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Methods for Measuring Enteric Methane Emissions in Ruminants: A Critical Review

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Accurate measurement of methane emissions from ruminants is crucial for developing effective mitigation strategies and reliable greenhouse gas inventories. Methane (CH_4) is a potent greenhouse gas, with a global warming potential 28 times higher than carbon dioxide over a 100-year time frame. Enteric methane emissions from ruminants, such as cattle, sheep, and goats, are a significant contributor to agricultural greenhouse gas emissions. Various techniques exist to measure methane emissions from ruminants, each with its own strengths and limitations. Respiration chambers, for example, are considered one of the most accurate methods, but they are labor-intensive and require specialized equipment. The Sulphur hexafluoride tracer method is another accurate technique, but it requires frequent calibration and equipment maintenance. Simplified techniques, such as GreenFeed, sniffer method, and laser methane detector, offer rapid and high-throughput measurements, but may be less accurate. These methods are often more practical for commercial farms and large-scale studies, but require careful consideration of their limitations and potential biases. In addition to direct measurement techniques, modeling approaches can be used to estimate methane emissions. Bottom-up approaches rely on empirical or mechanistic modeling to quantify the contribution of individual sources, while top-down approaches estimate emissions from atmospheric concentrations and models. The choice of technique depends on the objectives and resources available. For example, respiration chambers may be suitable for research studies, while GreenFeed or sniffer methods may be more practical for commercial farms. Understanding the advantages and disadvantages of each method, as well as animal behavior and welfare, is essential for accurate interpretation and effective mitigation strategies. The agricultural sector is under pressure to reduce greenhouse gas emissions, and accurate measurement of methane emissions is a critical step towards achieving this goal. By understanding the strengths and limitations of different measurement techniques, researchers

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and farmers can work together to develop effective mitigation strategies and reduce the environmental impact of ruminant production systems.

Introduction

Enteric methane emissions from ruminants are a significant contributor to agricultural greenhouse gas emissions, accounting for up to one-third of global methane emissions (Beauchemin *et al*., 2022). The atmospheric warming effect of methane is 28 times as strong as CO_2 (IPCC, 2019b). Accurate measurement of CH_4 emissions from ruminants is crucial for developing effective mitigation strategies and reliable GHG inventories. Various techniques exist, including respiration chambers, SF_6 tracer, GreenFeed, sniffer method, and laser methane detector, each with pros and cons (Cole *et al*., 2018; Bekele *et al*., 2022). Respiration chambers are considered one of the most accurate methods, but are labor-intensive and require specialized equipment (Gerrits and Labussière, 2015). The SF_6 tracer method is another accurate technique, but requires frequent calibration and equipment maintenance (Tedeschi, 2022). Simplified techniques, such as GreenFeed and sniffer method, offer rapid and high-throughput measurements, but may be less accurate (Henry *et al*., 2012). The choice of technique depends on objectives, resources, and animal welfare considerations. Understanding method limitations and animal behavior is essential for accurate interpretation and effective mitigation. Further research is needed to validate and improve existing methods, particularly for large-scale areas and complex production systems. Ruminant production systems are complex and involve various sources of GHG emissions, including enteric fermentation, manure management, and feed production (Gerber *et al*., 2013). Enteric fermentation is the largest source of CH_4 emissions, accounting for approximately 80% of total emissions (IPCC, 2019b). Manure management and feed production contribute to the remaining 20% of emissions. Mitigation strategies for reducing CH_4 emissions from ruminants include dietary modifications, feed additives, and manure management practices (Beauchemin *et al*., 2022). Dietary modifications, such as increasing the proportion of concentrate feeds, can reduce CH_4 emissions by up to 20% (Cole *et al*., 2018). Feed additives, such as ionophores and essential oils, can also reduce CH_4 emissions, but their effectiveness varies depending on the specific additive and production system (Tedeschi, 2022). Manure management practices, such as anaerobic digestion and composting, can reduce CH_4 emissions by up to 50, depending on the specific practice and production system (Ominski *et al*., 2021). However, the effectiveness of these practices can be influenced by factors such as temperature, moisture, and oxygen levels. The accuracy of CH_4 emission estimates is influenced by various factors, including the choice of measurement technique, data quality, and modeling approach (Tedeschi, 2022). The use of multiple measurement techniques and data sources can improve the accuracy of estimates, but increases the complexity and cost of the measurement process.

Measurement Techniques

a.) Respiration Chamber

Continuous measurement of methane (CH_4) emissions from ruminants is crucial for understanding and mitigating the environmental impact of livestock production. Chambers, also known as respiration chambers, are a widely used technique for measuring CH_4 emissions from individual animals or groups of animals. The chamber technique involves placing the animal in a sealed enclosure, where the air is circulated and the CH_4 concentration is measured over time. The CH_4 emission rate is calculated from the change in CH_4 concentration and the airflow rate through the chamber.

There are several types of chambers, including:

1. **Open-circuit chambers:** These chambers are ventilated with fresh air, and the CH_4 concentration is measured in the inlet and outlet air streams.
2. **Closed-circuit chambers:** These chambers are sealed, and the CH_4 concentration is measured over time as the animal consumes the oxygen and produces CO_2 and CH_4.

Chambers can be used to measure CH_4 emissions from a variety of ruminant species, including cattle, sheep, and goats. They can also be used to study the effects of different diets, feed additives, and management practices on CH_4 emissions.

Advantages of chamber measurements:

1. **High accuracy:** Chambers can provide highly accurate measurements of CH_4 emissions, with errors typically less than 5%.
2. **Flexibility:** Chambers can be used to measure CH_4 emissions from a variety of animal species and under different management conditions.
3. **Research tool:** Chambers are a valuable research tool for studying the effects of different factors on CH_4 emissions and developing mitigation strategies.

Limitations of chamber measurements:

1. **Animal stress:** Chambers can cause stress to the animals, which may affect their behavior and CH_4 emissions.
2. **Limited duration:** Chamber measurements are typically limited to short periods (e.g., 24-48 hours), which may not capture the full range of variability in CH_4 emissions.
3. **Labor-intensive:** Chamber measurements require careful setup, operation, and maintenance, which can be labor-intensive and expensive.

b.) Sulfur Hexafluoride Tracer Technique

The sulphur hexafluoride (SF_6) method is a relatively new technique for measuring methane (CH_4) emissions from ruminants, first described in 1993-1994 (Johnson *et al*., 1994; Lassey *et al*., 1997). The main purpose of the method was to investigate energy efficiency in free-ranging cattle, as it had been queried that results obtained in respiration chambers could not be applied to free-ranging animals (Johnson *et al*., 1994; Lassey *et al*., 1997). The SF6 method is widely used in countries such as New Zealand (Lassey *et al*., 1997; Ulyatt *et al*., 1999), Canada (Boadi *et al*., 2002; McMethane *et al*., 2002), Australia (Graham *et al*., 2005; Hegarty *et al*., 2007), and the US (Johnson *et al*., 1994; Pinares-Patiño *et al*., 2003). The basic idea behind the method is that methane emission can be measured if the emission rate of a tracer gas from the rumen is known. SF_6 was chosen as the tracer gas because it is non-toxic, physiologically inert, stable, and has an extremely low detection limit (Johnson *et al*., 1994). The SF_6 method involves filling small permeation tubes with SF_6, which are then placed in the rumen of the animal. The rate of diffusion of SF_6 out of the permeation tubes is measured by placing them in a 39°C water bath and measuring the daily weight loss until it is stable (Johnson *et al*., 1994). The sampling apparatus consists of a collection canister, a halter, and capillary tubing, which is placed at the nose of the animal and connected to the evacuated canister (Figure 3). The methane emission is calculated from the release rate of SF_6 and the concentration of SF_6 and CH_4 in the containers in excess of background level (Lassey *et al*., 1997), as described in Equation.

CH_4 emission = (SF_6 release rate x CH_4 concentration) / SF_6 concentration

The SF_6 method has been carefully tested over the last two decades, and several difficulties have been described. One of the main challenges is maintaining a constant release rate from the permeation tubes (Vlaming *et al*., 2007). The release rate can be affected by factors such as temperature, pressure, and the presence of other gases (Lassey *et al*., 1997). Another challenge is determining the background level of SF_6 and CH_4, which can be affected by wind direction and other animals in the field (Johnson *et al*., 1994). The SF_6 method has also been shown to have a higher within- and between-animal variation compared to chamber measurements (Pinares-Patiño *et al*., 2003). Despite these challenges, the SF_6 method is a valuable tool for measuring methane emissions from free-ranging ruminants. It is the only available method for measuring individual free-ranging animals on pasture, and it has been widely used in research studies (Graham *et al*., 2005; Hegarty *et al*., 2007).

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c.) The CO_2 Technique

The CO_2 technique is a newly developed method for estimating methane emissions from livestock, based on the use of CO_2 as a tracer gas (Madsen *et al*., 2010). Instead of using externally added SF6, the naturally emitted CO_2 is used to quantify CH_4 emission. The CH_4 / CO_2-ratio in the production of air of the animal(s) in question is measured at regular intervals and combined with the calculated total daily CO_2 production of the animal(s). The calculations are the same as for the SF_6 tracer technique (Equation 1), only with CO_2 as the tracer gas instead of SF_6. The use of CO_2 as a quantifier gas is based on knowledge compiled over more than 100 years from experiments measuring feed requirements and feed composition (Brouwer, 1965; Blaxter and Clapperton, 1965). The measured feed intake can be converted to heat-production, and there is a close relationship between heat- and CO_2 -production (Blaxter and Clapperton, 1965; McMahon *et al*., 2009). Animals at maintenance are thus emitting 1 L CO_2 per 21.5-22.0 KJ of heat produced. Corrections can be made for lactating animals or animals gaining weight. The relation between heat production and CO_2 production is partly related to the amount of fat deposited or mobilized and can in practice be as low as 20.0 KJ per L CO_2 when large amounts of feed carbohydrates are converted to fat as in high yielding dairy cows (Madsen *et al*., 2010). The total CO_2 production from stables with different animals, e.g., lactating dairy cows, dry cows and heifers, has likewise been determined by researchers working with ventilation (Pedersen *et al*., 2008). The CO_2 method can be used to quantify methane production under different circumstances. Two examples are the total CH_4 production from a whole stable with dairy cows (Madsen *et al*., 2010) and individual estimates for cows visiting an automated milking system (AMS) (Lassen *et al*., 2012). A comparison with respiration chamber measurements has recently been published (Hammond *et al*., 2016). The expiration air of cattle contains CO_2 and CH_4 in concentrations 100 and 1000 times higher than the concentrations in atmospheric air, respectively. Therefore, it is only necessary to have 5-10% of the animal's breath in the air being analyzed. This can easily be achieved in a stable or when individual cows visit an AMS. The method can potentially be developed for application to grazing cattle. As about 95% of CH_4 emissions from cows are excreted with expiration air (Murray *et al*., 1976), the small amounts excreted through the rectum can be ignored. Measurements of CH_4 and CO_2 can be conducted with different types of analyzers - so far the CO_2 method has used a portable equipment called Gasmet (Gasmet Technologies Oy, Helsinki, Finland), which is based on infrared measurements (Fourier Transformed Infrared (FTIR), (Esala *et al*., 2012)). The equipment is portable and can easily be used under very different circumstances. The main disadvantage is that the CO_2 production of animals is influenced by the same things as the animals' requirement for energy. This means that the size, activity and production of the animal influences the amount of CO_2 produced. This is not of importance when for instance the quantitative effect of different feeds or supplements on the methane production of different groups of equal animals is going to be established, but may produce larger errors when the quantitative methane production is going to be established on an individual animal or on different groups of animals. Combined with the only partial sampling of animal breath, the estimation of individual animal emissions with the CO_2 -technique is expected to produce higher day-to-day variation than observed in respiration chambers. Fortunately, the method can easily be applied to many animals making it possible to reduce the standard error of means from experiments.

d.) GreenFeed (GF)

GreenFeed (C-Lock Inc, Rapid City, SD, USA) is an automated head-chamber system combined with a portable feeding station for spot sampling of CH_4 emissions and gaseous exchange in ruminants (Hammond *et al*., 2015; Huhtanen *et al*., 2015). This system integrates the measurements of gas concentrations, airflow, bait feed intake and automated recognition of animal identification through a radiofrequency identification ear tag as animals approach the bait feed (Arthur *et al*., 2017). A gas sampling system is automated based on when an animal eats the feed in GF. The system sucks air through the animal's nose and mouth into a duct with airflow measured. Then a subsample is drawn into a gas analysis system, where CH_4 concentration is determined using a non-dispersive infrared sensor (Hammond *et al*., 2015). Gas concentrations of an animal are usually measured a few times a day within 3-7 min each time by controlling the feed supply in GF for a few days. A set of GF system is designed to measure as many as 20 animals (Hristov *et al*., 2015). The data of each individual animal collected in a few days are then used to calculate average daily CH_4 emissions (Hammond *et al*., 2015). The program installed in GF controls the timing and amount of feed availability for each animal and distributes the measurements evenly in a 24 h feeding cycle (Arthur *et al*., 2017; Hammond *et al*., 2015). Data are uploaded to a cloud-based analysis system in real-time developed by the GF manufacturer for CH_4 emission estimation (Hammond *et al*., 2015; Huhtanen *et al*., 2015). One advantage of GreenFeed is that it provides an alternative as a portable and automated technique in estimating individual animal's CH_4 flux under both indoor and grazing conditions (Hammond *et al*., 2015). Reliable results can be obtained if the timing and times of each animal measurement are well controlled, which is easily achievable by the operation of an investigator in a tie stall barn (Huhtanen *et al*., 2015). GreenFeed is capable of differentiating the higher emitters from the lower ones in dairy cows and beef heifers as Respiration Chamber (RC) (Arthur *et al*., 2017; Hammond *et al*., 2015). Huhtanen *et al*. (2015) reported that CH_4 production measured by GF was significantly correlated with that by RC (R2 = 0.92) in direct comparisons and also in line with CH_4 emissions calculated by prediction equations developed by RC data.

A disadvantage of GreenFeed is that it has high between-day and between-animal variations (Hammond *et al*., 2015). Hammond *et al*. (2015) found that the GF technique didn't detect the effects of diet and animal factors on CH_4 emissions when compared with RC and SF6. This is possibly due to the requirement of a bait feed supplement to encourage the animal to use the facility, which may not be consumed equally by different animals and will interact with the dietary treatments, thus introducing between-day and between-animal variation in the measurement (Hristov *et al*., 2015; Hammond *et al*., 2015). When used for animals freely grazing on pasture, it is voluntary for the animals to be assessed which could limit the measurement timing and frequency of individual animals and unbalance the number of animals measured in different treatment groups (Hammond *et al*., 2015). In addition, wind direction and speed changes could also impact measurement, which are major variation factors for grazing studies using GF (Hammond *et al*., 2015; Huhtanen *et al*., 2015). Furthermore, CH_4 emissions are strongly correlated with feed intake and form a clear diurnal rhythm in a 24 h feeding cycle (Hammond *et al*., 2015; Arthur *et al*., 2017). Therefore, many studies highlighted the importance of controlling number and timing of GF visits per animal to ensure sufficient numbers of measurements throughout the 24 h feeding cycle to obtain accurate estimates of daily CH_4 emissions (Hammond *et al*., 2015; Huhtanen *et al*., 2015; Arthur *et al*., 2017). Arbre *et al*. (2016) suggested that a repeatability of 70% in CH_4 yield (g/kg dry matter intake) measurement required 17 day periods and the repeatability could further increase to 90% up until 45 day periods when using the GF system. Therefore, the successful application of this technique relies on a sufficient number of animals, measurement periods and animal visits to GF.

e.) Sniffer Technique

The Sniffer Technique is a method developed by Garnsworthy *et al*. (2012) for measuring methane (CH_4) emissions from lactating dairy cows during milking. This technique is based on the hypothesis that there is a close relationship between daily CH_4 production and CH_4 concentration in eructations and the associated eructation frequency. In this method, gases are continuously sampled into a polyethylene sampling tube installed in the feed trough of an automatic milking system when the cows are eating and being milked. The Sniffer technique has several advantages, including the ability to measure CH_4 concentrations from a large number of individual lactating dairy cows repeatedly and rapidly during routine milking under commercial conditions (Garnsworthy *et al*., 2012). The CH_4 emission rate measured by the sniffer method during milking was linearly correlated with the CH_4 production measured in respiration chambers (RC) (Garnsworthy *et al*., 2012). Estimation of daily CH_4 emissions using the sniffer method also agreed well with the daily CH_4 emissions predicted using milk yield and body weight of dairy cows (Bell *et al*., 2014). However, the Sniffer technique also has some disadvantages. It exhibited a greater difference in between-cow and within-cow variability than the RC and SF_6 techniques (Garnsworthy *et al*., 2012; Bell *et al*., 2014). The accuracy of the sniffer technique is influenced by the uncertainties of dairy cow head movements in the feed trough, the various designs of feed trough, and the sampling point positions (Wu *et al*., 2018). All of these factors may result in different air-mixing conditions and different dilution effects of ambient air on the gas concentration in eructations (Huhtanen *et al*., 2015). The Sniffer method does not actually measure CH_4 flux or CH_4 production. It only provides prediction values of CH_4 emissions by CH_4 concentrations from existing regression equations developed using RC (Garnsworthy *et al*., 2012; Bell *et al*., 2014). Therefore, different equations may be required for different dietary scenarios.

f.) Facemask Technique

The Facemask technique is a spot sampling method used to measure CH_4 emissions from ruminants. It involves placing a mask over the animal's muzzle, which is connected to a gas analyzer. The mask is typically attached to the animal's head using a strap, and the gas analyzer measures the CH_4 concentration in the breath. The Facemask technique is relatively simple and inexpensive compared to other methods, making it a useful tool for researchers. However, it does require the animal to be restrained or trained to wear the mask, which can be a limitation (Oss *et al*., 2016). Studies have shown that the Facemask technique can provide accurate measurements of CH_4 emissions, with results comparable to those obtained using respiration chambers (Silveira *et al*., 2019). However, the technique may be less accurate for animals with high variability in breathing patterns or those that are stressed or uncomfortable wearing the mask.

g.) Ventilated Hood Technique

The Ventilated Hood technique is a method used to measure CH_4 emissions from ruminants, particularly cattle. It involves placing a hood over the animal's head, which is connected to a ventilation system and a gas analyzer. The hood is designed to capture the animal's breath and measure the CH_4 concentration.

The Ventilated Hood technique is considered to be a more accurate method than the Facemask technique, as it provides a more representative sample of the animal's breath (Suzuki *et al*., 2007). The technique is also relatively simple and can be used in a variety of settings, including farms and research facilities. However, the Ventilated Hood technique does require the animal to be trained to wear the hood, which can be time-consuming. Additionally, the technique may not be suitable for animals that are stressed or uncomfortable wearing the hood.

h.) Laser CH_4 detector

The Laser Methane Detector (LMD) is a hand-held device that remotely measures CH_4 concentrations in the air using infrared absorption spectroscopy, offering a convenient and non-intrusive way to estimate CH_4 emissions from ruminants (Chagunda *et al*., 2013). The LMD is originally applied in the detection of CH_4 accumulation in industry areas such as coal mines, landfills, and CH4 leakage in natural gas transmission pipelines, etc. The device can operate in an environment of −17 °C to 50 °C with 30% to 90% relative humidity, making it suitable for use in various settings (Tokyo Gas Engineering Solutions Inc., Tokyo, Japan). The LMD technique has been shown to provide accurate measurements, with a significant positive relationship with respiration chamber (RC) measurements (Chagunda *et al*., 2013; Ricci *et al*., 2016). The LMD is also able to discriminate between differences in mean CH_4 concentrations produced by different cow activities (Chagunda *et al*., 2013). However, the technique has limitations, including measuring concentration rather than flux, and being affected by factors such as wind direction, temperature, and humidity (Rey *et al*., 2017; Pickering *et al*., 2015). Ricci *et al*. (2016) reported that the correlation between LMD and RC was not consistent in different experimental periods when evaluating the LMD in estimating CH_4 emissions from ewes and steers. In particular, the most accurate estimations from LMD were located 3 to 5 h post feeding (Ricci *et al*., 2016). Thus, it is necessary to integrate the effects of feeding regime and animal behavior on eructation and respiration in the assessment of LMD measurement results. Rey *et al*. (2017) reported that the measurements of LMD were not as repeatable as those of the sniffer technique, which was probably due to the much longer distance between the device and the animals in LMD. This consequently introduced more variation sources such as wind direction and speed and adjacent animals' behavior and respiration. Moreover, other infrared absorbing compounds (e.g., water vapor in the air) can also affect the results. Similarly, particular attention should also be paid to changeable weather conditions when using LMD outdoors and in pastures for grazing animals, as variation in relative humidity, atmospheric pressure, and temperature may limit the potential application of LMD (Chagunda *et al*., 2013). Pickering *et al*. (2015) tried to use LMD measurement results in screening the genetic trait of CH_4 production in dairy cows. However, the repeatability within lactation was only 0.07 and across lactations was only 0.03. Therefore, it is still not fully qualified in the genetic evaluation of animals regarding CH_4 emissions, unless further research is carried out to improve its repeatability. In conclusion, the LMD is a convenient and non-intrusive technique for estimating CH_4 emissions from ruminants. However, its limitations, such as measuring concentration rather than flux, and being affected by environmental factors, need to be considered when interpreting the results. Further research is needed to improve the repeatability and accuracy of the LMD technique.

Discussion

Measuring CH_4 emissions from ruminants is a complex task, and no single method is suitable for all conditions. Each technique has its unique advantages and disadvantages, and the choice of method depends on the specific research question, experimental design, and animal management system. The Intergovernmental Panel on Climate Change (IPCC) recommends using respiration chambers (RC) and head enclosures (e.g., ventilated hood or head box) for measuring the CH_4 conversion factor (Ym), which is defined as the percentage of gross energy intake converted to CH_4 (IPCC, 2019). RC, SF6 tracer, and ventilated hood techniques are capable of continuous 24 h measurements of CH_4 flux for each individual animal, providing accurate reference methods used for research and inventory purposes (Hammond *et al*., 2016). However, these methods require relatively high labor input, time cost, and animal training, with a relatively low number of animal throughput, and are suitable for indoor use only (Suzuki *et al*., 2007). In contrast, SF6 tracer, GreenFeed (GF), and Laser Methane Detector (LMD) techniques have advantages that apply to outdoor or grazing systems (Chagunda *et al*., 2013; Hammond *et al*., 2016). However, reliable and accurate measurements of feed intake for outdoor or grazing animals are quite challenging (Hammond *et al*., 2016). Short-term methods, such as GF, sniffer, facemask, LMD, and portable accumulation chamber (PAC), introduce additional sources of variation, including numbers and timing of measurements obtained relative to the 24 h feeding cycle (Hammond *et al*., 2016). Therefore, short-term measurements can be meaningful only if a sufficient number of animals are examined with the measurements distributed across various representative times of the day over a long enough period, and if a good relationship with RC measurements can be obtained (Chagunda *et al*., 2013). GF could measure CH_4 flux, which provides important airflow data that are not available in sniffer, LMD, and PAC methods (Hammond *et al*., 2016). Meanwhile, it has much less interruption on animal behavior and welfare compared to the facemask method (Suzuki *et al*., 2007). There still needs to be considerable improvement in the reliability and repeatability of sniffer, LMD, and PAC when using their short-term concentration measurements to predict CH_4 production (Rey *et al*., 2017). However, the low-cost and simplicity of their application makes the short-term measurements suitable for a large number of measurements in individual animals under their practical production conditions (Pickering *et al*., 2015). This offers a potential opportunity in defining the CH_4 phenotype required for genetic and genomic improvement for breeding lower emitting animals (Pickering *et al*., 2015). Last but not least, the CH_4 emissions from hindgut fermentation (3% of that from the whole digestive tract) should be added in the results of SF6, GF, sniffer, ventilated hood, facemask, and LMD measurements because the animal's whole body is not sealed in these systems as it is when using the RC and PAC methods (Murray *et al*., 1976).

Table 1. Comparison of enteric CH4 emission measurement techniques.

Method	Indoor/Grazing	CH_4/Multi-Gas	Rumen/Hindgut	Continuous/ Short-Term	Flux/ Concentration
Respiration chambers	Indoor	CH_4, multi-gas	Rumen, hindgut	Continuous	Flux
Sulphur hexafluoride tracer	Indoor, grazing	CH_4	Rumen	Continuous	Flux
GreenFeed	Indoor, grazing	CH_4, multi-gas	Rumen	Short-term	Flux
Sniffer method	Indoor	CH_4, multi-gas	Rumen	Short-term	Concentration
Ventilated hood	Indoor	CH_4, multi-gas	Rumen	Continuous	Flux
Facemask	Indoor	CH_4, multi-gas	Rumen	Short-term	Flux
Laser CH_4 detector	Indoor, grazing	CH_4	Rumen	Short-term	Concentration
Portable accumulation chamber	Indoor	CH_4, multi-gas	Rumen, hindgut	Short-term	Concentration

Conclusion

The quality of CH_4 measurements is critical, but special attention must also be paid to the information given in publications in relation to measurement context and methods to reasonably and comprehensively contextualize the results obtained (Webb *et al*., 2021). Every method or methodology to quantify CH_4 emissions from livestock production has limitations brought about by their original intent of use. Della Rosa *et al*. (2021) assessed variations in technical procedures of respiration chambers, SF_6, and Greenfeed Emission Monitoring System for measuring CH_4 from ruminants and concluded that standardization within and between techniques could improve the reliability of the results. Therefore, using these technologies outside of their purpose is risky, and extrapolation of their estimates will undoubtedly result in unintended consequences. There is no one ideal method or methodology given the many different production scenarios worldwide, management strategies, and inherent assumptions associated with the method or methodology. Combining different methods might be the best approach, but more research is needed to validate individual methods, compare different methods in different production scenarios, and develop calibration and standardization protocols for existing methods and methodologies.

Correct and successful use of CH_4 emission measurement methods relies on the optimum matching between the objectives of the studies and the mechanism of each method. Respiration chambers and head enclosures are accurate enough for determining emission factors for IPCC inventory reporting, however they are not possible for use in grazing animals. Sulphur hexafluoride tracer technique is able to be applied in grazing situations, however the herbage feed intake relies on indirect prediction. The short-term techniques (i.e., GF, sniffer, facemask, LMD) provide potential opportunities in identifying high and low CH_4 emitters in a large group of animals for breeding purposes, although future research is still needed to improve their reliability and repeatability. Overall, ideal CH_4 measurement techniques should be accurate, rapid, cost-effective, and automated with an appreciation of animal behavior and welfare that enables measurement of animals under their practical production environment. The limitations of each method highlight the need for a comprehensive approach to measuring CH_4 emissions. This can be achieved by combining different methods, such as using respiration chambers for calibration and short-term techniques for large-scale measurements. Additionally, standardization of measurement protocols and data analysis is crucial for ensuring the accuracy and reliability of CH_4 emission estimates.

Furthermore, the development of new technologies and methodologies is necessary to improve the accuracy and efficiency of CH_4 emission measurements. This includes the use of advanced sensors, machine learning algorithms, and modeling approaches to predict CH_4 emissions from livestock production.

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