Challenges and strategies for reducing enteric methane emissions in sustainable animal production

Desafios e estratégias para a redução das emissões de metano entérico na produção animal sustentável

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ABSTRACT

Methane emissions in ruminants are influenced by various factors, including feed type and rumen microbial population. Mitigation strategies involve nutritional interventions, soil and plant management, and synergistic use of different forages. Effective management practices in pasture-based systems, such as monitoring forage mass and adjusting stocking rates, optimize intake and forage quality, resulting in reduced emissions and improved sustainability. Dry matter intake, diet profile, and quality significantly impact methane production, and interactions between microorganisms and ruminal ecology also influence emissions. While more efficient animals with lower feed intake may not necessarily emit less methane, understanding the differences in methanogenic profiles between efficient and inefficient animals is crucial and requires further investigation. Animal genotype is another factor influencing emissions. Comprehensive research considering diet, production, and farming systems is needed to develop effective strategies and achieve significant methane emission reductions.

Keywords: Climate change; Concentrate; Forage; Management; Ruminant
RESUMO
As emissões de metano em ruminantes são influenciadas por diversos fatores, incluindo o tipo de alimento e a população microbiana do rúmen. Estratégias para mitigação envolvem intervenções nutricionais, manejo do solo e das plantas, e o uso sinérgico de diferentes forragens. Práticas de manejo eficazes em sistemas baseados em pastagens, como monitoramento da massa de forragem e ajuste das taxas de lotação, otimizam a ingestão e a qualidade da forragem, resultando em emissões reduzidas e sustentabilidade. O consumo de matéria seca, o perfil e a qualidade da dieta têm impacto significativo na produção de metano, e as interações entre microrganismos e a ecologia ruminal também influenciam as emissões. Embora animais mais eficientes com menor consumo de alimentos não necessariamente emitam menos metano, entender as diferenças nos perfis metanogênicos entre animais eficientes e ineficientes é crucial e requer investigação adicional. O genótipo animal também é outro fator que influencia nas emissões. Pesquisas abrangentes considerando dieta, produção e sistemas de criação são necessárias para desenvolver estratégias eficazes e alcançar reduções significativas nas emissões de metano.

Palavras-chave: Concentrado; Forragem; Manejo; Mudanças climáticas; Ruminante

INTRODUCTION

In the past two decades, technological advancements have revolutionized the livestock sector, particularly in the field of bovine farming, leading to increased animal productivity. However, this progress has come with its own set of challenges. In 2020, global methane emissions from enteric fermentation accounted for 68.3%, with cattle contributing to approximately 90% of this total (FAO, 2023). Given the significance of cattle farming and the raised concerns surrounding the livestock industry, it has become an urgent necessity to control and reduce methane emissions, particularly from cattle. This concern is justified as carbon dioxide ($CO_2$) and methane ($CH_4$) are two greenhouse gases (GHGs) produced during the digestive process of ruminant animals.

These criticisms, accompanied by significant concerns, emerged in 1988 with the establishment of the Intergovernmental Panel on Climate Change (IPCC) and the publication of its initial reports. These documents quantitatively exposed the impact of human activities on global warming, and unfortunately, the findings were far from optimistic.

Cattle have emerged as a central focus of global warming concerns within the livestock sector. This prompted the United Nations (UN) to officially prioritize sustainability in 1992. Subsequently, extensive efforts have been dedicated to education, research, and extension activities aimed at identifying sustainable pathways and implementing effective actions. The development of innovative technologies and the establishment of strategic management approaches have demonstrated considerable potential in reducing greenhouse gas (GHG) emissions from cattle, thus playing a vital role in mitigating the detrimental impacts on the environment and climate.
To comprehend the intricate relationship between livestock farming and climate change, and the nutritional challenges it poses for quality production, it is crucial to acknowledge that economically important ruminant species naturally produce CO\textsubscript{2} and CH\textsubscript{4} as byproducts of anaerobic fermentation within their digestive systems.

Quantitatively, the latest data indicates that beef cattle can produce between 22 to 102 kg of CH\textsubscript{4} per day, with considerable variation attributed to individual animal characteristics, age, farming systems, and nutritional management (DeRAMUS et al., 2003; BEAUCHEMIN and McGINN, 2005; VELAZCO et al., 2014; COTTLE et al., 2015; REBELO et al., 2019; VELAZCO et al., 2017; MANAFIAZAR et al., 2020; MÉO-FILHO et al., 2020). In the case of dairy cows, emissions can range from 99 to 170 kg of CH\textsubscript{4} per year (ULYATT et al., 2002; HINDRICHSEN et al., 2006; JIAO et al., 2014; MUÑOZ et al., 2019; OH et al., 2019; DENNINGER et al., 2020; MOATE et al., 2020).

Apart from the environmental impact, CH\textsubscript{4} production represents an energy loss for the animals, ranging between 2 and 15% (JOHNSON and JOHNSON, 1995; ROSSI et al., 2001; REBELO et al., 2019). The efficiency of energy utilization from feed, as well as the intensity of CH\textsubscript{4} emissions, depend on various factors, including individual animal characteristics (including breed and within-species variations) and the type, quality, and quantity of feed provided.

It is essential to assess technologies that effectively mitigate CH\textsubscript{4} production and enhance feed efficiency through an integrated approach. It is noteworthy that isolated strategies may yield limited outcomes in reducing methane emissions. However, when implemented in conjunction with sustainable nutritional and management practices, they synergistically contribute to carbon sequestration and significantly diminish the livestock sector's environmental footprint in relation to climate change.

**REVISION**

**A Brief account on methane and its synthesis in ruminants**

Methane (CH\textsubscript{4}) assumes a significant role as the primary greenhouse gas (GHG) emitted by ruminants. While carbon dioxide (CO\textsubscript{2}) is the most abundant anthropogenic GHG, a single molecule of CH\textsubscript{4} possesses a 25-fold greater capacity to retain heat in the atmosphere. From an environmental and climate change perspective, it is essential to prioritize our efforts towards strategies that effectively control and reduce CH\textsubscript{4} emissions. This is particularly important given the extensive data sources from the Intergovernmental Panel on Climate Change (IPCC), which consistently demonstrates the remarkable contribution of livestock farming to anthropogenic emissions originating from agricultural activities.
It is important to emphasize that the term "livestock farming" encompasses a complex system involving interactions between soil, plants, and animals. Within each component, there is room for the implementation of strategies with varying efficiency levels, yet all converge towards a common purpose: mitigation of greenhouse gas emissions. Therefore, it is imperative to adopt holistic approaches that consider the integration of effective measures at all stages of the agricultural system, aiming to reduce the environmental impacts associated with livestock activities and contribute to achieving global sustainability goals.

From a nutritional standpoint, considering the animal itself, the production of CH₄ is deemed undesirable as it represents a loss of energy derived from the consumed diet (JOHNSON and JOHNSON, 1995; ROSSI et al., 2001; SUBEPANG et al., 2019; CONGIO et al., 2021). However, it is important to highlight that CH₄ production plays a crucial role in maintaining the environmental conditions in the rumen, facilitating the activities of the ruminal microbiome (PEREIRA et al., 2022). This CH₄ production is an acquired characteristic throughout the evolution of ruminant species.

To understand the origin of CH₄, it is necessary to clarify that ruminant herbivores, such as cattle, naturally produce this gas through ruminal fermentation, buffalo, sheep, and goats naturally produce this gas through ruminal fermentation. This process occurs under anaerobic conditions and is promoted by microorganisms with an affinity for carbohydrates and proteins, which are converted into useful products such as short-chain fatty acids (SCFAs), microbial protein, ammonia, and vitamins. As part of this process, microorganisms from the Archaea domain, predominantly belonging to the phylum *Euryarchaeota* and representing approximately 3 to 5% of the microbial population, are responsible for CH₄ production, which is subsequently released into the environment through eructation (HENDERSON et al., 2015; MOISSL-EICHINGER et al., 2018; MALIK et al., 2021).

The anaerobic conversion of organic matter into CH₄ involves a complex interaction among ruminal microorganisms, with the final step carried out by methanogenic archaea. In this process, microorganisms such as bacteria, protozoa, and fungi hydrolyze monomeric units of carbohydrates and proteins from the diet, which are metabolized to produce SCFAs, ammonia, H₂, and CO₂. In order for CH₄ to be formed, methanogenic archaea remove H₂ from the environment and reduce CO₂ (McALLISTER et al., 1996; MOISSL-EICHINGER et al., 2018; PEREIRA et al., 2022). The utilization of hydrogen in the rumen is necessary as high concentrations inhibit the reoxidation of NADH and lead to the accumulation of lactate or ethanol, resulting in a decrease in pH values. Therefore, CH₄ production by methanogens is an essential process as it serves as a hydrogen sink, maintaining ruminal balance and facilitating the growth of microorganisms that degrade dietary fiber (JOHNSON and JOHNSON, 1995). For this reason, the manipulation of H₂ in the rumen is a key factor in controlling CH₄ production, which can be mitigated through various means including diet type and intake, the use of alternative hydrogen sources.
sinks, and products that directly inhibit methanogenesis (KUMAR et al., 2009; JAFARI et al., 2019; ZHOU et al., 2020; ORZUNA-ORZUNA et al., 2021).

Factors Affecting Methane Production in Ruminants

The emission of CH$_4$ from ruminal fermentation depends on factors such as feed intake, diet type, feed processing, feed digestibility, animal-related characteristics, and manipulation of ruminal microbiota (JOHNSON and JOHNSON, 1995; McALLISTER et al., 1996; AUFFRET et al., 2018; JEYANATHAN et al., 2019; SUBEPANG et al., 2019; CONGIO et al., 2021). These factors are interconnected and can impact enteric CH$_4$ production in various dimensions.

Dietary Intake and Characteristics Impacting the Animal

Dry matter intake (DMI) is an important factor influencing CH$_4$ emissions, as it is directly related to the availability of substrate for ruminal fermentation and, consequently, hydrogen production for methanogenesis (BEAUCHEMIN and McGINN, 2006; GRAINGER et al., 2007). However, assessing intake alone is not sufficient, as the dietary profile and quality can affect the digestive dynamics (HAMMOND et al., 2014; CONGIO et al., 2021). Moreover, interactions between microorganisms, their byproducts, and ruminal ecology also play a significant role, especially in animals with high and low residual intakes (SHABAT et al., 2016; XIE et al., 2022).

Studies such as Hammond et al. (2014) have shown that increased intake reduces methane emissions per unit of dry matter (CH$_4$/kg DM), but this effect is a result of higher rates of solid and liquid passage, which ultimately reduce dry matter digestibility. This behavior has been observed across ruminant species and is influenced by the nutritional characteristics of diets (JOHNSON and JOHNSON, 1995; YAN et al., 2010; HAMMOND et al., 2013; MALIK et al., 2021).

According to Flay et al. (2019), the question raised was whether more efficient animals would indeed emit less methane in relation to intake. The authors found that DMI was lower in animals with lower residual feed intake (RFI), but when CH$_4$ production per day or per body weight was compared, it was the same regardless of the higher or lower feed efficiency in dairy cows from different genetic groups. When expressing CH$_4$ emissions in relation to DMI (g/kg DM), the more efficient animals, regardless of genetic group, produced more CH$_4$, which, according to the authors, was due to higher digestibility of both dry matter and fiber. Although there is a positive relationship between more efficient animals and reduced CH$_4$ production, the
divergence in the literature regarding the findings points to three complex factors: the genetic
diversity of the ruminant population, the different production systems worldwide, and the wide
variation in diet profiles and ingredients (McDONNELL et al., 2016; OLIVEIRA et al., 2018;
MANAFIAZAR et al., 2020; ARCE-RECRNOS et al., 2022). Additionally, different techniques
for measuring CH₄ production contribute to these factors.

Basarab et al. (2013), in an extensive review, highlighted the differences between animals
selected for feed efficiency, specifically residual feed intake (RFI), as an indirect measure to
assess CH₄ emissions in ruminants. Regarding ingestive behavior, the authors found that efficient
and inefficient animals exhibit distinct diurnal patterns of feeding behavior. Efficient animals
have shorter feeding durations, lower feeding frequencies, and lower food consumption. Inefficient animals have 14 to 22% more daily feeding events than efficient animals, thus
spending 2 to 5% more energy on feeding activities. Furthermore, according to Lassey (2007),
methanogenesis does not occur homogeneously throughout the day and is influenced by numerous
factors related to feed and animals, with the latter being the most important cause of variations in
the efficiency of energy utilization and the subsequent amounts of CH₄ produced in the rumen
(CONGIO et al., 2021).

This evidence highlights the correlation between rumen bacterial profiles and variations
in feed efficiency among animals (GUAN et al., 2008; CARBERRY et al., 2012; JAMI et al.,
2014; McGOVER et al., 2020; XIE et al., 2022). In the study conducted by Guan et al. (2008),
the profiles generated for efficient and inefficient animals were different, indicating that the
rumen microbial population is related to feed efficiency. Xie et al. (2022) observed that the rumen
microbiota of low-efficiency dairy cows possesses stronger abilities to degrade carbohydrates and
produce methane.

Differences in methanogenic profiles have also been studied and may be associated with
feed efficiency in cattle. In inefficient animals, the proportions of Methanosphaera stadtmanae
(which utilizes methanol for CH₄ synthesis) and Methanobrevibacter sp. AbM4 (related to
Methanobrevibacter smithii, a species that utilizes acetate for CH₄ production) were higher
compared to efficient animals (ZHOU et al., 2009). Although methane production was not
quantified in these studies, these results suggest the existence of diversity in methanogenic
profiles between inefficient and efficient animals, indicating the need for further investigation.

Furthermore, methane emissions are also related to animal genotype. Primavesi et al.
(2004) evaluated lactating dairy cattle grazing tropical grasses in the Brazilian Cerrado region and
found that Holstein animals emitted less methane (42 to 46 g CH₄/kg digestible dry matter intake)
compared to crossbred animals of Holstein x Zebu (56 to 69 g CH₄/kg digestible dry matter
intake). Similarly, Pedreira et al. (2009) observed variations in daily enteric methane emissions
between crossbred cows (¾ Holstein x ¼ Zebu) and Holstein cows.
These studies indicate that both methanogenic profiles and animal genotype can influence methane emissions, highlighting their importance in understanding and mitigating greenhouse gas emissions in livestock production. However, further research is needed to gain a comprehensive understanding of the underlying mechanisms and to establish effective methane reduction strategies.

Despite the significant correlation between feed intake, animal characteristics, and methane production, further investigation is necessary to comprehensively explore the dynamics and nutritional parameters influenced by diet composition, animal attributes, production levels, farming systems, and other relevant factors. While these factors are interconnected and require adjustments, the increase in productivity can offset methane emissions, establishing a balance in the system. The challenge for nutritionists is to effectively mitigate ruminant contributions to methane, irrespective of the metric employed. Although recent IPCC reports acknowledge the efforts and benefits of diverse nutritional, management, and animal selection strategies, practical outcomes rely on raw data rather than expressions relative to animal production levels. To effectively reduce the livestock sector's environmental impact, a holistic approach that encompasses the soil-plant-animal system should be embraced, transcending a narrow focus on individual animals.

The influence of forage and the use of concentrated feeds

Based on their research, Kurihara et al. (1999) highlighted the classification of feedstuffs according to their decreasing methane emissions: tropical forages, temperate forages, and grain-based diets. These authors observed that roughage-based diets resulted in energy losses in the form of methane of approximately 10.9%, whereas grain-based diets accounted for only 6.7%.

In tropical regions, forages are the predominant constituents of ruminant diets, exhibiting substantial compositional variability and exerting a notable influence on diet digestibility. The utilization of forages in ruminant nutrition necessitates the implementation of diverse strategies, encompassing nutritional interventions as well as soil and plant management, to effectively mitigate methane emissions.

Forages can be classified into two categories, C3 and C4 plants, based on their photosynthetic metabolic pathway. In the case of grasses, they are classified as either tropical (utilizing the C4 pathway) or temperate (utilizing the C3 pathway). It is worth noting that all tropical leguminous forages exhibit the characteristic of utilizing the C3 metabolic pathway during photosynthesis.

Ruminants fed with C4 grasses exhibit higher CH$_4$ emissions compared to those fed with C3 grasses. Archimède et al. (2011) conducted a meta-analysis to investigate CH$_4$ production differences among C4 grasses, C3 grasses, and legumes. The authors found no difference in CH$_4$ production between C3 grasses and legumes. However, among C4 grasses, CH$_4$ production (per
kg of organic matter intake) was 17% higher compared to animals fed with C3 grasses, primarily due to the higher fiber content in C4 grasses. It is important to note that the superior quality of grasses, along with the implementation of nutritional strategies such as supplementation, can minimize the potential for CH₄ production (ZUBIETA et al., 2021). Benchaar et al. (2001) observed that the utilization of more digestible forage resulted in a 15 to 21% reduction in CH₄ production. Therefore, CH₄ production can vary among grasses and legumes, as well as their maturity stages. However, adopting soil and plant management practices, improving the fibrous composition and digestibility of forage, can contribute to lower CH₄ production (BERHANU et al., 2019).

Legumes, apart from their differences in carbohydrate composition (fiber) and crude protein, also exhibit a distinct fibrous constitution due to lignin and secondary metabolites such as tannins, which significantly influence animal CH₄ production. These metabolites have the capacity to modify the process of methanogenesis in the ruminal environment (BERHANU et al., 2019; ORZUNA-ORZUNA et al., 2021; ROSSI et al., 2021; WANG et al., 2023). The combined utilization of grasses and legumes serves not only to reduce reliance on a single forage species but also enhances animal performance and contributes to CH₄ reduction. Additionally, this practice ensures a continuous nitrogen supply to the pasture and enables greater biomass production, thereby enhancing the system’s carbon sequestration capacity (MARTUSCELLO et al., 2011; RIBEIRO et al., 2011; BODDEY et al., 2020).

In pasture-based ruminant production systems, key strategies such as monitoring pre-grazing forage mass, adjusting stocking rates through increased defoliation frequency (continuous or rotational), and intensification via supplementation are essential. These strategies help to reduce the forage harvest interval and modify pasture structure, resulting in improved forage quality, animal intake, performance, decreased energy loss as CH₄, and consequently, lower enteric CH₄ emissions (PEDREIRA et al., 2009; COLE et al., 2020; RUGGIERI et al., 2020; CONGIO et al., 2021; JAYASINGHE et al., 2022; MACHADO et al., 2022). Therefore, appropriate management practices and the implementation of intensified production strategies optimize pasture utilization and lead to increased productivity and sustainability outcomes.

There is a clear relationship between organic matter digestibility, intake of concentrated feed or starch, and ruminal fermentation patterns. Unlike diets rich in forage, diets based on non-fiber carbohydrates biochemically promote higher propionate production, lower H₂ release in the rumen, and consequently, lower CH₄ production per unit of digested feed (YAN et al., 2000; HANSEN et al., 2022; WANG et al., 2023).

In general, the inclusion of concentrated feed in ruminant diets reduces enteric CH₄ emissions, particularly when the inclusion level exceeds 35 to 40% (BEAUCHEMIN and McGINN, 2005; SAUVANT and GIGER-REVERDIN, 2007; AGUERRE et al., 2011). This is because these diets typically contain high amounts of corn (dry, rehydrated, fermented) or whole
corn grain, and the introduction of large quantities of starch into the rumen can influence CH\textsubscript{4} production. It can either inhibit the activity of methanogenic microorganisms due to low pH or affect starch degradation or passage rate.

In some diets, concentrates are abundant, but their richness is not necessarily attributed to starch. Other carbohydrate sources can substitute part or all of the corn ingredient, bringing in diverse carbohydrate types. The varying rates of degradation for these carbohydrates have significant implications for methane production. Diets comprising slowly degradable carbohydrates have a higher chance of bypassing the rumen, leading to reduced CH\textsubscript{4} production. Conversely, highly degradable carbohydrates such as sucrose and pectin contribute to increased CH\textsubscript{4} production (SUN et al., 2022). Therefore, understanding the carbohydrate profile of diets, including both concentrated feeds and wet forages, as well as their degradation rates, plays a critical role in managing CH\textsubscript{4} production.

Pasture-based intensive systems, such as rearing, fattening, and integrated crop-livestock/forestry systems, involve proper pasture management and increased concentrate supplementation. This combined nutritional approach is a strategy that contributes to mitigating the impact of livestock farming on climate change (VILELA et al., 2011; SOUZA FILHO et al., 2019; CONGIO et al., 2021).

**HIGHLIGHTS**

Methane emissions from ruminants are influenced by multiple factors, including the quantity and quality of feed, intake, fermentation, production of short-chain fatty acids, animal energy efficiency, and the production system. Introducing more efficient animals into the system can contribute to methane reduction by optimizing feed energy utilization and increasing animal productivity.

The quality of the diet plays a significant role in methane emissions, with forage-based diets having a higher potential for methane production per unit of digested feed. Conversely, diets with higher grain and non-fiber carbohydrate content can help reduce methane emissions. Enhancing the quality of the feed provided to animals is crucial in all production systems, as more digestible feed allows for a decrease in methane emissions per unit of digested feed while simultaneously increasing animal productivity.

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