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Impact of Rumen Methanogenesis on Climate Change: A Review

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Abstract—*The aim of this review is to summarize the current knowledge of livestock and climate change particularly methane (CH_4) production from ruminants. The objectives are to assess the scope of livestock and climate change, enteric methane production, identify the factors affecting CH_4 production and mitigation strategies to reduce methane emission. Methane is a potent greenhouse gas which has a global warming potential 23 times that of carbon dioxide. Agriculture contributes 27% in emission of green house gas (GHG) and out of this, livestock is responsible for the largest part at nearly 80-92% of total agricultural GHG emissions. This is specifically due to methane emission from enteric fermentation and manure handling. Many factors influence ruminants methane production, including type and quality of feeds, level of feed intake, animal size, energy consumption, growth rate, level of production, environmental temperature and humidity. The methane emission values in dairy cows range from 151 to 497 g/day, lactating cows 354 g/day than dry cows 269 g/day and heifers 223 g/day. Dairy ewe emits 8.4 kg/head annually. Holstein emitted 299 g/day CH_4 more than the crossbred cow 264 g/day. The amount of CH_4 emission by heifers grazing on fertilized pasture was higher 223 g/day than heifers grazed on unfertilized pasture 179 g/day. Beef cattle emit 161-323 g/day and Sheep 22-25 g/day. The annual emissions from the pens and storage pond at dairy farm approaches 120 kg/cow. The five methane measuring techniques from the rumen of ruminants are Respiration calorimeter, Ventilated hood, Facemask, Backpack and Tracer gas techniques. The needful methane mitigation strategies are supplying protein rich diet, vaccine and antibiotics treatment, capturing manure and convert into natural gas and improving the genetic makeup of livestock that ensures both economic benefit and environmental health.*

Keywords*: Climate, Methane, Measurement Technique, Mitigation Strategies, Ruminant*

1. INTRODUCTION

The growth of global population and increased purchasing power has advocated a rapid increase in the need for food from animal sources. The world population will have reached 9 billion by 2050, while the demand for milk and meat products is expected to increase to 1.043 million tons and 465 million tons, respectively [16]. Despite the importance of agriculture in food production and revenue, there is a lot of debates about the environmental impact of livestock and agricultural activities in relation to climate change. Agriculture is responsible for around 27% of global anthropogenic greenhouse gas (GHG) emissions except land use change [17], [1] and [2]. Livestock is recognized as a potential victim of green house gas emission and climate change [3] and [4]. Livestock is assumed to be liable for the largest part at nearly 80-92% of total agricultural GHG emissions [19]. This is particularly due to methane (CH_4) emissions from enteric fermentation and manure handling [5] and [7]. Methane is the major GHG produced from enteric fermentation during the normal digestive process of ruminants [8] and [9]. It is relevant to note that production of greenhouse gases from animals and their impact on climate changes are a major concern of today [10] and [11]. Cattle are considered to cause an increase in emissions with about 4.6 Gt (gigatonnes) of CO_2, representing 65% of sector emissions. Average emission intensities are 2.8 kg CO_2 per kg of fat and 46.2 kg CO_2 per kg of carcass weight for beef [12]. Significant quantities of CH_4 can also arise from microbial fermentation of amino acids, the end products of which are ammonia, volatile fatty acids and CH_4. Methane accounts for a significant energy loss to the ruminant animal, amounting to about 8% of gross energy at maintenance level of intake. Increased understanding and improved quantification of CH_4 production in the rumen has implications not only for global environmental protection but also for efficient animal production. Livestock CH_4 emissions have been measured using respiration calorimeter systems such as whole body chambers, head boxes, ventilated hoods, Backpack, face mask and tracer gas technique [30].

2. METHANE

Methane is among the three main greenhouse gases, together with CO_2 and nitrous oxide (N_2O), its global warming potential is 23 fold than of CO_2. CH_4 also affects the degradation of the ozone layer [3] and [13]. Men are responsible for about two third of the total global CH_4 emission called total anthropogenic methane [14]. Agriculture accounts for 47-56% of total anthropogenic CH_4 emissions [1], [15]. Of this amount may be 12-37% of enteric origin [8], [18]. However, amount GHG percentages originating from enteric fermentation of ruminants often differ. While [20] indicated 87%, [21] inform that enteric CH_4 was the largest contributing source of GHG judging for 63% of total emissions. Study [8] indicated enteric CH_4 was 12% of the global, 19% of the anthropogenic, and 36% of the agricultural CH_4 emissions. Within the beef production cycle, the cow-calf system counted for about 80% of total GHG emissions and the feedlot system for about 20%. About 84% of enteric methane was from the cow-calf operation, mostly from mature cows [21]. 10-15% of the total amount, which ruminants emitted, is formed from manure handling and storage [22], [24]. Reference [25] reviewed literature sources showed that the global enteric methane source was estimated in absolute values at 74 Tg (teragrams) for 1982 year of that 74% were supplied by cattle and 8-9% by each of buffalo and sheep. According to [25], it was 84 Tg for 1990 year, 80 Tg for 1994 year, and 71 Tg, including 44 Tg from grassland derived feed for year of 2003. There are a lot of differences in emission intensity between beef produced from dairy herds and from specialized beef herds. The related emissions amount to 1.1 Gt, are representing 46% or 43% of the total emissions in dairy and beef herds, respectively [12]. Human related methane emissions are mainly produced by domestic ruminants, carbon mines, rice fields, waste management, and natural gas usage [14]. In developing or developed countries where agricultural activities are a major component of economy the contribution of CH_4 to the total anthropogenic greenhouse gas emissions is comparable to the CO_2 emission. On the other hand, methane from natural sources are mainly constituted by wetlands, including shallow marine water [26], [27]. Minor contributions come from non-domestic ruminants and termites [14]. Recent studies suggested that plants emit CH_4 directly as a consequence of metabolic processes [14], [28]. Among animals, ruminants are the primary emitters of CH_4. Their rumen has a continuous fermentation system. The rumen occupies about 80% of the total stomach capacity and its volume is about 100-150 litre in cattle and 15 litre in sheep [15]. Methane production obtained principally from microbial fermentation of hydrolyzed carbohydrates and is considered as an energy loss for the host [6], [29]. Many factors influence ruminant CH_4 production, including level of intake, type and quality of feeds, energy consumption, animal size, growth rate, level of production, genetics, and environmental temperature [15], [29].

3. METHANE OF RUMINAL ORIGIN

Methane is an inflammable, colorless, odorless and tasteless gas that is the primary element of natural gas. It has been reported that methane is lighter than air and has a specific gravity of 0.554, density 0.717 kg/m^{-3}, melting point -187˚C (86 K), boiling point -161˚C (112 K). This gas is poorly soluble in water, but soluble in organic solvents. Naturally occurring methane is mainly produced by the process of methanogenesis [35]. Enteric methane is a by-product of ruminant digestion mainly produced by methanogenic microorganism Archaea in a process called methanogenesis. The rate and type of fermentation is influenced by animal factors such as regurgitation, chewing, salivation and digesta kinetics [42], [43]. Cattle produced about 7 and 9 times as much CH_4 than sheep and goats, respectively. Enteric methane that produce mainly in the rumen is about 87% - 90% and about13% - 10% in the large intestine [44], [45]. Animals release methane into the atmosphere by exhaling the gas mainly through the nostrils and mouth [23]. Of the CH_4 produced by rumen enteric fermentation in the fore-stomach, 95% was excreted by eructation and in the hindgut 89% was found to be excreted through the breath and about 11% through the anus [44]. The concentration in the breath is variable with a relatively low concentration when the expired gas comes from the lungs and a higher concentration when the breath gases belched from the fore-stomachs, although breath from lungs also contain absorbed methane and inhaled together with air. In a barn system or larger room, the concentration will to a large extent be influenced by the air exchange, but the concentration of CH_4 will be a total mix of the CH_4 obtained from belch, breath and fart [24]. The rumen chamber is an anaerobic environment, in which the breakdown of plant composition occurs in a very short time as compared with other anaerobic ecosystems such as wetlands and the fermentation products are different. Some of the microbial species have coevolved with ruminants and hindgut fermenting mammals and do not exist in any other environment such as rumen protozoa [47] and [48]. Digestion of feed components by the microbiota such as bacteria, protozoa, fungi results in the production of volatile fatty acids (VFA). These volatile fatty acids, mainly acetate, propionate and butyrate are used by the animal as source of energy. During the operation gases are also formed and their production eliminated mainly through eructation. CO_2 and H_2 are using to form methane, and thus degenerating the metabolic H_2 produced during microbial metabolism [4] [49]. Fermentation is an oxidative process, during which reduced cofactors such as NADH, NADPH, FADH are re-oxidized and formed into NAD-1, NADP-1, FAD-1 through dehydrogenation reactions releasing hydrogen in the rumen. This multistep process is used by microorganisms as an energy source and the reaction is indicated as $CO_2 + 8H^+ + 8e^- \rightarrow CH_4 + 2H_2O$. As soon as produced, hydrogen is used by methanogenic archaea, a microbial group distinct from Eubacteria, to reduce CO_2 into CH_4 [11]. Note that enteric methane produced by ruminants is a loss of feed energy from the diet and represents inefficient utilization of the feed [23]. In addition to the environmental impacts, ruminant methanogenesis represents a loss of 8-12% of the gross energy intake [29], [47], [50] and [51].

4. METHANE FROM MANURE

In addition to enteric CH_4, excreta are another source of CH_4, especially when stored an aerobically [52]. Methane generated from manure from ruminant and no ruminant livestock contributes 2% and 0.4% of global CH_4 and GHG emissions, respectively. In regions with low input is enteric fermentation undoubtedly the main emission source. However, in industrialized regions with high production and food processing manure is important source of emissions used as fertilizer [12]. Manure CH_4 emissions are a larger proportion of total farm CH_4 emissions in intensively managed dairy operations with manure storage systems aerobically and much lower in grazing operations [48]. Manure emissions are relatively high in areas where manure from the dairy sector is managed in liquid systems that produce greater quantities of CH_4 emissions [12]. During manure storage, CH_4 is generated through a reaction similar to that of enteric fermentation. Cellulose in the manure is degenerated by microbes, serving as input substrates for methanogenesis [40]. Livestock manure contains portion of organic solids such as proteins, carbohydrates and fats that are used as food and energy sources for growth of anaerobic bacteria. The benefit from methane production could be the energy value of the gas itself [54]. But the gas production from manure depends upon the efficiency of operating methods for it. Gas yield can be a certain amount of gas produced per unit of solids degraded by the anaerobic bacteria [53]. Anaerobic digestion is a natural process in which the microbes utilize organic matter under an anaerobic environment. It results in production of microbial biomass and greenhouse gases (CO_2 and CH_4).

5. EFFECT OF FEEDS ON METHANE PRODUCTION

Feed intake is the superior factor of total CH_4 production [55]. The amount of enteric CH_4 is mainly linked to the type, quality and quantity of feed [15], [56]. Gross energy (GE) is negatively related to feeding level and dietary fat composition and positively to diet digestibility, whereas dietary carbohydrate composition has only minor effects. As the daily feed intake increases, CH_4 production also generally increases [15]. Most studies agreed that dry matter intake (DMI) is the main driver of daily methane output, although methane output per kilogram of DMI decreases with increasing feeding level, quantity of feed [60], quality of feed, diet digestibility, and with increasing proportions of concentrates or lipids in the diet [8], [61]. There were found higher variability in the quantity of CH_4 emitted per unit of feed intake in grazing ruminants [51], [62] and [65]. The work of [66] suggests that non-grazing low forage feeding system result in the lowest enteric CH_4 emissions per kg energy corrected milk, with about 13% less enteric CH_4 compared to a high forage feeding system at the same farm. Body weight and milk yield accounted for significant proportions of variation in CH_4 emission. Both parameters were positively related to methane concentrations [67]. The composition of feed or the quality of forage influences CH_4 production in ruminants. Digestion of feeds in the rumen depends on the activity of microorganisms, which requires energy, nitrogen and minerals [8], [15]. Therefore, the quality of forage affects the activity of rumen microbes and CH_4 production in the rumen. Forage species, forage processing, proportion of forage in the diet, and the source of the grain also influence CH_4 production in ruminants. Methane production tends to decrease as the protein proportion of feed increases, and increases as the fiber level of feed increases [15], [29]. CH_4 production was positively related to diet digestibility and negatively related to dietary fat concentration, whereas the dietary carbohydrate composition had only minor effects [68]. Production of CH_4 has a negative impact on animal productivity, resulting in lost energy ranging from 8-12% of the animal's GEI [55] and [69].

6. AMOUNT OF METHANE PRODUCED

Authors [73] calculated enteric CH_4 emission rates using a procedure that reflects the development of rumen and feed properties of calves. Methane emissions by dairy cows vary with body weight, diet composition, level of feed intake, and milk yield. When cows are fed the same diet at the same intake level, variation between cows in CH_4 emissions can be substantial [74]. Study [45] estimated by using SF6 tracer technique adapted to collect breath gas samples over 5 day periods expressed methane emission in grazing dairy cows as absolute value (368 g/day or 516 L/day). [67] using the relationship between CH_4 emission rate during milking and daily CH_4 emissions measured in respiration chambers observed for cows on the same dietary regimen, the overall mean CH_4 emissions was 369 g/day and the range was 278 to 456 g/day. Lactating cows emit approximately twice the amount of CH_4 as compared to either dry cows or heifers due to their increased feed intake, although ration and animal size also have an effect. These emission factors may include emissions from feces deposited on the barn floor, which could be less than emissions from enteric fermentation [40]. Reference [20] recorded annual CH_4 emission from enteric fermentation 107 kg for dairy cow with a milk yield of 7870 kg/head. The corresponding value for dairy ewe was 8.4 kg/head. Authors [76] evaluated dairy cows fed a diet with forage: concentrate ratio of 500:500 or 900:100 g/kg of DM of total DMI. Mean CH_4 productions were 267 and 339 g/day/cow, respectively. Author [46] found at the DMI of 17.5 kg/day and milk yield of 22.9 kg/day CH4 measured by sulfur hexafluoride technique of 469 g/day (292 - 647), and CH_4 measured by respiration chamber as 422 g/day (275 - 577). The study of [77] recorded from lactating and dry cows and heifers on pasture under tropical conditions, using the tracer gas technique that Holstein produced more CH_4 299.3 g/day than the crossbred 264.2 g/day. Lactating cows produced more CH_4 353.8 g/day than dry cows 268.8 g/day and heifers 222.6

g/day. Dairy cows emit approximately 430 g/day at peak lactation down to 250 g/day as milk yield declines [71], [72]. Holstein cows produced less CH_4 per unit of dry matter intake (19.1 g/kg) than the crossbred (22.0 g/kg). Methane emission by heifers grazing on fertilized pasture was higher (222.6 g/day) than that of heifers on unfertilized pasture (179.2 g/day) [77]. Mature beef cows emit CH4 from 240 g/day to 350 g/day [71], [72] and Suffolk sheep emit 22 - 25 g/day [71], [57]. The annual emissions from the pens and storage pond at the dairy farms were 120 kg/cow.

7. METHANE SAMPLING TECHNIQUES

There are many options available by which CH4 emissions from ruminants could be measured. Screening of mitigation strategies may be best evaluated using individual animal response before large scale tests on herds of animals are conducted [31].

7.1. Respiration calorimeter

The classical standard for ruminant CH_4 measurement by nutritionists is the respiration chamber or calorimeter. Respiration calorimetry techniques such as whole animal chambers, head boxes, or ventilated hoods and face masks have been used effectively to collect most of the available information concerning CH_4 emissions in livestock. The predominant use of calorimeters has been to measure gaseous exchange as part of energy balance measurements, CH_4 loss being a necessary part of this procedure. There are various designs of calorimeters [32], but the most common one being the open circuit calorimeter. The principle behind open-circuit indirect-respiration techniques is that outside air is circulated around the animal's head, mouth and nose and well mixed inside air is collected [33]. The animal is placed in open circuit respiration chamber for a period of several days, the inputs (feed, oxygen, CO_2) and outputs (excretion, oxygen, CO_2 and CH_4) were measured from the chamber. The chamber should be well sealed and capable of a slight negative pressure. This ensures that all leaks will be inward and not result in a net loss of CH_4.

7.2. Ventilated hood

This technique involves the use of an airtight box that surrounds the animal's head. A sleeve or drape could be placed around the neck of the animal to minimize air leakage. The box must be big enough to allow the animal to move its head in an unrestricted manner and allows access to feed and water [73].

7.3. Facemask

The principle behind the use of the facemask is the same as that of the chamber and hood and used to quantify the expired gas from the grazing animals periodically and estimate CH_4 production [36].

7.4. Tracer gas technique

The tracer can either be isotopic or non-isotopic. Isotopic tracer techniques generally require simple experimental designs and relatively straightforward calculations, at least for the lower number pools [30].Using the continuous infusion technique, infusion lines deliver the labeled gas to the ventral part of rumen and sampling of gas takes place in the dorsal rumen. After determining the specific activity of the radio-labeled methane gas, total methane production can be calculated. It is also possible to measure CH_4 production from a single dose of injection of tracer [37].

7.5. Back pack

The backpack manages to capture and collect the gases emitted through the cow's mouth or intestinal tract via a tube inserted through the cow's skin (which the researchers claim is painless). The gas is then condensed and ready to use to provide power for the farm on which the cow lives, for example, for activities such as cooking, lighting a home or even driving a car [66].

8. MITIGATION STRATEGIES TO REDUCE METHANE PRODUCTION

8.1. Diet quality and digestibility

In diets containing all forage, the relative quality of that forage as measured by fiber content is a main determinant of CH_4 production. [68] wintered growing cattle on four qualities of alfalfa-grass silage that varied in NDF content from 46.4 to 60.8%. Cattle fed the lowest quality silage (containing 60.8% NDF and 46.4% ADF) had the lowest DMI. [30] reported a 1.6% decrease in GE lost as CH_4 for each level of intake increase, which [22] found will shift methanogenesis to the hindgut, potentially offsetting decreases in rumen CH_4. Manipulation of dietary composition has proven to be an effective mitigation strategy [51]. As 20% of the diet is composed of concentrate, CH_4 production decreases by 20% [34]. [39] reported that CH_4 production increases as corn replaces hay in the diet for 20-40% but declines markedly as the proportion of corn in the diet increases to 60, 85, and 95%. [75] reported that in diets with 1% increase in dietary fat would result in a decrease of 1 g CH_4 /kg DMI. Diets composed of a starchy concentrate (barely; 20% starch and 23% NDF) result in 23.4% less feed GE lost of CH_4 as compared to a diet composed of a fibrous concentrate (beet pulp; 2% starch and 31% NDF) [34]. A higher proportion of concentrate in the diet leads to a reduction in CH_4 emissions as a proportion of energy intake [70]. Replacing plant fibre in the diet with starch induces a shift of VFA production from acetate towards propionate occurs, which results in less hydrogen production. A positive response to high levels of grain based concentrate on methane reduction has also been reported by others [75], [59]. The metabolic pathways involved in hydrogen production and utilization and the activity of methanogens are two important factors that should be considered when developing strategies to control methane emissions by ruminants. The most promising approach for reducing methane emissions from livestock is replacement of dietary NDF with dietary starch. Therefore, the basic principle is to increase the digestibility of feedstuff [64].

8.2. Vaccines and Antibiotics

Vaccines are used to prevent or control disease for a particular period, but the utilization of vaccines reduces methanogens population and increase productivity. The anti-methanogens vaccine triggers the immune system of ruminants and produces antibodies against methanogens population in the ruminants. Immune potential in sheep has lowered methane production by 8%, while further testing was failed to confirm its efficacy in other geographical regions [38]. Streptomyces cinnamonens is secondary metabolite known as monensin that inhibits the gram positive bacteria, which is responsible for supplying a substrate to methanogens and reduces the acetate to propionate ratio in the rumen and effectively reducing methane production [65]. Saponins, tanins and oils have anti-microbial activity which can be used as additives to reduce methanogen population in the rumen and change methane emission [58].

8.3. Manure management

Manure from confined livestock operations is most often stored in solid or liquid form before being applied to agricultural land. The excreta of animals grazing in the morning emitted much more CH_4 than that of animals grazing in the afternoon. The CH_4 emission depends on the physical form of the faeces (shape, size, density, humidity), the amount of digestible material, the climate (temperature and humidity) and the time they remained intact [57]. Strategies to mitigate net emissions aim to change manure properties under which CH_4 and N_2O are produced and consumed during manure storage and treatment. One such strategy is to manipulate livestock diet composition and/or include feed additives to alter manure pH, concentration and solubility of carbon and nitrogen, and other properties that are pertinent to CH_4 and N_2O emissions. Composting technology, control of aeration, use of amendments, or co-composting livestock manure with other organic waste could also potentially modify conditions for GHG production and emission. The use of covers may also help to retain N nutrients during storage. Manure mitigation includes both low technology oriented strategies like covering and cooling manure lagoons during storage and fermentation [19]. More advanced technologies include frequent manure removal from animal houses and bedding areas into covered storage using scraping systems [26] as well as centralized digesters for biogas generation to create heat or electricity utilization and use of renewable natural gas [63].

8.4. Potential of genetics to reduce methane emission in ruminants

The key micro biota Archea is a very small population and it emits large portion of methane in rumen. Molecular analysis provided that methyl coenzyme-M reductase gene [39] is a genetic marker common for the Methanogenic population. Genetic variation suggests that 11-26% methane mitigation in10 years could be more in a genetic selection program. To convert grains and forages into meat, wool and milk, genetic traits are more important. Genetic improvements can result into higher birth rates and weaning weights, disease resistance, biological efficiency and results into reduced methane emission per unit meat produced. Uses of biotechnology tools had offered a scientific basis for managing natural populations by studying the genetic diversity and provide a means of adaptation to new stresses in short periods of time [78].

9. CONCLUSIONS

This review summarizes the current state of knowledge on CH_4 production relevant to climate change and environmental aspects. Enteric fermentation products from livestock ruminants are large sources of methane, which has a global warming potential 23 times that of carbon dioxide. The methane emission potential of dairy cattle represents values from 26 to 497 g/day. The average CH_4 emission in beef cattle ranges from 161-396 g/day. Dairy ewe generates 8.4 kg/head of CH_4 annually and Suffolk sheep emits 22 - 25 g/day. The CH_4 emission from manure depends on the physical form of the faeces (shape, size, density, and humidity), the amount of digestible material, the climate (temperature and humidity) and the time they remained intact. The five methane measuring techniques from the rumen of ruminants are Respiration calorimeter, Ventilated hood, Facemask, Backpack and Tracer gas techniques. The needful methane mitigation strategies are supplying protein rich diet, vaccine and antibiotics treatment, capturing manure and convert into natural gas and improving the genetic makeup of livestock. An extended review indicated that more research is still required to better quantify GHG emissions from farms of ruminants, non ruminants, poultry, sheep and goats, housing systems and manure management. Then, quantifying CH_4 emissions can often simultaneously increase productivity and thereby contributing to food security and economic development.

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