-consumable foods to dairy cows could recover human-edible nutrients in milk [55]. The most crucial step in achieving food production and environmental objectives is boosting the efficiency of natural resource utilization. This involves significantly enhancing crop yields beyond historical (linear) rates, as well as substantially raising the output of milk and meat per hectare of pasture, per animal, and per kilogram of fertilizer [56].

Controlling the sources of emissions

Enteric fermentation

The mitigation of emissions from enteric fermentation includes feed supplementation and feeding management (Table 4). The principle of feed supplementation is to disrupt either methanogenic bacteria or the methanogenesis process so that less CH_4 is produced. Common feed supplements include inhibitors, electron receptors, and dietary lipids. A variety of potential feed supplements have been the subject of research and development, such as 3-nitrooxypropanol (3-NOP), bromocholomethane, essential oils, monensin, NO_3^-, probiotics, saponins, and seaweed [57]. A meta-analysis by Kebreab et al. [58] found that supplementing feed with 3-NOP reduced CH_4 emissions by around 30.9% to 32.7%, depending on the rate. Araújo et al. [59] found that 3-NOP supplementation decreased CH_4 emissions by 49.3% from feedlot cattle in a tropical condition. Tseten et al. [60] summarized various studies on essential oils from different sources (garlic, thyme, rosemary, oregano, clove, eucalyptus, lavender, peppermint) for reducing CH_4 emissions that shows various result, yet promising. The highest reduction was the highest by 73%–91% from garlic essential oils [61,62] and eucalyptus by up to 85% [63]. The research on feed supplement to reduce enteric CH_4 have been widely conducted. The most is supplementing feed with lipids and essential oils. Arndt et al. [64] conducted meta-analysis to reveal the efficacy of feed supplementations to

 https://doi.org/10.5187/jast.2024.e86

Table 4. Feasible mitigation options to control the sources of GHG emissions

Emission sources	Mitigation options	Measures	Mechanisms	Reference
Enteric fermentation	Plant bioactive compounds	Tannins	Changing the VFA proportions in ruminal fluid results in a reduction in fermentation	[80]
	Dietary lipids		Increasing fat concentration decreased mean ruminal pH and increased the duration of pH below 6	[81]
	Concentrate inclusion		Increased starch intake reduces ruminal pH, affecting DM and NDF digestibility and favors propionate rather than acetate in the rumen	[82]
	Improving forage quality and management		With lower quality of forage, the fiber contents increase, thus higher CH_4 production occurs	[83]
	Processing of low-quality feeds	Reducing herd size	Improving nutritive value of low-quality feeds could increase productivity, thus reducing herd size and concomitant reduction in herd GHG emissions	[31]
		Macro-supplementation (when deficient)	Improve animal performance by supplementing available N for microbial protein synthesis in the rumen and balancing rations for macro and micro nutrients	[31]
Manure management	Dietary manipulation and nutrient balance	Reduced dietary protein	Lower urea-N in urine and TAN results in lower NH_3	[84]
	Housing	Biofiltration	High porosity of bio filter media containing a mixture of organic and inorganic media allowed sufficient oxygen transfer for methane oxidation	[85]
		Manure system		
	Manure treatment	Anaerobic digestion	Manure composition changes. NPK are transformed from organic forms to inorganic forms, whereas C is transformed to biogas for use as fuel	[86]
	Manure storage	Decreased storage time	When storage time is decreased and manure is applied directly to land, less CH_4 occurs after land application of manure	[31]
	Manure application	Timing of application	Application of manure on land before rain can decrease emission spike	[31]
		Soil nutrient balance		

Adopted from Hristov et al. [31] with the following criteria: enteric fermentation (effectiveness applicable to all regions), manure management (effectiveness on a minimum of two gases -CH_4, N_2O, NH_3-, applicable to all regions).

reduce enteric CH_4. The CH_4 inhibitors reduce CH_4 yield up to 34%, oil and fats reduce CH_4 yield by 15%, and oilseeds reduce CH_4 yield by 14%.

Slightly different from feed supplements, feeding management concentrates on diet manipulation/feed manipulation including manipulation of rumen archaea and bacteria so that the feed is fully digested and CH_4, a byproduct of the digestive process, is decreased. Feeding management aims to increase feed efficiency [31]. Dietary manipulation is a simple and practical approach for improving animal productivity while also reducing CH_4 emissions [65]. The reduction in CH_4 emissions can be achieved by using high-quality forage or replacing it with maize silage [65] because methanogenesis tends to be lower in ensiled forage [66].

Methane reduction can also be achieved by controlling the concentration and composition of the concentrate [65]. Raising concentrates in the feed composition leads to a decrease in CH_4 emissions, as milk and meat as the output product require a significant amount of energy to produce [67]. Many concentrates with high energy content are known to promote increased dry matter intake, rumen fermentation rate, and feed turnover rate. This leads to significant changes in the rumen environment and microbial composition [67]. Feeding ruminants with more starch reduces enteric CH_4 production [68].

Other methods include fat supplementation and antibiotics such as ionophores, probiotics, condensed tannins, and saponins [65]. Enhancing the microbial diversity in the rumen of ruminants through chemical interventions, such as the use of halogenated compounds and chloroform, or by introducing competitive or predatory microorganisms, and by direct immunization, can decrease methanogenesis [69].

The most recent method involves adding *Asparagopsis taxiformis* and *Oedogonium* sp. *In vitro* studies have shown that seaweed can potentially reduce enteric CH_4 emissions from ruminants, although this effect depends on multiple factors [70,71]. Furthermore, *A. taxiformis* reduced enteric fermentation by up to 80% when supplemented in a ruminant diet [72]. Machado et al. [73] found that *Oedogonium* sp. is a potent anti-methanogen, although less potent than *Asparagopsis* sp.

Manure management

CH_4 emissions abatement is a mitigation analysis of the livestock sector that involves improved manure management (Table 4). The emissions from manure management are correlated with the manner in which manure is handled because each manure management strategy generates different amounts of emissions [31]. The common principle of manure management is to fully degrade the organic matter inside the manure and use it to lower emissions production.

Despite improvements in manure management systems, using additives has become an alternative to reduce CH_4 emissions from manure management. The addition of gypsum-based commercial additives to liquid manure and slurry significantly reduced CO_2, CH_4, NH_3, and N_2O emissions and reduced the odor intensity [74,75]. Other additives, such as urease and nitrification inhibitors, have been widely used to mitigate nitrogen loss in agricultural fields. When applied to manure, both inhibitors have potential as strategies for reducing GHG emissions from manure management [76].

Kreidenweis et al. [77] compared four manure treatment processes: biochar, anaerobic digestion, composting, and storage. It was shown that across all GHGs, anaerobic digestion showed the lowest emissions among all treatments with net emissions of −432 kgCO_2-eq/ton of manure while composting showed the highest net emissions of 216 kgCO_2-eq. The outcome indicates that anaerobic digestion and the generation of biogas from broiler manure can be a viable treatment solution that leads to minimal GHG emissions.

A meta-analysis from Mohankumar Sajeev et al. [78] showed the effectiveness of several abatement options to reduce N_2O, CH_4 and NH_3. Feeding management such as reduced crude protein decrease N_2O by 30%. Abatement in manure management showed promising results. Frequent removals, anaerobic digesters, and acidification decreased N_2O emissions by 41%, 23%, and 55%, respectively. Same treatments also reduce CH_4 by 55%, 29%, and 74%, respectively. This shows that frequent removal, anaerobic digesters, and acidification reduce both N_2O and CH_4 emissions. Other treatment such as scrubber and cover only reduce CH_4 emissions by 6% and 11%. Ambrose et al. [79] reviewed studies on various mitigation treatment for CH_4 emissions from manure management. Among different methods, acidification to pH 5.5 has showed about 60%–90% reduction in CH_4 emissions, and among the physical methods, permeable covers reduce CH_4 emission from liquid slurry storage.

CONCLUSION

The ability of the GHG inventory to distinguish sectoral emissions is why it was selected as the main reporting tool for GHG emissions internationally. This major point designates the GHG inventory as the baseline to prioritize mitigation and track the emission reduction goal, including those from the livestock sector. While its calculation has been regulated using IPCC GL to maintain its transparency, accuracy, completeness, comparability and consistency, the differences in each guideline may create distinguished differences in estimations while changing guidelines;

 https://doi.org/10.5187/jast.2024.e86

thus, careful consideration should be taken when countries plan to change the guidelines. This possibility highlights the need for stakeholders to cautiously calculate the GHG inventory so that it can function as a monitoring tool and foundation for efforts to reduce emissions through mitigation strategies and policies. More recommendations and regulations are needed to ensure that the consistency of the GHG inventory is maintained, although the guidelines have changed. In addition, developing a country-specific methodology in accordance with the IPCC GL may minimize the inconsistency and inaccuracy of the GHG inventory throughout different periods; thus, the GHG inventory will function as intended.

There are various methods available to decrease GHG emissions from manure management. Some treatments have been demonstrated to reduce both CH_4 and N_2O emissions, while others only target one of these GHG emissions. Therefore, it is crucial to select the most appropriate treatment that targets the desired reduction of GHG emissions carefully. In this context, an accurate and consistent GHG inventory is essential. Consequently, based on the GHG inventory, reduction priorities can be proposed, and the most suitable mitigation option can be applied.

This review presents opportunities to examine other studies related to improving methodology for GHG inventory, policy-making, and climate change mitigation. Examining country-specific methodologies in greater depth is crucial to guarantee the accuracy and consistency of GHG inventory. Moreover, the need for a thorough investigation of the role of inventory in the decision-making process for mitigation strategies is crucial, given the importance of precise GHG inventory and effective climate policies in addressing climate change issues.

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