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Feeding strategies to reduce methane emissions: A review

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Abstract

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This review provides information on the influence of the ration composition, botanical composition of the pasture grass, and the type and quality of the silages on the release of methane emissions in livestock farming. Modeling rumen fermentation is the most important method to optimize feed utilization, ensure maximum microbial protein synthesis, increase productivity, and limit released methane emissions as a result of the digestion processes. There is a limited number of studies on the effect of feeding systems and feeding regimes, as well as the extent of methane emissions released from the digestion of sheep, goats, buffalo, and other ruminants. Feeding strategies need to be revised and developed, which should minimize ruminant energy loss and lead to increased productivity by reducing the number or activity of methanogens. Although methane production can be reduced by current strategies, due to the variety of adaptive mechanisms, they may only be effective temporarily. Therefore, further research is needed to study the effect of rations and rumen fermentation inhibitors with particular attention to methane production and changes in methanogenic microorganisms.

Keywords: methane; reduction; feeding strategies

Introduction

Ruminants are considered a major source of methane emissions, and political pressure to reduce both methane and other pollutants from livestock excrements globally is constantly increasing. Intensive livestock farming systems often attract public criticism for their harmful impact on the environment, animal welfare and food safety. Greenhouse gas (GHG) emissions from agriculture contribute to 14.5% of global gas emissions (Gerber et al., 2013), and improvements in farm management can help reduce them. Lactating cows are the largest source of greenhouse gas emissions of all categories of farm animals.

Cattle produce 250 to 500 L of enteric CH_4 per day. This level of gas production for over 50–100 years is less than 2% of the total greenhouse gas emissions (Johnson & Johnson, 1995). The CH_4 reduction may be due to increased regulation and possibly increased efficiency of CH_4 production processes. In 2014, 81% of greenhouse gas emissions were CO_2, 11% – CH_4, 6% – N_2O and 3% – fluorinated gases. In 2014, agriculture produced 9% of the total amount of greenhouse gas emissions.

Methane (CH_4) is recognized as the second most important greenhouse gas emitted from anthropogenic sources (Wuebbles & Hayhoe, 2002; IPCC, 2006). Ruminants contribute to approximately a quarter of all anthropogenic sources of CH_4 emissions (Beauchemin et al., 2008). Feed composition is believed to be an important factor influencing CH_4 production, which can be reduced by providing higher levels of concentrate in diets (Johnson & Johnson, 1995).

The main greenhouse gases (CH_4 and CO_2) release during fermentation in the digestive system of ruminants. CH_4 production deprives the host animal of carbon resources and leads to energy loss (13.3 Mcal/kg CH_4), which worsen feeding efficiency (Johnson & Johnson, 1995). Maximizing rumen metabolic hydrogen (H) flow from CH_4 to VFA would increase the production efficiency of ruminants and reduce its environmental impact.

In the livestock sector, methane is one of the gaseous products of feed ingredients fermentation by microbes in the rumen. Ruminants produce more than 75% of methane emissions of the total greenhouse emissions. The release of methane leads to an increase in the concentration of CH_4 in the athmosphere and causes an energy loss of 6–13% of the diet (Miller et al., 2002). Many animal nutritionists try to reduce methane production because they feel responsible for the livestock sector's contribution to methane pollution of the atmosphere, as one of the pollutants used to be associated with global warming (Moss et al., 2000). Reduced methane production in the rumen is closely related to the metabolic activity of protozoa (Dohme et al., 1999). Ciliated protozoa in the rumen are in symbiosis with methane bacteria, so reducing the population of ciliated protozoa will reduce the availability of hydrogen for methane formation (Jordan et al., 2006).

Methane Formation in the Digestive System of Ruminants

Enteric methane (CH_4) is a natural end product of microbial fermentation of organic matter (OM) in the rumen and to a small extent in the large intestine. Methanogenesis is a strictly anaerobic process that involves a consortium of microorganisms in the rumen (bacteria, protozoa, archaea and fungi), with the last step being carried out by methanogenic archaea. The main products of rumen fermentation are volatile fatty acids (VFA), carbon dioxide (CO_2), hydrogen (H_2) and ammonia (Hungate, 1984). Acting as a source of CO_2, formate is also a precursor of enteric CH_4 and accounts for about 15–20% of CH_4 in the rumen (Hungate, 1970). During methanogenesis, H_2 is also used by methanogens to reduce CO_2 up to form CH_4 (Ermler et al., 1997). Along with CO_2, which has not been used by the microbes in the rumen, enteric CH_4 goes from the rumen into the atmosphere mainly by belching (Immig, 1996).

Methanogenesis is carried out by methanogenic bacteria in the rumen. Methanogens form methane from basic substrates (CO_2 and H_2). On one hand, methanogenesis helps prevent the accumulation of H_2, which may otherwise lead to a drop in pH and subsequent inhibition of many rumen microorganisms that are essential for the breakdown of nutrients, especially fiber. On the other hand, methanogenesis contributes to the loss of 6–10% of gross energy intake or 8–14% of digestible energy intake of ruminants (Cottle et al., 2011). Therefore, reducing enteric methane without altering overall rumen fermentation is one of the key roles to improve production efficiency in cattle.

The rumen contains a wide variety of prokaryotic and eukaryotic microorganisms that allow ruminants to use lignocellulose to convert non-protein nitrogen into microbial protein to obtain energy and amino acids (Newbold & Ramos-Morales, 2020). However, rumen fermentation has potential harmful consequences related to greenhouse gas emissions, excessive nitrogen released in manure and may also adversely affect the nutritional value of ruminant products. There are strategies for optimizing ruminant nutrition, identifying the key microorganisms involved and their activities that are essential for successful manipulation of rumen processes. Ration is the most obvious factor affecting the rumen microbiome and fermentation. The ban on antimicrobial growth promoters in livestock systems has led to a growing interest in the use of plant extracts to manipulate rumen processes. Plant extracts (for example saponins, polyphenolic compounds, essential oils) have shown potential to reduce methane emissions and improve nitrogen use efficiency. It has been proved that the animal can also influence the rumen microbial population both as a hereditary trait and as effect of nutrition on the structure and function of the microbial population in adult ruminants. The introduction and integration of metagenomic, transcriptomic, proteomic and metabolomic techniques offers the greatest potential to achieve a real understanding of rumen processes as studies focus on the prokaryotic population. With the increasing importance of describing the rumen microbiome through both ribosomal gene amplicon sequencing and metagenomic sequencing, there is increasing interest in linking the changes in rumen microbiome to the changes in rumen fermentation and metabolites.

Regulated Feeding and Feed Analysis

Accurate prediction of animal requirements and accurate feed analyzes are closely related to minimizing feed waste, maximizing production and reducing greenhouse gas emissions per unit of animal product. Precise feeding likely has an indirect effect on CH_4 emissions by maintaining a healthy rumen and maximizing microbial protein synthesis, which is important for improving feed efficiency and reducing CH_4 emissions.

Great progress in increasing animal productiveness and reducing CH_4 emissions from bovine animals can be achieved through proper ration composition. Garg et al. (2013) registered remarkable improvement in animal productiveness using a balanced ration feeding program on lactating cows and buffaloes in India. The evaluation of the nutritional status of the animals showed that in 71% of the animals, the protein and energy intake was higher and in 65%, the intake of Ca and P was lower than the requirements. Ration balancing has significantly improved milk yield by 2 to 14% and increased milk fat content by 0.2 to 15%. Feed conversion efficiency, nitrogen efficiency for milk production and farmers' net daily income also increased as a result of ration balancing. It is therefore of the utmost importance that science-based nutrition and feed analysis systems are gradually introduced in developing countries. This will not only have a measurable economic benefit to farmers, but will also help maximize feed production and utilization and therefore reduce greenhouse gas emissions from farm animals.

Accurate feed composition analysis is an important step in the process of precision feeding. Even in developed countries with established feed analysis networks, there is still considerable variation in feed analysis between commercial laboratories (Hristov et al., 2010a; Balthrop et al., 2011) and hence the need to standardize analytical procedures. In intensive dairy systems, daily feed monitoring, especially silage, can have a large effect on precise feeding of cows for achieving maximum productivity and profitability. Feed analysis technologies such as near-infrared reflectance spectroscopy (NIRS) have developed rapidly since the late 1980s and have been commonly used to analyze the quality and components of grain, oilseeds and forages in recent two decades. The rapidity and low cost of NIRS analysis makes it possible for producers to purchase ingredients based on quality and precisely formulate rations to meet the nutritional needs of animals to minimize over-or under-feeding.

Feeding Systems

Little research is available on the effect of feeding system (i.e. component feeding or selection of feed and concentrates versus TMR feeding) on CH_4 production.

The advantages of feeding complete rations (i.e., TMR) are more precise distribution of nutrients (Coppock, 1977) and more precise feeding of supplements and micronutrients. Nocek et al. (1986) studied rations for dairy cows with feeding forage and concentrates separately or as TMR and observed higher feed efficiency with the separate feeding system due to lower feed intake. In contrast, Maekawa et al. (2002) reported no differences in feed intake or milk production and composition of dairy cows fed ingredients such as TMR or separately. They concluded that the separate feeding increased the risk of acidosis because cows ate more of the concentrate than intended (total rumen pH tended to be lower compared to 50% forage: 50% concentrate for TMR). More research is needed to determine feeding regimes that improve feeding efficiency and lower CH_4 emissions.

There are few studies on the effect of feeding frequency on CH_4 emissions. The reason for including this discussion in relation to CH_4 emissions is that the synchronization of rumen energy and protein availability has long been proposed as a tool to optimize rumen function and maximize microbial protein synthesis. Earlier studies investigated the effect of feeding frequency in terms of optimizing carbohydrate fermentation in the rumen. Mathers & Walters (1982) for example tested feeding sheep every 2 h and concluded that even with frequent feeding there was a significant deviation from steady state in the rate of rumen carbohydrate fermentation. Methane production increased rapidly, within 30 min after feeding and then declined until the next 2-h cycle. A series of experiments in the 1980s held at the laboratory of M. Kirchgessner at the University of Munich in Germany found that frequent feeding did not improve energy intake from feed but increased CH_4 emissions when the concentrate was given more frequently and separately from forage or with rations of higher protein concentration (Muller et al., 1980; Röhrmoser et al., 1983).

Frequency of feeding did not affect CH_4 production in dairy cows according to Crompton et al. (2010). In practical conditions, animals consumed feed repeatedly during the feeding cycle, even if they were fed once a day. As a result, meal frequency did not appear to have an effect on food intake. For example, feeding first lactation dairy cows once or 4 times per day had no effect on dry matter intake (DMI) or milk production (Nocek & Braund, 1985). Similarly, Dhiman et al. (2002) reported no production benefits from feeding lactating dairy cows once or 4 times per day.

Carbohydrates Content in the Ration

There is a clear relationship between feed organic matter digestibility, concentrate or starch intake and the rumen fermentation pattern. In a meta-analysis, Bannink et al. (2008) predicted that fermentation of sugars and starch shifts rumen fermentation to propionate production when rumen pH decreases. A ration with concentrate of 72% vs. 52% resulted in a 59% increase in rumen propionate concentration and a 44% decrease in the Ac: Pr ratio in lactating dairy cows, accompanied by a depression of milk fat – 3.20 vs. 4.20%, respectively (Agle et al., 2010). Therefore, due to the strong relationship between forage: concentrate and Ac: Pr, increasing the inclusion of grain (or feeding higher starch forages such as whole crop silages) in ruminant rations should reduce CH_4 production.

Increasing concentrate in the ration reduces CH_4 emissions per unit feed intake and animal product if productivity remains the same or increases, as demonstrated in the studies of Flatt et al. (1969) and Tyrrell & Moe (1972) and supported by others such as Ferris et al. (1999), Yan et al.

(2000) etc. Some experiments with lactating dairy cows and beef cattle have shown a linear decrease in CH_4 emissions with increasing concentrate in the ration (Aguerre et al., 2011; McGeough et al., 2010). In a meta-analysis of the results of 260 experiments involving growing and lactating cattle, sheep and goats, Sauvant & Giger-Reverdin (2009) concluded that significant improvements in methane emissions could be expected after 35% to 40% incorporation of grain in the ration and this also depends on the level of food intake. Based on these data, a small to moderate variation in concentrate ratio is unlikely to affect CH_4 emissions. However, concentrates generally provide more digestible nutrients (per unit of feed) than roughage, which can increase animal productivity.

Starch is an important energy source in feeding ruminants. This carbohydrate is often used to improve rumen fermentation, optimize digestion of structural carbohydrates, and increase protein flow to the small intestine. Microbial and digestive enzymes participate in starch digestion, generating products that can positively or negatively affect animal productivity and health, depending on the starch content of the ration. Ingestion of large amounts of starch can cause ruminal acidosis. However, its rational use in the diet has a positive effect on methane emissions, and on milk yield and composition.

In North America, cattle are responsible for about 85% of greenhouse gas emissions, where weaned calves at 6 to 7 months of age are adapted to a high-grain ration for 1 to 1.5 months, then fed for 6 months and slaughtered at 14 to 16 months of age (Beauchemin et al., 2010; Basarab et al., 2012a). The high proportion of CH_4 associated with the cow herd is due to the consumption of a higher proportion of the feed in the calf-beef system, the inherent low biological efficiency of the beef cow and the very high proportion of the cow ration as canned feed, pastures, and crop residues rather than concentrates (Allen et al., 1992; Verge et al., 2008; Capper, 2011). The effect of roughage versus concentrate rations on increasing CH_4 emissions in ruminant systems is well known (Johnson & Johnson, 1995; Beauchemin & McGinn, 2005; Beauchemin et al., 2008). Reducing daily CH_4 emissions by increasing the content of the grain component of the main and final rations and increasing the starch content of grain and corn silages can be an effective method of limiting them in cattle fattening systems (Beauchemin & McGinn, 2005; Beauchemin et al., 2009).

Pasture Management

Pasture management can be an important practice to reduce CH_4. DeRamus et al. (2003) reported that intensively managed grazing offered more efficient use of pasture forage crops and more efficient conversion of forage to meat and milk, resulting in a 22% reduction in projected annual CH_4 emissions from beef cattle. In other studies, however, the level of rearing of heifers on pasture had no effect on CH_4 emissions (Pinares-Patiño et al., 2007).

W. de Souza Filho et al. (2019) evaluated the effect of different intensities of bull grazing on animal productivity, grass intake and CH_4 emissions in the growing period in an integrated soybean and beef cattle farming system in southern Brazil. Treatments consisted of different grazing intensities determined by target grass heights (10, 20, 30 and 40 cm) of mixed black oat (*Avena strigosa* Schreb.) and Italian ryegrass (*Lolium multiflorum* Lam.) pastures. Grazing management affects grass utilization and therefore animal productivity and CH_4 emissions. At individual level, CH_4 emissions and animal performance showed optimal values when pasture height is managed in the range of 23–30 cm. At farm level, a positive linear effect of grazing intensity on animal live weight gain per hectare and the associated environmental cost of land use was found. Live weight gain increased by 90 g ha^{-1} day^{-1} and CH_4 emissions increased by 500 g CO_2 eq ha^{-1} day^{-1} for each cm of target reduction in grass height. Considering that most producers use pastures with very low grass height, the large-scale use of pastures within 23–30 cm in southern Brazil has the potential to achieve a 13–14% reduction in GHG emissions from the entire agricultural sector and 22– 25% of the enteric fermentation target from the livestock sector promised by the Brazilian government in the Paris Agreement. This means that adequate grazing management is the key strategy to improve livestock productivity and reduce the environmental impact of cattle.

Methane reduction in cows can be achieved by improving the digestibility of annual and perennial forages, through grazing management, increasing the composition of leguminous plants and using species containing secondary metabolites such as tannins or saponins that affect methanogenesis in the rumen (Beauchemin et al., 2008; 2009). The use of varieties of perennial ryegrass with a high sugar content (*Lolium multiflorum* L.) and the cultivation of alfalfa (*Medicago sativa* L.) and clover (*Trifolium repens* L.) can help to improve forage digestibility, although increasing the content of legumes may prove difficult in the long term (Dewhurst et al., 2009).

There is interest in so-called “high sugar grasses” (HSG; grasses with increased concentrations of water-soluble carbohydrates) as a means of reducing the environmental impact of animals. According to Parsons et al. (2011) the prospect of reducing CH_4 emissions, whether per hectare or per unit of energy input or animal product, with HSG is uncertain. According to a simulation model, HSG may actually increase CH_4 emissions, but this depends on ration composition (e.g. if sugars replace CP, NDF, or both), DMI, and the units chosen to express CH_4 emissions (Ellis et al., 2012b). Staerfl et al. (2012) reported no effect of HSG on CH_4 emissions in dairy cows.

Hammond et al. (2011) reported no differences in CH_4 production (23.0 g/kg DMI) measured in sheep fed either fresh ryegrass or white clover, despite a two times higher difference in the ratio of easy fermentable carbohydrate: NDF. Sun et al. (2011) also reported similar CH_4 emissions from sheep fed either fresh chicory or ryegrass (23.3 g/kg DMI), which differed significantly in chemical composition. This is even more evident when comparing data from observations of sheep fed clover or chicory (above mentioned) with previous reports by Waghorn et al. (2002) showing that sheep fed white clover, chicory, Lotus pedunculatus and other legumes had much lower CH_4 yields (12 to 17 g CH_4/kg DMI) compared to sheep fed ryegrass (21 g CH_4/kg DMI).

In the Midwest of the United States, the most common pasture composition is a mixture of alfalfa and cocksfoot grass (*Dactylis glomerata*), which has a relatively high nutritional value. In a meta-analysis of CH_4 production from different forages, Archimède et al. (2011) indicated that cool-season forages, typical for Midwestern United States, produced lower CH_4 emissions in the intestinies than warm-season grasses per unit of DMI (dry matter intake). Although there is inconsistency in research results, the inclusion of legumes in pastures can reduce CH_4 emissions through increased dry matter intake and rumen passage rate, reduced fiber content and improved animal productivity (Beauchemin et al., 2008; Hristov, 2013).

Silages – Influence of their Composition on Methane Production

The whole silage production process is divided into four consecutive biological processes: (1) hydrolyzate of complex organic molecules to soluble monomers; (2) acidogenesis or fermentation is the process by which soluble monomers from hydrolysis are converted to alcohols, volatile fatty acids (VFAs), namely acetic, propionic and butyric acids, and CO_2 and hydrogen; (3) acetogenesis is the stage where several of the pre-produced VFAs and alcohols are converted to acetate, which is a major molecule used by methanogens as a substrate; and (4) methanogenesis is the final step in which various archaea can use acetate, CO_2, and hydrogen to produce methane as an end product.

A comprehensive review of the different aspects of feeding corn silages versus legume silages and grass silages for lactating dairy cows is provided by Dewhurst (2012). Based on this review, the lower fiber content and higher passage rate of legumes appears to reduce CH_4 production compared to grasses, which has been reported in earlier studies (McCaughey et al., 1999). Dewhurst (2012) also concluded that corn silage-based rations are expected to increase DMI and milk production in dairy cows; similar trends, although less convincing, have been reported for legume versus grass silages. The author suggests that more research is needed to clarify the effect of different silages on CH_4 production, especially in the case of legume silages, which have the added benefit of reducing the carbon footprint of the production system by replacing inorganic nitrogen fertilizers. The potential increase in the total carbon footprint due to land use change and increased fertilizer input associated with corn silage production compared to permanent pasture must also be considered (Vellinga & Hoving, 2011; Van Middelaar et al., 2012).

Some studies have shown reduced CH_4 production in corn versus grass silages. A UK Department for Environment, Food and Rural Affairs Report (DEFRA, 2010) showed a 13% and 6% reduction in CH_4 per unit of dry matter intake and per unit of milk production, respectively, when feeding 25:75 grass silage: corn silage ration compared to a 75:25 grass silage: corn silage ration. Urinary N excretion also tended to be reduced with a ration higher in corn silage. The ration high in corn silage increased milk yield (by about 4%, which was a result of increased forage intake), although the difference was not statistically significant. Another comparison of corn versus grass silage reported similar results (Doreau et al., 2012).

Grass silage is usually the main component in cow rations in the Scandinavian countries. Maturity at harvesting is the main factor affecting the nutritional value of silage due to its effect on digestibility. Digestibility is the most important factor affecting silage dry matter intake (Huhtanen et al., 2007) and therefore nutrient supply. Although CH_4 release generally increases as forage digestibility improves (Blaxter & Clapperton, 1965; Ramin & Huhtanen, 2013), when expressed per unit of digestible energy it decreases.

Feed quality, forage processing and precision feeding have the best prospects as a means of managing methane emissions (Gerber et al., 2013). High fiber content forages, such as plantation wastes not only reduce feed utilization efficiency (Steinfeld et al., 2006), but also increase methane (CH_4) production.

Intensive ruminant production systems encourage the inclusion of large amounts of grains or easily degradable byproducts in the ration to maintain high milk yield or high average daily gain (Zebeli et al., 2012). Although these feeding practices appear to improve production in the short term, they do not deal with the physiology of cattle digestion. The most important consequence is a damaged ecosystem of the gastrointestinal tract with major consequences for the intestines. Visibly healthy animals suffer from subclinical and chronic disorders and have lower production efficiency.

Conclusion

This review provides information on the influence of the ration composition, botanical composition of the pasture grass, the type and quality of the silages on the release of methane emissions in the rearing of ruminants. Modeling rumen fermentation is the most important method to optimize feed utilization, ensure maximum microbial protein synthesis, increase productivity and limit released methane emissions as a result of the digestion process.

There is lack of research on the effect of feeding systems and feeding regimes, as well as the extent of methane emissions release from the digestion of sheep, goats, buffalo and other ruminants.

Strategies to reduce methane emissions are feeding strategies (i.e. concentrate ratio, feed quality) and rumen modification strategies (defaunation, ionophores, oils, dicarboxylic acids, methane analogs) according to Iqbal et al. (2008). Many of these strategies cannot ensure long-term effects due to possible microbial adaptation. Some methods are expensive, while some can harm animal health and limit digestion in the rumen. On account of these limitations, there is a need for new approaches to mitigate methane production in cattle. Among the various strategies studied to reduce rumen methanogenesis is the use of direct feeding microbes (DFM). From a practical point of view, the concept of DFM is familiar to farmers as it is already used to increase animal productivity and improve animal health. Ruminants are the largest source of CH_4 emissions from agriculture, globally contributing about 40% of emissions produced by human-related activities (Steinfeld et al., 2006).

Strategies to reduce greenhouse gases must be evaluated at farm level. Interventions aiming to reduce the release of one greenhouse gas may accelerate the loss of another greenhouse gas (Tamminga et al., 2007). Since most of the models currently in use are empirical in nature, the use of dynamic mechanic models is recommended to predict greenhouse gas losses and to evaluate mitigation strategies. Many recent studies have been based on short-term *in vitro* experiments. Before the results of such experiments can be applied in practice, they must be thoroughly evaluated in long-term *in vivo* experiments.

Feeding strategies need to be developed, which should provide minimization of ruminant energy loss and leading to increased productivity by reducing the number or activity of methanogens. Although methane production can be reduced by current strategies, due to the variety of adaptive mechanisms, they may only be effective for a short period of time. Therefore, further research is needed to study the effect of rations as well as rumen fermentation inhibitors with particular attention to methane production and changes in methanogenic microorganisms.

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