GENETIC AND DIETARY STRATEGIES FOR MITIGATING ENTERIC METHANE EMISSIONS IN RUMINANT ANIMAL PRODUCTION: A REVIEW

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ABSTRACT

Methane (CH_4) as an important greenhouse gas is detrimental to livestock production and human well-being as it contributes to climate change. The occurrence, sources by sector, mechanism and biochemistry, effects and mitigation strategies of enteric methane emission were hereby reviewed. The Global Warming Potential (GWP) of CH_4 is 28 - 36 times higher than CO_2. Sectors causing anthropogenic methane emissions include agriculture, energy, industry and waste. Livestock are major sources of methane emissions accounting for between 30 and 50% of the total greenhouse gas emitted. Enteric methane production accounts for about 39 and 80% of the methane emissions from the agricultural and livestock sector respectively. Additionally, methane represents between 2 and 12% loss of gross energy (GE) intake. Strategies for effective mitigation of methane emissions and feed energy loss in ruminant animals include selection and breeding of animals with improved productivity, supplementation with dietary lipids and lipid by-products at optimum level, optimal use of concentrates in the diet, feeding forages with high digestibility and feeding silage instead of hay.

Keywords: Greenhouse gases, Global warming, Methane, Enteric fermentation, Mitigation strategies, Ruminant animal

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INTRODUCTION

Methane (CH_4) is an important greenhouse gas. Greenhouse gases result in climate changes by affecting the atmosphere chemically in the long term (Dogan, 2005; 2007). Methane is one of the three main Green House Gases (GHG), together with carbon (IV) oxide (CO_2) and nitrous oxide (N_2O). Methane is formed as a result of decomposition of organic materials in an environment without oxygen. It is released from natural and anthropogenic sources. It has been reported that 40% of global methane emissions come from natural sources, whereas 60% of global methane emission is released from anthropogenic sources (USEPA, 2016; Karakurt *et al.,* 2012). Methane as an important greenhouse gas is detrimental. This is because the Global Warming Potentials (GWP) of N_2O and CH_4 are 265 and 28 times higher than CO_2, respectively (IPCC, 2013). USEPA (2016) reported that methane has 28 – 36 times global warming potential than carbon dioxide. Also, the life time of methane in the atmosphere is 9-15 years; and over the last two centuries, methane atmospheric concentrations have more than doubled, arising 1 % yearly in comparison with 0.5 % of carbon (IV) oxide (Mirzaei-Aghsaghali *et al.,* 2015). Sectors causing anthropogenic methane emissions include agriculture, energy, industry and waste (EPA, 2006).

Livestock are major sources of methane emission, contributing about 81 to 92 metric tonnes of methane per annum globally (Patra, 2012; IPCC, 2007). The fore stomach of ruminant animals contain diverse microbial population that produce significant quantities of methane during feed digestion which contributes to greenhouse gas emissions as well as global warming. Enteric methane is the largest source of agricultural emission, accounting for 40 % of total emission (World Bank Report, 2016; FAOSTAT, 2014). Enteric methane accounts for about 80% of the methane emissions from the livestock sector (Karri *et al.,* 2015; Gerber *et al.* 2013). Methane also represents a significant energy loss to the animal ranging from 2 to 12% of gross energy (GE) intake (Mahesh *et al.,* 2013; Zhi-hua *et al.,* 2012; Johnson and Johnson, 1995). So, decreasing the production of enteric CH_4 from ruminants without altering animal production is desirable both as a strategy to reduce global GHG emissions and as a means of improving animal productivity.

Owing to the loss of feed energy as methane, interest in reducing methane (CH_4) emissions by cattle has increased recently. Methane (CH_4) can be mitigated in ruminants through various strategies. Many reviews on the different strategies to mitigate enteric CH_4 production by ruminants have been published (Karri *et al.*, 2015; Mirzaei-Aghsaghali *et al.,* 2015; Hristov *et al.*, 2013; Buddle *et al.,* 2011; Hook *et al.,* 2010; Beauchemin *et al.,* 2008; Iqbal *et al.,* 2008; Moss *et al.,* 2000). Feed intake and dietary characteristics are the main determinants of methane production and have been widely studied in growing and finishing beef cattle (Johnson and Johnson, 1995). Manipulation of dietary composition has proven to be an effective mitigation strategy. Progress has also been made in identifying nutritional factors that may reduce methane production (Hristov *et al.*, 2013). Thus, this paper will review the different sectors contributing to anthropogenic methane emission and thus contributing to global warming, the mechanism of enteric methane production and emission, as well as current dietary strategies employed in enteric methane mitigation in ruminant animals.

METHANE EMISSIONS FROM VARIOUS SECTORS

The different sectors causing anthropogenic methane emissions include agriculture, energy, industry and waste. Methane emission from energy sector include those from coal mining activities, natural gas and oil systems, stationary and mobile combustion and biomass combustion; while methane emission from industry include those from chemical production, iron and steel production, metal production, mineral products, petrochemical production and silicon carbide production (Karakurt *et al.,* 2012; Gerber *et al.,* 2013; FAOSTAT, 2014; World Bank Group Report, 2016). From the agricultural sector, methane is generated via enteric fermentation, manure and fertilizers management, rice cultivation, and other agricultural activities. Methane emission from waste include those from landfilling of solid waste, waste water, waste combustion and the use of solvent and other products (Karakurt *et al.,* 2012; Gerber *et al.,* 2013; FAOSTAT, 2014; World Bank Group Report, 2016).

This review examines the contribution of the agricultural sector to CH_4 emissions, with particular reference to enteric fermentation, eructation and their mitigation strategies.

METHANE EMISSIONS FROM THE AGRICULTURAL SECTOR

Figure 1 shows the contribution of the different subsectors to global CH_4 emissions. Methane emissions from agricultural sources have increased from 4,656 Mt CO_2-eq in 2000 to 5,382 Mt CO_2-eq in 2012 (World Bank Group Report, 2016; FAOSTAT, 2014). This value makes the agricultural sector to be the biggest emitter that is responsible for the majority of methane emissions from anthropogenic sources. In other words, 50.63% of anthropogenic methane emissions are released as a result of agricultural activities. Sources causing methane emissions in agriculture sector as indicated in Figure 1 are enteric fermentation (40 %), manure management (25%), fertilizers (13%), rice cultivation (10%) and other agricultural sources (12%; Gerber *et al.,* 2013).

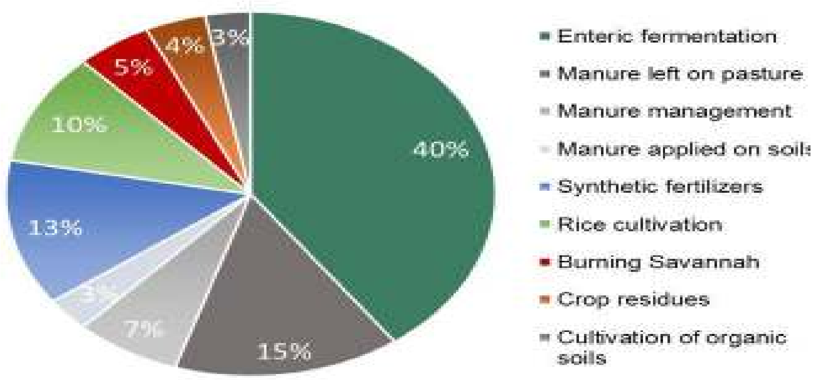

Figure 1: Agriculture emissions by subsector
Source: Gerber *et al.* (2013).

Enteric fermentation deals with the fermentation of feedstuffs by microbes in an animal's digestive system (Moss *et al.,* 2000). As a result of this process, methane is released by eructation. Domesticated ruminants such as cattle, buffalos, sheep, goats, and camels account for the majority of methane emissions in this sector (Wittenberg, 2010; Gworgwor *et al*., 2006). Other domesticated non-ruminants such as swine and horses also produce methane as a by-product of enteric fermentation, but emissions per animal species vary significantly. Figure 2 shows the contribution of different farm animals' species to enteric methane production. Total methane emissions from sector are related to livestock type and population and quality and type of feed (Mangino and Peterson, 2010; EPA, 2006). .

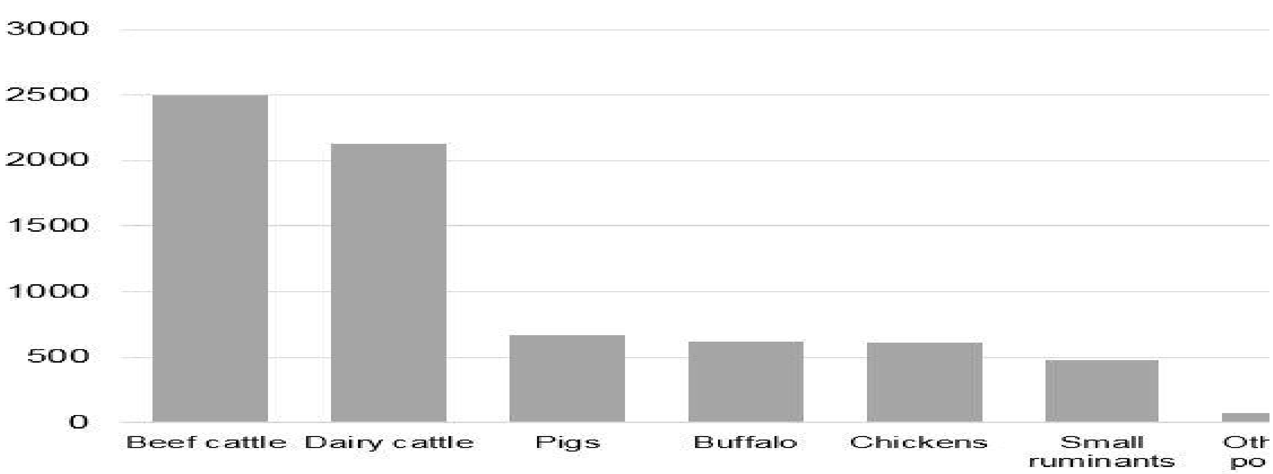

Figure 2: Global estimated emissions by species.
Source: Gerber *et al.* (2013).

When manure is stored or treated in liquid systems such as lagoons, ponds or pits, anaerobic conditions will be developed and methane emissions result from the decomposition process (Steed and Hashimoto, 1994). The amount of methane from manure varies with respect to the types of animals and diets, composition of manure, moisture conditions and ambient temperature for storage (Karakurt *et al.,* 2012). The decomposition of organic materials in an environment without oxygen in flooded rice fields also lead to the release of methane. When the rice fields are flooded, decomposition of organic materials gradually consumes the oxygen which is available in soil and water. Once the oxygen in the environment is consumed, methanogenic bacteria release methane. The amount of methane from rice paddies is under the control of several factors including the quantity of organic materials and water management (IPCC, 2009; Anand *et al.*, 2005). Other agricultural sources causing methane emissions include burning of biomass, savanna burning, burning of agricultural residues, cultivation of organic soils and burning of forest clearings (EPA, 2006). This review will dwell on enteric methane production and mitigation strategies.

MECHANISM OF ENTERIC METHANE PRODUCTION

Methanogens:

Enteric methane (87 - 90%) is produced in rumen, the remainder being released from fermentation in the large intestine (Lascano and Cárdenas, 2010). Methane production in the rumen occurs due to the presence of organisms belonging to the kingdom *Archaea* (Van Soest, 1982). They are considered to be an ancient and unique group of organisms which are the strictest of anaerobes and inhabit some of the harshest and most primitive environments on earth (Hook *et al.*, 2010). One of these unique environments happens to be the rumen. Methanogens are found in a variety of other ecosystems including swamps, heat vents on the ocean floor, rice fields, and in the gut of termites (Hook *et al.,* 2010), and these sources are quantitatively important to worldwide methane emissions (Pesta, 2015).

Seven orders of methanogens have been classified by taxonomists; Methanobacteriales, Methanococcales, Methanomicrobiales, Methanosarcinales, Methanocellales, Methanopyrales, and most recently discovered, Methanomassiliicoccales (Pesta, 2015; Borrel *et al.,* 2013). Methanogens in the order Methanopyrales thrive on conditions greater than 60° C and therefore are not present in ruminants. Members of the order Methanococcales are commonly isolated around submarine hydrothermal vents.

Hook *et al.* (2010) in their review reported the identification of orders Methanobacteriales, Methanomicrobiales, and Methanosarcinales in the gastrointestinal tract of ruminants. Species within the order Methanobacteriales have been the most commonly identified methanogens in the rumen (Hook *et al.,* 2010). Wright *et al.* (2006) reported the presence of clones from Methanomicrobiales in ovine rumen fluid while Whitford *et al.* (2001) reported that two members of the order Methanobacteriales (*Methanobrevibacter ruminantium* and *Methanosphaera stadtmanae*) were the largest groups of methanogens found in the rumen of dairy cattle fed a total mixed ration. *Methanobrevibacter ruminantium* almost exclusively utilizes CO_2 reduced with H_2 as a source of electrons, along with formate, which is degraded to CO_2 and H_2 (Pesta, 2015; Hook *et al.,* 2010).

The order of Methanosarcinales, which have cytochromes that act in the oxidation of methyl groups to CO_2, are slower growing than the other 2 orders of methanogens in the rumen but are the most versatile methanogens, as they are capable of utilizing four different pathways for methanogenesis (Borrel, *et al.,* 2013). Some examples of these organisms include *Methanosarcina barkeri* and *Methanosarcina mazeii* which can use a wider variety of substrates including acetate, methylamines, and methanol (Hook *et al.,* 2010). Nicholson *et al*. (2007) found Methanosarcinales species in fluid from cattle and sheep.

Biochemistry of Methane Production in the Rumen:

Kim and Gadd (2008) described the grouping of methanogenesis pathways according to the electron donors used; hydrogenotrophic, methylotrophic, and aceticlastic. Hydrogenotropic is the most common pathway used by methanogens found in the reticulorumen of ruminant livestock (Hook *et al.,* 2010). There is also evidence for a fourth pathway which is a specific type of methylotrophic methanogenesis: H_2-dependent methylotrophic methanogenesis (Welander and Metcalf, 2005). Regardless of grouping, CO_2 is the major electron acceptor in methanogenesis. A variety of electron donors are utilized by methanogens, including H_2, formate, methanol, acetate, methylamines, and carbon monoxide, although the majority of known methanogens grow when H_2 is used as the electron donor (Kim and Gadd, 2008). Multiple unique cofactors are required for methanogens to function, the most prevalent of which are coenzyme F420, coenzyme B (7-mercaptoheptanoylthreonine phosphate), coenzyme M (2-mercaptoethanesulfonate), methanofuran, and 5,6,7,8-tetrahydromethanopterin (Deppenmeier, 2002).

Reduction of CO_2 to CH_4 is an important component of the rumen ecosystem due to its role as a recycler of NAD^+ (Russell, 2002). Two molecules of NADH are produced when a molecule of glucose is fermented to pyruvate in the rumen via the Embden-Meyerhoff/glycolytic pathway. Under aerobic conditions, an additional 8 moles of NADH are produced through the citric acid cycle, and are re-oxidized to NAD^+ through the electron transport chain. In anaerobic fermentation, oxygen is not available to be an electron acceptor and a replacement must be used for the terminal end of the electron transport chain. The electron acceptor during methanogenesis is H+, which serves an important role by receiving electrons from NADH, thus regenerating NAD+ and producing H_2 (Russell, 2002). Methanogens use this H_2 as an electron donor to produce CH_4. In the absence of methanogens, interspecies hydrogen transfer is accomplished through bacterial fermentation which produces lactate, acetate, ethanol, succinate, or propionate (Wolin, 1982). Through this process, it becomes clear that energetic losses due to methane production are due to a loss of H+, not a loss of carbon.

METHANE MITIGATION STRATEGIES

The methane mitigation strategies that will be reviewed in this paper include animal genetic selection and breeding as well as improved dietary provisions.

Animal Genetic Selection and Breeding

Livestock production has been intensified through better breeding and feeding programmes to decrease global greenhouse gas emissions (Martin *et al.,* 2009). Animal production efficiency has been increased by selection of animals with improved genetic merit (the ratio of an animal's performance with the group average). Factors responsible for variability between animals are the rate of passage, salivation rate, feeding rate, drinking rate, rumen volumes, microbial activity, fermentation conditions, seasonal variation and grazing behavior (Mirzaei-Aghsaghali *et al.,* 2015; Pinares-Patiño *et al.*, 2003). In dairy cows, body weight, milk yield, and type of roughage influence CH_4 production. Animals with high genetic merits produce 7 - 27% less methane, as a percentage of gross energy (GE) intakes (Boadi and Wittenberg, 2002). Nkrumah *et al.* (2006) reported that low Residual Feed Intake (RFI) animals (i.e., efficient animals) emit up to 28% less methane than high RFI counterparts. Cattle that eat less than their peers of equivalent live weight and average daily gain have a low residual feed intake and are more feed efficient. RFI is a measure of net feed efficiency. RFI is a moderately heritable trait (Herd and Arthur, 2009).

Ulyatt *et al.* (2002) reported that 71 – 95% of variation in methane emission from dairy cows and breeding ewes grazing ryegrass/white clover pasture in New Zealand between days was attributable to animals. Pinares-Patino *et al.* (2003) also reported that about 85 % of the variation in daily CH_4 production (g/day) from sheep grazing temperate pastures was due to variation between animals. This degree of variability reported is a strong indication that breeding animals with low methane emissions but with uncompromised performance will go a long way in mitigating enteric methane emissions (Buddle *et al.,* 2011).

Improved Dietary Provisions

Some dietary or nutritional strategies to mitigate methane production have been identified and adopted in dairy animals and these includes the addition of ionophores, dietary Lipids supplementation, the use of high-quality forages or *preserved forages (Silage)*, and increased use of grains and concentrates; addition of modern feed additives like probiotics, acetogens, bacteriocins, archaeal viruses, organic acids, plant extracts (e.g., essential oils) to the diet (Boadi *et al*., 2004).

Dietary Lipids Supplementation:

Vegetables and animal lipids were originally used in ruminant rations to increase their energy density. However, lipids are also considered useful today to reduce enteric methanogenesis (Brask *et al.* 2013; Beauchemin *et al.,* 2007). Supplemental fat is the most commonly studied dietary component that can act as an H^+ sink to reduce methanogenesis. However, there are several modes of action by which fats can inhibit CH_4 production: by directly inhibiting methanogens and protozoa, by directing H^+ toward bio-hydrogenation of unsaturated fats, by increasing propionate production or likely by a combination of bio-hydrogenation of unsaturated fatty acids and direct inhibition of activities of different microbes including methanogens (Hook *et al.,* 2010; Beauchemin *et al.,* 2007). Factors that may account for varying effects of lipids on methane abatement are the ruminant species, experimental diet, and the type of lipid used (Hook *et al.,* 2010)

A meta-analysis by Grainger and Beauchemin (2011) found that in diets with 8% or less dietary fat, a 1% increase in dietary fat would result in a decrease of 1g CH_4/kg DMI. Beauchemin *et al.* (2008) observed a 5.6% methane reduction per percentage unit of lipid added to the diet of cattle and sheep. Comparison of the effects of different fatty acids revealed that lauric, myristic and linoleic acids were the most potent reducers of methanogenesis (Zhou *et al*., 2013; Ding *et al.,* 2012; Jordan *et al.,* 2006).

The potential of essential oils as additive to manipulate rumen fermentation and decrease methane emissions has been extensively investigated and reviewed (Benchaar and Greathead 2011; Calsamiglia *et al*., 2007). A wide range of essential oils (derived from garlic (*Allium sativum*), eucalyptus (*Eucalyptus globules*) thyme, neem (*Azadirachta indica*), oregano, cinnamon, rhubarb, frangula) has been shown to decrease methane production *in vitro* by 55.8% (Sirohi *et al.,* 2013).

The addition of different oil (soya, coconut, canola, rapeseed, etc.) to ruminant diets have been shown to reduce methane production between 19% and 62% in sheep (Ding *et al.*, 2012), beef cattle (Jordan *et al.,* 2006) and dairy cows (Brask *et al.*, 2013; Odongo *et al.,* 2007). Refined soy oil based diet fed to beef bulls reduced methane by 39% (Jordan *et al.*, 2006). Martin *et al.* (2008) reported a 55.8 – 64% reduction in grams of methane per day by lactating dairy cows fed linseed oil supplemented at a level of 5% of DM. Beauchemin and McGinn (2006) reported a 21% decrease in CH_4 as a percentage of GE intakes and a 15% decrease in DM digestibility when they fed canola oil. Differences in performance were observed in a study by Fiorentini *et al.* (2014), in which steers were fed whole soybean, linseed oil, or palm oil as sources of fat that differed in saturation. Linseed oil and whole soybeans, rich in unsaturated fatty acids, decreased CH_4 by 1.1g/kg DMI for every 10g of fat consumed. Palm oil however, a saturated fatty acid, decreased CH_4 by 1.8g/kg DMI for every 10g of fat consumed and severely decreased DMI, average daily gain (ADG) and feed conversion ratio. The authors attributed the additional CH_4-mitigating effect of palm oil compared to unsaturated fats to the greater content of medium chain fatty acids in palm oil, which can be toxic to methanogenic *archaea*.

However, the inclusion of lipids at levels above 6 – 7% of dry matter intake can affect palatability; reduce feed intake and fibre digestibility, resulting in lower performance, lower milk yield and composition or daily gain (Patra, 2012; Odongo *et al.,* 2007; Jordan *et al.,* 2006). Thus, when oils are used, decreases in CH_4 must be balanced against decreased digestibility, DMI and animal performance.

Dietary Lipids By-Products:

High-oil by-products from the biofuel industries - dry distillers grains (DDG) or wet distillers grains (WDG) alone or with solubles (DDGS and WDGS, respectively) and mechanically extracted oilseed meals can naturally serve as CH_4 mitigating feed, if included in the diet to decrease feed cost (Hristov *et al.,* 2013). McGinn *et al.* (2009), for example, reported up to 24% less CH_4 emissions when DDG replaced barley grain in the back grounding diet of beef cattle by supplementing an additional 3% lipid to the dietary DM. However, the effects of distillers' grains on CH_4 production are not consistent and might depend on the rest of the diet. Hales *et al.* (2013) fed diets containing 0 to 45% WDGS (substituting steam-flaked corn) to Jersey steers and observed a linear increase in CH_4 emission per unit of DMI (up to 64% increase with the highest inclusion rate), due primarily to increased NDF intake, although the ether extract (EE) content of the diet increased from 5.9 to 8.3%. High-oil by-product feeds might have the same suppressive effect on feed intake as free lipids, so caution must be exercised to prevent negative effects on animal productivity or milk fat depression in lactating cows (Schingoethe *et al.,* 2009).

Inclusions of Concentrates

It is well established that increasing the level of concentrate in the diet leads to a reduction in CH_4 emissions as a proportion of energy intake or expressed by unit of animal product (milk and meat) if production remains the same or is increased. Concentrate feeding can reduce methane output by reducing the protozoal population (Van Soest, 1982) or by changing rumen volatile fatty acids (VFAs) concentrations to favour the production of more propionate and less acetate.

Decreases in CH_4 emissions per kilogram of animal product (19.26 and 16.02g of CH_4/kg of fat-corrected milk) have been reported (Lovett *et al.*, 2005) with an increase in the proportion of concentrate in the diet (Aguerre *et al.*, 2011; Beauchemin and McGinn, 2006). However, increasing the concentrate proportion in the diet above certain levels, however, might have a negative effect on fiber digestibility (Ferraretto *et al.,* 2013;), which, in addition to a potential loss of production, could result in increased concentration of fermentable OM in manure and perhaps increased CH_4 emissions from stored manure (Hristov *et al.,* 2013). Increased levels of concentrates may also result in health problems e.g. acidosis.

Forage type and Quality

The CH_4 emissions (g/kg DMI) from animals fed forage legumes is usually (McCaughey *et al*., 1999), but not always (Hammond *et al*., 2011) lower than emissions from animals fed predominantly grasses. Decreased CH_4 production of 10 – 21% per unit of product has been reported for highly digestible forages such as lucerne (Benchaar *et al*., 2001; McCaughey *et al*., 1999). Factors responsible for lower emissions for animals fed legumes are often explained by the presence of condensed tannins, lower fibre content, higher DMI and faster rate of passage from the rumen.

Forage quality, especially its digestibility also affects the CH_4 production potential of the forage. The effects of forage quality on CH_4 emissions are often contradictory (Hart *et al.,* 2009; Molano and Clark, 2008; Pinares-Patiño *et al*., 2003). Feeds with higher digestibility recorded increased DMI but depressed CH_4 produced per unit of feed consumed (Hammond *et al.,* 2009, 2013), whereas, increased intake of poor-quality, less-digestible preserved forages has little effect on CH_4 production when expressed on a DMI basis (Johnson and Johnson, 1995). Forages from temperate rangelands (C3 grasses) emit less methane (17%) per unit of intake than grasses from tropical regions which are C4 grasses (Ulyatt *et al*., 2002). Forage maturity at the time of harvest also influence CH_4 emissions, with increased CH_4 emission reported (5 - 6.5%). with forage maturity (Chaves *et al*., 2006).

Using Preserved Forages: Silage

Forage preservation and processing also affect enteric CH_4 production. Methanogenesis tends to be lower when forages are ensiled than when they are preserved as hay, and when they are finely ground or pelleted than when coarsely chopped (Beauchemin *et al.,* 2008). Benchaar *et al.* (2001) reported that total methane production was depressed (–33%) by the utilization of alfalfa silage instead of alfalfa hay. They also reported that fractions of GE intake and DE lost as methane were also lower (–32 and –28%, respectively) with alfalfa silage than with alfalfa hay. Varga *et al.* (1985) reported a decrease in methane production from cattle consuming alfalfa silage compared to orchard grass silage. Some studies have indicated reduced CH_4 production with corn vs. grass silages (Doreau *et al.,* 2012). Dewhurst (2012) gave a comprehensive overview of the various aspects of feeding corn versus legume versus grass silages for lactating dairy cows. The author concluded that the lower fiber content and higher passage rates of legumes appeared to decrease CH_4 production compared with grasses, which was reported in earlier studies (McCaughey *et al.,* 1999).

CONCLUSIONS

- Sub-sectors contributing to the global agricultural CH_4 emissions include enteric fermentation, manure management, fertilizers application and rice cultivation, with enteric fermentation contributing 40%. In order to regenerate NAD^+, the methanogens utilized H^+ as an electron acceptor of H^+ in NADH to produce H_2. Methanogens then used the H_2 as an electron donor to reduce CO_2 to CH_4. Thus, to reduce global warming as well as improve animal productivity, animals with high genetic potentials should be selected.

- Inclusion of lipids and lipid by-products in the diet at optimum level, use of highly digestibility forages, optimum inclusion of concentrate in the diet and the use of legumes and preserved forages like silage will also go a long way in the mitigation of enteric methane emissions.

REFERENCES

Aguerre, M. J., Wattiaux, M.A., Powell, J.M., Broderick, G.A. and Arndt, C. 2011. Effect of forage-to-concentrate ratio in dairy cow diets on emission of methane, carbon dioxide, and ammonia, lactation performance, and manure excretion. *J. Dairy Sci.* 94: 3081– 3093.

Anand, S., Dahiya, R.P., Talyan, V. and Vrat, P. 2005. Investigations of methane emissions from rice cultivation in Indian context. *Environment International*. 31:469 - 482.

Beauchemin, K.A. and McGinn, S.M. 2006. Methane emissions from beef cattle: effects of fumaric acid, essential oil, and canola oil. *Journal of Animal Science.* 84: 1489 – 1496.

Beauchemin, K.A., Kreuzer, M., O'Mara, F. and McAllister, T.A. 2008. Nutritional management for enteric methane abatement: a review. *Australian Journal of Experimental Agriculture.* 48: 21 – 27.

Beauchemin, K., McGinn, S.M. Petit, H.V. 2007. Methane abatement strategies for cattle: lipid supplementation of diets. *Can J Anim Sci*. 87: 431 – 440.

Benchaar, C. and Greathead, H. 2011. Essential oils and opportunities to mitigate enteric methane emissions from ruminants. *Anim. Feed Sci. Technol*. 166 – 167: 338 – 355

Benchaar, C., Pomar, C. and Chiquette, J. 2001. Evaluation of dietary strategies to reduce methane production in ruminants: A modelling approach. *Can. J. Anim. Sci.* 81: 563 - 574.

Boadi, D.A. and Wittenberg, K.M. 2002. Methane production from dairy and beef heifers fed forages differing in nutrient density using the sulphur hexafluoride (SF6) tracer gas technique. *Canadian Journal of Animal Sc*ience. 82(2): 201 - 206.

Boadi, D., Benchaar, C., Chiquette, J. and Massé, D. 2004. Mitigation strategies to reduce enteric methane emissions from dairy cows: Update review. *Canadian Journal of Animal Science.* 84: 319–335.

Borrel, G.P., O'Toole, W., Harris, H.M.B., Peyret, P., Brugere, J.F. and Gribaldo, S. 2013. Phylogenic data support a seventh order of methylotrophic methanogens and provide insights into the evolution of methanogenesis. *Genome Biol. Evol*. 5(10): 1769 - 1780. doi:10.1093/qbe/evt128.

Buddle, B.M., Denis, M., Attwood, G.T. Altermann, E., Janssen, P.H., Ronimus, R.S., Pinares-Patiño, C.S., Muetzel, S. and Wedlock, D.N. 2011. Strategies to reduce methane emissions from farmed ruminants grazing on pasture. *The Veterinary Journal*. 188: 11 – 17.

Calsamiglia, S., Busquet, M., Cardozo, P., Castillejos, L. and Ferret, A. 2007. Invited review: essential oils as modifiers of rumen microbial fermentation. *J Dairy Sci*. 90: 2580 – 2595.

Chaves, A.V., Thompson, L.C, Iwaasa, A.D., Scott, S.L. and Olson, M.E. 2006. Effect of pasture type (alfalfa vs. grass) on methane and carbon dioxide production by yearling beef heifer. *Canadian Journal of Animal Science.* 86: 409 – 418.

Deppenmeier, U. 2002. The unique biochemistry of methanogenesis. *Progress in Nucleic Acid Research and Molec. Bio*. 71: 224 - 283.

Dewhurst, R.J. 2012. Milk production from silage: Comparison of grass, legume and maize silages and their mixtures. In: K. Kuoppala, M. Rinne, and A. Vanhatalo, (eds), Proc. XVI Int. Silage Conf. MTT Agrifood Research Finland, University of Helsinki. Hameenlinna, Finland. Pp. 134 – 135.

Ding, X., Long, R., Zhang, Q., Huang, X., Guo, X. and Mi, J. 2012. Reducing methane emissions and the methanogen population in the rumen of Tibetan sheep by dietary supplementation with coconut oil. *Trop Anim Health Prod*. 44: 1541 – 1545.

Dogan, S. 2005. Türkiye'nin Küresel _Iklim De_gis¸ ikli_ginde Rolü ve Önleyici Küresel Çabaya Katılım Giris¸ imleri, C.Ü. _Iktisadi ve _Idari Bilimler Dergisi. 6(2) [in Turkish].

Dogan, S. 2007. Iklim De_gis¸ ikli_gi'nde Türkiye'nin Adımları. Available at: http://www. bitem.gazi.edu.tr/pdf/iklimturkiye.pdf; 2007 (in Turkish). Accessed 10/01/2016.

Doreau, M., Rochette, Y. and Martin, C. 2012. Effect of type of forage (maize silage vs. grass silage) and protein source (soybean meal vs. dehydrated lucerne) in dairy cow diet on methane emission and on nitrogen losses. In: Proc. Symp. Emissions of Gas and Dust by Livestock, Saint-Malo, France. Pp. 4.

EPA. 2006. Global anthropogenic Non-CO_2 greenhouse gas emissions: 1990-2020. Available at: http://www.epa.gov/nonco2/econinv/pdfs/global_emission. Accessed on 10/01/2016.

FAOSTAT. 2014. FAO Statistical Yearbook 2014: Latin America and the Caribbean Food and Agriculture. http://www.fao.org/3/a-i3592e.pdf.

Ferraretto, L.F., Crump, P.M. and Shaver, R.D. 2013. Effect of cereal grain type and corn grain harvesting and processing methods on intake, digestion, and milk production by dairy cows through a meta-analysis. *J. Dairy Sci.* 96: 533 – 550.

Fiorentini, G.I., Carvalho, P.C., Messana, J.D., Castagnino, P.S., Berndt, A., Canesin, R.C., Frighetto, R.T.S. and Berchielli, T.T. 2014. Effect of lipid sources with different fatty acid profiles on the intake, performance, and methane emissions of feedlot Nellore steers. *J. Anim. Sci.* 92: 1613 - 1620.

Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A. and Tempio, G. 2013. Tackling climate change through livestock: a global assessment of emissions and mitigation opportunities. Food and Agriculture Organization of the United Nations (FAO), Rome.

Grainger, C. and Beauchemin, K.A. 2011. Can enteric methane emissions from ruminants be lowered without lowering their production? *Anim Feed Sci Technol*. 166 -167: 308 – 320.

Gworgwor, A.Z, Mbahi, F.T. and Yakubu, B. 2006. Environmental Implications of methane production by ruminants: a review. *Journal of Sustainable Development in Agriculture and Environment*. 2(1): 1 - 14.

Hales, K.E., Cole, N.A. and MacDonald, J.C. 2013. Effects of increasing concentrations of wet distillers grains with solubles in steam-flaked, corn-based diets on energy metabolism, carbon-nitrogen balance, and methane emissions of beef cattle. *J. Anim. Sci.* 91: 819 - 828.

Hammond, K.J., Burke, J.L. Koolaard, J.P., Muetzel, S. Pinares-Patiño, C.S. and Waghorn, G.C. 2013. The effect of feed intake on enteric methane emissions from sheep fed fresh white clover (*Trifolium repens*) and perennial ryegrass (*Lolium perenne*) forages. *Anim. Feed Sci. Technol.* 179: 121 – 132.

Hammond, K.J., Hoskin, S.O., Burke, J.L., Waghorn, G.C., Koolaard, J.P. and Muetzel, S. 2011. Effects of feeding fresh white clover (*Trifolium repens*) or perennial ryegrass (*Lolium perenne*) on enteric methane emissions from sheep. *Anim. Feed Sci. Technol.* 166–167: 398 - 404.

Hammond, K.J., Muetzel, S., Waghorn, G.C., Pinares-Patino, C.S., Burke, J.L. and Hoskin, S.O. 2009. Exploring variation in methane emissions from sheep and cattle fed pasture determined by either SF_6 marker dilution or direct calorimetry. Proc. N. Z. Soc. Anim. Prod. 69: 174 – 178.

Hart, K.J., Martin, P.G., Foley, P.A., Kenny, D.A. and Boland, T.M. 2009. Effect of sward dry matter digestibility on methane production, ruminal fermentation, and microbial populations of zero-grazed beef cattle. *J. Anim. Sci*. 87: 3342 – 3350.

Herd, R.M. and Arthur, P.F. 2009. Physiological basis for residual feed intake. *Journal of Animal Science*. 87: E64 – E71.

Hook, S.E., Wright, A.G. and McBride, B.W. 2010. Methanogens: Methane producers of the rumen and mitigation strategies. *Archaea.* Article ID 945785. doi:10.1155/2010/945785. Accessed on 10.01.2016.

Hristov, A.N., Lee, C., Cassidy, T., Heyler, K., Tekippe, J.A., Varga, G.A., Corl, B. and Brandt, R.C. 2013. Effect of *Origanum vulgare* L. leaves on rumen fermentation, production, and milk fatty acid composition in lactating dairy cows. *J. Dairy Sci.* 96: 1189 – 1202.

Hristov, A.N., Oh, J., Firkins, J.L., Dijkstra, J., Kebreab, E., Waghorn, G., Makkar, H.P.S., Adesogan, A.T., Yang, W., Lee, C., Gerber, P.J., Henderson, B. and Tricarico, J.M. 2013. Special Topics—Mitigation of methane and nitrous oxide emissions from animal operations: I. A review of enteric methane mitigation options. *J. Anim. Sci.* 91: 5045 – 5069. doi:10.2527/jas2013-6583.

IPCC. 2007. Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change Cambridge, United Kingdom and New York, NY, USA. (Available at: http://www.ipcc.ch/publications_and_data/ar4/wg3/en/contents.html). Accessed 08/05/2016.

IPCC. (2013). Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University United Kingdom and New York, NY, USA. http://www.climatechange2013.org/report/. Accessed 20/7/2017.

IPCC. 2009. Methane Emissions from rice cultivation: flooded rice fields. Available at: http://www.ipccnggip.iges.or.jp/public/gl/guidelin/ch4ref5.pdf. Accessed 20/01/2016.

Iqbal, M.F., Cheng, Y-F., Zhu, W-Y. and Zeshan, B. 2008. Mitigation of ruminant methane production: current strategies, constraints and future options. *World Journal of Microbiology and* Biotechnology. 24: 2747 - 2755.

Johnson, K. and Johnson, D.E. 1995. Methane emissions from cattle. *J Anim Sci*. 73: 2483 – 2492.

Jordan, E., Lovett, D., Monahan, F., Callan, J., Flynn, B. and O'Mara, F. 2006. Effect of refined coconut oil or copra meal on methane output and on intake and performance of beef heifers. *J Anim Sci*. 84: 162 – 170.

Karakurt, I., Aydin, G. and Aydiner, K. 2012. Sources and mitigation of methane emissions by sectors: A critical review. *Renewable Energy.* 39: 40 – 48.

Karri, S., Talla, S.G. and Sirohi, S.K. 2015. An overview of the role of rumen methanogens in methane emission and its reduction strategies. *African Journal of Biotechnology*. 14 (16): 1427 – 1438.

Kim, B.H. and Gadd, G.M. 2008. Bacterial Physiology and Metabolism. Cambridge University Press, Cambridge, U.K.

Lascano, C.E. and Cárdenas, E. 2010. Alternatives for methane emission mitigation in livestock systems. *Rev Bras Zootec.* 39: 175 – 182.

Lovett, D.K., Stack, L.J., Lovell, S., Callan, J., Flynn, B., Hawkins, M. and O'Mara, F.P. 2005. Manipulating enteric methane emissions and animal performance of late-lactation dairy cows through concentrate supplementation at pasture. *Journal of Dairy Science*. 88: 2836 – 2842.

Mahesh, M., Mohini, M., Kumar, D., Sheel, R., Sawant, S. and Jha, P. 2013. Influence of biologically treated wheat straw diet on in vitro rumen fermentation, methanogenesis and digestibility. *Scientific Journal of Animal Science*. 2(6): 173 - 179.

Mangino, M.J. and Peterson, M.K. 2010. Development of an emissions model to estimate methane from enteric fermentation in cattle. Available at: http://www.coalinfo.net.cn/coalbed/meeting/2203/papers/agriculture/AG007.pdf. Accessed 20/01/2016.

Martin, C., Morgavi, D. P. and Doreau, M. 2009. Methane mitigation in ruminants: from microbe to the farm scale. *The Animal Consortium*. 4(3): 351–365.

Martin, C., Rouel, J., Jouany, J.P.,Doreau, M. and Chilliard, Y. 2008. Methane output and diet digestibility in response to feeding dairy cow crude linseed, extruded linseed, or linseed oil. *J. Anim. Sci.* 86: 2642 – 2650.

McCaughey, W.P., Wittenberg, K. and Corrigan, D. 1999. Impact of pasture type on methane production by lactating beef cows. *Can. J. Anim. Sci.* 79: 221 – 226.

McGinn, S.M, Chung, Y.H., Beauchemin, K.A., Iwaasa, A.D. and Grainger, C. 2009. Use of corn distillers' dried grains to reduce enteric methane loss from beef cattle. *Can. J. Anim. Sci.* 89: 49-413.

Mirzaei-Aghsaghali, A., Maheri-Sis, N., Siadati, S.A. and Jalilnejad, N. 2015. Factors Affecting Mitigation of Methane Emission from Ruminants: Management Strategies. *Ecologia Balkanica*. 7 (1): 171 - 190. http://eb.bio.uni-plovdiv.bg.

Molano, G. and Clark, H. 2008. The effect of level of intake and forage quality on methane production by sheep. *Aust. J. Exp. Agric.* 48: 219 – 222.

Moss, A.R., Jouany, J.P. and Newbold, J. 2000. Methane production by ruminants: its contribution to global warming. *Annales de Zootechnie.* 49: 231 – 253.

Nicholson, M., Nicholson, J., Evans, P.N. and Joblin, K.N. 2007. Analysis of methanogen diversity in the rumen using temporal temperature gradient gel electrophoresis: identification of uncultured methanogens. *Microbial Ecology*. 54: 141 - 150. doi:10.1007/s00248-006-9182-1.

Nkrumah, J.D., Okine, E.K., Mathison, G.W., Schmid, K., Li, C., Basarab, J.A., Price, M.A.,Wang, Z. and Moore, S.S. 2006. Relationships of feedlot efficiency, performance, and feeding behaviour with metabolic rate, methane production, and energy partitioning in beef cattle. *Journal of Animal Science* 84: 145 - 153.

Odongo, N.E., Bagg, R., Vessie, G., Dick, P., Or-Rashid, M.M., Hook, S.E., Gray, J.T., Kebreab, E., France, J. and McBride, B.W. 2007. Long-term effects of feeding monensin on methane production in lactating dairy cows. *J. Dairy Sci.* 90: 1781 - 1788.

Patra, A.K. 2012. Enteric methane mitigation technologies for ruminant livestock: a synthesis of current research and future directions. *Environ. Monit. Assess.* 184: 1929 – 1952.

Pesta, A.C. 2015. Dietary Strategies for Mitigation of Methane Production by Growing and Finishing Cattle. *Theses and Dissertations in Animal Science.* Paper 109. http://digitalcommons.unl.edu/animalscidiss/109.

Pinares-Patino, C.S., Ulyatt, M.J., Lassey, K.R., Barry, T.N. and Holmes, C.W. 2003. Persistence of differences between sheep in methane emission under generous grazing conditions. *Journal of Agriculture Science*. 140: 227 – 233.

Russell, J.B. 2002. Rumen Microbiology and Its Role in Ruminant Nutrition. Published by James B. Russell, Ithaca, NY.

Schingoethe, D.J., Kalscheur, K.F., Hippen, A.R. and Garcia, A.D. 2009. The use of distiller's products in dairy cattle diets. *J. Dairy Sci.* 92: 5802 – 5813.

Sirohi, S.K., Chaudhary, P.P., Singh, N., Singh, D. and Puniya, A.K. 2013. The 16S rRNA and mcrA gene based comparative diversity of methanogens in cattle fed on high fibre based diet. *Gene*. 523: 161 – 166.

Steed, J. and Hashimoto, A.G. 1994. Methane emissions from typical manure management systems. *Bioresource Technology*. 50 (2): 123 - 130.

Ulyatt, M.J., Lassey, K.R., Shelton, I.D., and Walker, C.F. 2002. Seasonal variation in methane emission from dairy cows and breeding ewes grazing ryegrass/white clover pasture in New Zealand. *New Zealand Journal of Agricultural Research*. 45: 217 - 226.

United States Environmental Protection Agency. 2016. Climate Change, Greenhouse Gas Emissions. https://www3.epa.gov/climatechange/ghgemissions/gases/ch4.html. Accessed February, 2017.

Van Soest, P.J. 1982. Nutritional Ecology of the Ruminant. Cornell University Press, Ithaca, N. Y.

Varga, G.A., Tyrrell, H.F., Waldo, D.R., Huntington, G.B. and Glenn, B.P. 1985. Effect of alfalfa or orchard grass silage on energy and nitrogen utilization for growth by Holstein steers. In: Moe, P. W., Tyrrell, H. F., Reynolds, P. J. (Eds.). Energy metabolism of farm animals. The Netherlands. Wageningen Press, EAAP Publication. Pp. 86 - 89.

Welander, P.V. and Metcalf, W.W. 2005. Loss of the *mtr* operon in *Methanosarcina* blocks growth on methanol, but not methanogenesis, and reveals an unknown methanogenic pathway. *Proc Natl Acad Sci*. USA. 102:10664–10669.

Whitford, M.F., Teather, R.M. and Forster, R.J. 2001. Phylogenetic analysis of methanogens from the bovine rumen. *BMC Microbiology*. 1: 1 - 5.

Wittenberg, K. M. 2010. Enteric methane emissions and mitigation opportunities for Canadian cattle production systems. Accessed on 20/01/2016 at: http://www.vido.org/beefinfonet/otherareas/pdf/CcbMethaneemmissionsWittenburg.pdf.

Wolin, M.J. 1982. Microbial Interactions and Communities. A. T. Bull and J. H. Slater (Ed.). Academic Press, NY. Vol. 1.

World Bank Group Report. 2016. Greenhouse Gas Mitigation Opportunities in Agricultural Landscapes: A Practitioner's Guide to Agricultural and Land Resources Management. Edited by Ademola K. Braimoh, Xiaoyue Hou, Christine Heumesser and Yuxuan Zhao. www.worldbank.org.

Wright, A.D., Toovey, A.F. and Pimm, C.L. 2006. Molecular identification of methanogenic *archaea* from sheep in Queensland, Australia reveals more uncultured novel archaea. *Anaerobe* .12: 134 - 139. doi:10.1016/j.anaerobe.2006.02.002.

Zhi-Hua, F.G., Yu-Feng, C., Yan-Xia, G., Qiu-Feng, L. and Jian-Guo, L. 2012. Effect of gross saponin of tribulus terrestris on ruminal fermentation and methane production *in vitro*. *Journal of Animal and Veterinary Advances*. 11: 2121 – 2125.

Zhou, X., Meile, L., Kreuzer, M. and Zeitz, J.O. 2013. The effect of lauric acid on methane production and cell viability of *Methanobrevibacter ruminantium*. *Adv. Anim. Biosci.* 4(2): 458.