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Factors Affecting Mitigation of Methane Emission from Ruminants I: Feeding Strategies

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ABSTRACT

The aim of this study is to review effective factors on decrease methane emission by enteric fermentation, mainly by ruminants. Global surface temperatures are predicted to increase between 1 to 6°C during the twenty-first century; primarily due to increased levels of Greenhouse Gases (GHGs) principally carbon dioxide (CO₂), methane (CH₄) and Nitrous Oxide (N₂O) in the atmosphere. Agricultural emissions of methane have recently been estimated at 10.2 million tonnes per year. Of these, approximately two-thirds come from enteric fermentation and one-third from livestock manure. To discuss factors relation to emissions of GHG's (specific methane gas) from ruminants, we need to divide them in four groups; nutrition, management, biotechnology and microbiology. In this article, we discussed nutritional factors related to emission of methane gases in ruminants. Other factors (factors related to management, biotechnology and microbiology) will discuss in further articles.

Key words: Greenhouse gases, methane, enteric fermentation, ruminant, nutrition

INTRODUCTION

Climate change is a subject of global environmental concern. Increased anthropogenic Greenhouse Gas (GHG) emissions have increased the global temperature the last 100 to 200 years. Global surface temperatures are predicted to increase between 1 to 6°C during the twenty-first century, primarily due to increased levels of Greenhouse Gases (GHGs) principally carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O) in the atmosphere (Sommer, 2005; Hopkins and Loblely, 2009; Leahy *et al.*, 2010). These gases absorb and re-emit long-wave radiation released by the earth back to the surface (GHGMP, 2005). Globally methane (CH₄) is contributing with 22% and nitrous oxide (N₂O) contributing to 6% of the total from all of the long-lived and globally mixed greenhouse gases. The high impact of N₂O and CH₄ on climate changes is due to respectively a 21 and a 310 times higher climate warming potential than that of carbon dioxide (Sommer, 2005).

Methane released to the atmosphere by domestic ruminant livestock is considered to be one of the three largest sources on a global scale. CH₄ emissions from agriculture represent around 40% of the emissions produced by human-related activities. Methane is the largest potential contributor to the global warming phenomenon. Fermentation of feeds in the rumen is the largest source of methane from enteric fermentation. It is estimated that enteric fermentation of ruminants contributes with 13-15% and livestock manure contributes 5% to the total emission of CH₄ in the 1990 ies. This influences the production of the different volatile fatty acids which has a marked effect on production of methane in the rumen. Acetate and butyrate promote methane production

while propionate formations can consider as a competitive pathway for hydrogen use in the rumen (Sommer, 2005; Gworgwor *et al.*, 2006; Leahy *et al.*, 2010).

EFFECT OF GHGs

While the regional impacts, magnitude and rate of change is subject to discussion, it is generally accepted that the average global temperatures will rise, along with many consequences on the environment, human and animal life. The National Institute of Water and Atmosphere New Zealand predicts that as a result of global warming, temperatures will increase by 0.3 to 1.4°C by 2030 and projected increases for 2070 of between 0.6 and 2.8 degrees. This will create a rise in sea levels up to 35 cm over the next 30-70 years (The Kyoto Protocol, 2001). Moss *et al.* (2000) similarly reported that by the year 2030 the world is likely to be 1.2°C warmer than today, however, given the full range of uncertainties, the range could be from 0.5 to 2.50°C. The concomitant rise in global mean sea level is 17 to 26 cm, with a full range of 5 to 44 cm; this is due mainly to thermal expansion of the oceans and increased melting of ice in the Arctic and Antarctic areas. Chaotic weather changes may result in droughts or floods and eventually massive erosion. These rise in temperatures will alter precipitation patterns, triggers extreme weather conditions and a rise in sea levels as mentioned above which can threaten fresh water sources, change delicate ecosystems, unmanaged types e.g. forest and others such as mountain flora and fauna, coral reefs and Islands, coastal regions, deserts and national parks. It will disrupt farming, fishing, forestry and many other industries that rely on the weather and natural ecosystems. There will be decreased crop yields and decreased arable land availability with subsequent starvation and malnutrition. This rise in temperature will alter the range of disease that threaten animals or human health such diseases include malaria, sleeping sickness and other infections disease that will affect the availability of human resources for the agricultural sector. Disease outbreaks will be rampant and the immune system of the animals will be lowered due to rise in temperature. It will also endanger animal habitat. Climate change will affect livestock productivity directly by influencing the balance between heat dissipation and heat production and indirectly through its effects on the availability of feed and fodder (Gworgwor *et al.*, 2006; Rowlinson *et al.*, 2008). However, it is notable that, nowadays greenhouse technology is using as useful agricultural technology in plant production (Kumar *et al.*, 2006).

APPLICATIONS OF METHANE GAS

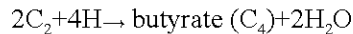
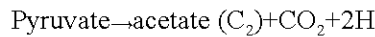
Biogas is a combustible mixture of gases, typically produced through a process known as anaerobic digestion of biomass. Anaerobic digestion can be seen as “composting without air”. Under normal conditions, such as in a compost bin, aerobic (oxygen breathing) organisms break down biodegradable organic materials into simpler forms of matter, producing carbon dioxide (CO₂) in the process. But in anaerobic digestion, biomass is decomposed under exclusion of air. In the absence of oxygen, a different type of (anaerobic) microorganisms breaks down the biomass, producing methane (CH₄), a combustible gas. In practice, biogas produced through anaerobic digestion is usually a mixture of methane (45-85%) and carbon dioxide (15-45%) with small amounts of other gases. It can be purified to achieve higher methane concentrations. The energy value of biogas depends on the methane concentration. Pure methane gas has an energy value of around 10 kWh m⁻³; biogas with a methane concentration of 60% can provide around 6 kWh m⁻³. Biogas should not be confused with what is known as “natural gas”, a gaseous fossil fuel consisting primarily of methane. Chemically, purified biogas and some types of natural gas are very similar and can be used with the same appliances. The important difference is that natural gas is a fossil fuel that

causes global warming, whereas biogas can be a sustainable, carbon-neutral energy source. Where biogas replaces firewood as a fuel for cooking, this technology helps to reduce deforestation. Also, as biogas burns much cleaner than traditional wood stoves, it helps to reduce eye and respiratory diseases caused by smoke in unventilated houses (the World Health Organization estimates that Exposure to indoor air pollution may be responsible for nearly 2 million excess deaths in developing countries). Anaerobic digestion has been very successful in developing countries with warmer climates. India and China have promoted biogas for more than 50 years and today there are several million installed digesters. The ultimate yield of biogas depends on the composition and biodegradability of the organic feedstock, but its production rate will depend on the population of microorganisms, their growth conditions and fermentation temperature. Depending on the digestion process, the methane content of biogas is generally between 55-80% (Jemmett, 2006; CAT, 2010).

METHANE PRODUCTION MECHANISMS

In the anaerobic conditions prevailing in the rumen, the oxidation reactions required to obtain energy in the form of ATP release hydrogen. The amount of hydrogen produced is highly dependant on the diet and type of rumen microbes as the microbial fermentation of feeds produces different end products that are not equivalent in term of hydrogen output. For instance, the formation of propionic acid consumes hydrogen whereas the formation of acetic and butyric acids releases hydrogen.

- 2H producing reactions
- H using reactions



From this it can be concluded that if ruminal fermentation patterns are shifted from acetate to propionate, both hydrogen and methane production will be reduced. This relationship between methane emissions and the ratio of the various VFA has been well documented and it provides opportunities to reduce methane emissions. Methanogenesis is the mechanism favoured by the rumen to avoid hydrogen accumulation. Free hydrogen inhibits dehydrogenases and affects the fermentation process. The utilisation of hydrogen and CO₂ to produce CH₄ is a specificity of methanogenic archaea. The methanogens interact with other rumen microorganisms enhancing the energy efficiency and extent of feed digestion. Positive interactions have been described for cellulolytic (*Ruminococcus albus* and *R. flavefaciens*) and non-cellulolytic bacteria (*Selenomonas ruminantium*), protozoa and fungi (O'Mara, 2004; Mirzaei-Aghsaghali *et al.*, 2008).

In addition to that in the rumen, also fermentation in the hindgut contributes to enteric CH₄ production. This contribution appears generally to be less than 10% and slightly lower than the contribution of the hindgut to the digestion of organic matter (Kebreab *et al.*, 2006). The opposite would be expected because hindgut fermentation yields relatively less propionate; hence more H₂ is formed than in the rumen. Apparently, the stoichiometry of VFA production differs between rumen and hindgut. A possible explanation is a higher contribution of acetogenesis to remove the H₂, because in comparison to the rumen conditions, fermentation conditions in the hindgut may be

more favourable for acetogenesis than for methanogenesis. With acetogenesis, acetate rather than CH₄ is formed from CO₂ and H₂. Hence, removal of H₂ by acetogenesis reduces CH₄ yield (Offner and Sauvant, 2006; Tamminga *et al.*, 2007).

On average the amount of CH₄ produced by a sheep is about 30 litres each day and a dairy cow up to almost 200 litres per day (GHGMP, 2005). Globally, ruminant livestock produce 80 million tonnes of CH₄ annually accounting for 33% of anthropogenic emissions of CH₄ (Beauchemin *et al.*, 2008). Enteric CH₄ is produced under anaerobic conditions in the rumen, by methanogenic Archaea, utilising CO₂ and H₂ to form CH₄, thus reducing metabolic H₂ produced during microbial metabolism (McAllister and Newbold, 2008). If H₂ accumulates, re-oxidation of NADH is inhibited, inhibiting microbial growth, forage digestion and the associated production of acetate, propionate and butyrate. Thus any mitigation strategy aimed at reducing methanogen populations must include an alternative pathway for H₂ removal from the rumen as well. With an energy content of 55.22 MJ kg⁻¹ CH₄ represents a significant loss of dietary energy from the production system. Typically, about 6 to 10% of the total gross energy consumed by the dairy cow is converted to CH₄ and released via the breath. Thus reducing enteric CH₄ production may also lead to production benefits (Brouwer, 1965; Joblin, 1999).

FACTORS RELATED TO NUTRITION

Forage: Although the capacity to perform pregastric fermentation enables ruminants to utilise forage species unsuitable for other animals, their environmental impact is disproportionate. Due to the size of the 'global herd' (estimated to be 3.45 billion cattle, buffalo, sheep and goats in 2007), relatively modest improvements in performance could result in significant effects in terms of lowering the generation of undesirable emissions. In the case of ruminants most of the GHG production is related to enteric fermentation (40%), the second most relevant contribution being that related to the production of forages and feeds (36%). Forage rich diets result in acetic type fermentation, with an increase of methane production compared to propionic type fermentation which, on the other hand, is stimulated by concentrates (Rowlinson *et al.*, 2008; Kingeston-Smith *et al.*, 2010). Johnson and Johnson (1995) reported a methane energy loss of 6 to 7% of gross energy intake when forages were fed at the maintenance plane of nutrition. Increasing forage digestibility increases daily methane emissions because of increased intake. However, at high intake levels, the proportion of energy lost as methane decreases as the digestibility of the diet increases (Johnson and Johnson, 1995). In addition, improving forage digestibility will improve productivity because DM and energy intake are increased. Kurihara *et al.* (1997) reported methane production of 33-75 g per kg digested organic matter intake for forage-based beef cattle in tropical Australia. However, Selecting forages high in non fiber carbohydrates could reduce methane emissions. There is also evidence that using clovers and grasses with high WSC in animal diets can directly reduce methane emissions (Lovett *et al.*, 2004). It has been demonstrated that increasing the WSC content in perennial ryegrass by 33 g kg⁻¹ reduces methane production in vitro by 9% (Rowlinson *et al.*, 2008).

Quality and maturity: Forage quality has a significance impact on enteric CH₄ emissions (Sejian *et al.*, 2011). Improving forage quality, either through feeding forages with lower fibre and higher soluble carbohydrates, changing from C₄ to C₃ grasses, or even grazing less mature pastures can reduce CH₄ production (Beauchemin *et al.*, 2008; Ulyatt *et al.*, 2002). Methane production per unit of cellulose digested has been shown to be three times that of hemicellulose (Moe and Tyrell, 1979), while cellulose and hemicellulose ferment at a slower rate than non-structural carbohydrate,

thus yielding more CH₄ per unit of substrate digested (McAllister *et al.*, 1996). Improving forage quality tends to increase voluntary intake and reduces retention time in the rumen, promoting energetically more efficient post-ruminal digestion and reducing the proportion of dietary energy converted to CH₄ (Blaxter and Clapperton, 1965). Methane emissions are also commonly lower with higher proportions of forage legumes in the diet, partly due to lower fibre content, faster rate of passage and in some cases the presence of condensed tannins (Beauchemin *et al.*, 2008). Improving diet quality can both improve animal performance and reduce CH₄ production, but also improve efficiency by reducing CH₄ emissions per unit of animal product. Methane up to 15-18% of the digestible energy may be produced where cattle are fed on poor quality forage. Johnson and Johnson (1995) reported that methane emissions from enteric fermentation represent about 6% of dietary gross energy, but this varies with diet from about 2% (cattle in feedlots) to 12% (animals eating very poor quality forage) (O'Mara, 2004). Supplementing forages whether of low or high quality, with energy and protein supplements, is well-documented to increase microbial growth efficiency and digestibility. The direct effect however, on methanogenesis is still variable and unclear, but indirectly, methane production per unit product will decline (Gworgwor *et al.*, 2006).

Increasing forage quality combined with the management of stocking rates and rotational grazing strategies have been demonstrated to reduce enteric methane emissions (FAO, 2010). Researchers observed that a reduction in forage *in vitro* organic matter digestibility (i.e., decline in forage quality) also resulted in an increase in CH₄ emissions when animals were fed *ad libitum*. Some other feed characteristics can affect methane production. It increases when mature dried forages are fed or when they are coarsely chopped rather than finely ground or pelleted and decreases when forages are preserved in ensiled form. Because they stimulate the rumen degradation of plant cell walls, alkali-treatments of poor-quality forages have been shown to increase the amount of methane emissions. Generally, the correlation between forage quality and CH₄ emissions is low (Boadi *et al.*, 2004; Pinares-Patino *et al.*, 2007; Beauchemin *et al.*, 2008).

Processing and preservation: Forage processing and preservation affect enteric CH₄ production but limited information with regard to these effects is available in the literature. Methanogenesis tends to be lower when forages are ensiled than when they are dried and when they are finely ground or pelleted than when coarsely chopped (Martin *et al.*, 2010). Grinding or pelleting of forages to improve the utilization by ruminants has been shown to decrease CH₄ losses per unit of feed intake by 20-40% when fed at high intakes. The explanation for the decline in CH₄ production is due to the lower fibre digestibility, decreased ruminally available organic matter and faster rate of passage associated with ground or pelleted forages (GHGMP, 2005). The main limitation to the potential use of more processed forage feed to reduce CH₄ emission is the economical cost to cattle producers. Woodward *et al.* (2001) observed some of the highest CH₄ losses reported in the literature associated with feeding ryegrass silage and lotus silage. This would not be unexpected since digestion is reduced in the rumen with ensiled forages due to the extensive fermentation that occurs during silage making. However, these nutritional strategies need additional research.

Species and maturity: It is recognized that CH₄ production in ruminants generally increases with forage maturity and that CH₄ yield from the ruminal fermentation of legume and legume-grass forages is also generally lower than the yield from grass forages (McAllister *et al.*, 1996; Moss *et al.*, 2000); Although, Van Dorland *et al.* (2007) reported no differences. Explanation for the reduced CH₄ emissions can be attributed to the lower proportion of structural carbohydrates in legumes and

faster rate of passage which shift the fermentation pattern towards higher propionate production (Johnson and Johnson, 1995). However, it has also been reported that legumes give rise to reduced methane emissions when fed at comparable intake levels (Beever *et al.*, 1985). There are substantial differences in the carbohydrate fractions of forages such as grass silage, maize silage or whole crop wheat silage which will affect their methanogenic potential. In addition, these forages can give rise to differences in productivity: e.g. maize silage supports higher intake and performance than grass silage. Within a forage species, there may be potential to select cultivars that result in reduced methane production. Recent *in vitro* work (Lovett *et al.*, 2003) has demonstrated differences between cultivars of perennial ryegrass in their methanogenic potential. The differences were significantly related to chemical composition of the cultivars, but differences between cultivars could also be due to differences in contents of organic acids. According to the prediction model of Benchaar *et al.* (2001), the substitution of timothy hay by Lucerne decreases CH₄ emissions by 21% (expressed as % of digestible energy). Mirzaei-Aghsaghali *et al.* (2008) and Maheri-Sis *et al.* (2008a) have demonstrated gas production volume and difference of methane emission between cultivars of Lucerne and also between legume (Lucerne) and weed grasses (quack grass). They are reported that amount of methane production from grasses was higher than that of legumes. Higher fibre content leads to higher methane production. In a direct comparison, McCaughey *et al.* (1999) observed on grazing beef cattle a 10% decrease in CH₄ production by unit of product when grasses were replaced by a mixture of Lucerne and grasses (70:30). The authors concluded that this was due to the higher intake observed for Lucerne-fed animals which was related with a higher digestibility rate and an increased passage of feed particles out of the rumen. Tropical grasses fed to ruminants are generally 13% less digestible than temperate grasses which are due to differences in the anatomical structure of the plants and higher temperatures at which tropical species are grown (Minson, 1990). Margan *et al.* (1988) measured methane (% GE intake) for sheep offered two tropical forages (i.e., *Setaria speculata* and *Digetaria decumbens* (Pangola)) and two temperate forages (i.e., *Lolium perenne* (Ryegrass) and *Trifolium resupinatum* (Persian clover)). They showed that methane yield was higher for the tropical forages than for the temperate forages. MCR (methane conversion rate) of tropical forage species is presumably related to the relatively high levels of fibre and lignin, low levels of non-fibre carbohydrate (Van Soest, 1994) and low digestibility (Minson, 1990) compared with temperate forage species. These observations suggest that tropical forage species may have higher MCR than temperate forage diets; however, before concluding this wider range of tropical species should be investigated.

Concentrate: The composition of the feed has been shown to influence enteric fermentation and emission of CH₄ from the rumen or the hindgut. In ruminants the effect of feed composition is much higher (Rowlinson *et al.*, 2008). Diets with a high proportion of concentrates that promote a high propionate type of ruminal fermentation are conducive to reducing ruminal methane production, but the effect on total farm GHG emissions may be less (O'Mara, 2004). The forage to concentrate ratio of the ration has an impact on the rumen fermentation and hence the acetate: propionate ratio (declines with F: C ratio). It would therefore be expected that methane production would be less when high concentrate diets are fed (Moss *et al.*, 2000). Johnson and Johnson (1995) reported a methane energy loss of 6 to 7% of gross energy intake when forages were fed at the maintenance plane of nutrition and this reduced to 2-3% when high grain concentrates (>90%) were offered at near *ad libitum* intake levels.

Concentrate proportion: The proportion of concentrates in dairy diets is often included as an explanatory factor in empirical models of CH₄ production (Yan *et al.*, 2000). Increasing the dietary proportion of concentrates usually reduces CH₄ losses. The CH₄ reduction is well in line with the observations of Bannink *et al.* (1997) that concentrate rich diets showed lower and higher coefficients of conversion of substrate into acetate and propionate, respectively. Increasing the proportion of concentrates is limited by a required minimum level of physical structure in the diet (prevention of (sub-) clinical acidosis) and the balance between energy intake and requirements (prevention of excessive overfeeding) in low producing animals (dry and late lactation cows, young stock) (Tamminga *et al.*, 2007).

The proportion of concentrate within the diet has been reported to be negatively correlated with methane emissions (Yan *et al.*, 2000). Concentrates contain less structural carbohydrates than forages and the effect of increasing the proportion of concentrates in the diet on ruminal VFA concentrations is well documented, with an increase in the proportion of propionate and a decrease in the proportion of acetate (and sometimes butyrate). This would be expected to impact on methane production. Also, increasing the proportion of concentrate in the diet will generally reduce rumen pH and as methanogens are pH sensitive, this will also tend to reduce methane emissions. Sometimes the effect of concentrate proportion is compounded by increases in total intake, but when expressed as a proportion of gross energy intake, reductions in methane production are generally found as the proportion of concentrate increases, with these reductions being most dramatic when concentrates form the major proportion of the diet (Johnson and Johnson, 1995).

As indicated by the equations proposed by Giger-Reverdin *et al.* (2000), CH₄ production in the rumen decreases when the proportion of concentrate in the ration increases. The composition of the diet also affects the excretion of N and organic matter which both will affect the emission of GHG (N₂O and CH₄, respectively) during manure storage and spreading. As a consequence, improving the composition of the diet to decrease N excretion which is often proposed to reduce eutrophication (NO₃⁻) and acidification (NH₃) impacts, might also be of interest for the reduction GHG (Rowlinson *et al.*, 2008). However, many experimental databases suggest that a higher proportion of concentrate in the diet leads to a reduction in CH₄ emissions as a proportion of energy intake (Blaxter and Clapperton, 1965; Yan *et al.*, 2000) due mainly to an increased proportion of propionate in ruminal VFA. The scope for reductions in CH₄ emissions depends on the starting level of concentrates, as there are dietary limitations and there are large differences in current usage of concentrates in different regions of the world (Rowlinson *et al.*, 2008).

Replacing plant fibre in the diet with starch induces a decrease in ruminal pH and modifications in microbial populations. A shift of VFA production from acetate towards propionate occurs which results in less hydrogen production. The poor tolerance to low pH by protozoa and cellulolytic bacteria decreases further hydrogen production. A positive correlation between cellulolytic and methanogens in the rumen of different animal species (cattle, sheep, deer) has been shown (Rowlinson *et al.*, 2008), except in the buffalo. This exception was explained by the fact that *F. succinogenes*, a non-hydrogen-producing cellulolytic species, was the major cellulolytic bacteria of this animal. The relationship between concentrate proportion in the diet and methane production is curvilinear (Sauvant and Giger-Reverdin, 2007) with a marked decrease in methane observed when dietary starch is higher than 40%. This has been assessed in young bulls by Martin *et al.* (2007) compared to diets containing 30% starch, a diet containing 45% starch decreased methane production by 56% without altering animal growth.

On the contrary to other researchers, Sejian *et al.* (2011) reported that higher proportion of forage to concentrate resulted in decreasing ruminal methane production. They are stated that

lower CH₄ production from high forage: grain diet can be attributed to the effect of the high content of fat in the diet which could potentially reduce fiber degradation and amount of feed that is fermentable as well as forage grinding effects.

It is important that form of the statement of methane production can be different and missed concept in the different investigations (i.e. methane production per day per animal, per day per live weight or metabolic weight of animal and per day per production level such as milk yield, etc).

Concentrate type or nature: Moss *et al.* (2000) found a similar effect when grass silage was supplemented with barley. Van Soest (1982) indicated that a high grain diet and the addition of soluble carbohydrates gave a shift in fermentation pattern in the rumen which give rise to a more hostile environment for the methanogenic bacteria in which passage rates are increased, ruminal pH is lowered and certain populations of protozoa, ruminal ciliates and methanogenic bacteria may be eliminated or inhibited. The work of Lana *et al.* (1998) supports this theory confirming that low rumen pH regulates methane production. Consequently a greater net benefit to the atmosphere might result from the use of more fibrous concentrates due to their lower embedded GHG emissions. However, there has been little work to compare methane production on different concentrates. This could be of interest as there is a large selection of concentrate ingredients available, ranging from cereals (low in fibre, high in starch) to cereal-by-products (high in fibre, low in starch), pulps (high fibre), molasses (high sugar), oilseed meals (high in protein, variable in fibre), etc. Ovenell-Roy *et al.* (1998) reported differences in methane production from 4 cultivars of barley fed to lambs. The higher methanogenic potential of fibrous feedstuffs has been mentioned. Yurtseven and Ozturk (2009) observed that amount of ruminal methane produced from corn was lower than that of barley grain in ruminant. This is may be due to higher starch content and slow starch degradability of corn vs. barley grain. Johnson and Johnson (1995) noted that soluble sugars have a higher methanogenic potential than starch. Research is required to establish if concentrates can be formulated to bring about significant reductions in methane production.

Reductions of CH₄ losses will be limited to less than 5%. When dealing with concentrates, the report assumes a further increase in the amount of concentrate consumption per animal. With regard to the ingredient composition of concentrates, selecting carefully defined carbohydrate fractions, such as more starch of a higher rumen resistance and less soluble sugars could significantly contribute to a reduction in CH₄ emission (Tamminga *et al.*, 2007).

Concentrates and concentrate ingredients are quite variable with regard to their content of structural (cellulose, hemicelluloses) and non-structural (starch, sugars) carbohydrates. The degradative behaviour of both groups of carbohydrates also varies widely, notably the rate of degradation of starch. Consequently, VFA profile and CH₄ loss vary accordingly. In beef cattle it was shown (Johnson and Johnson, 1995) that digested cell walls normally lead to higher losses than non cell wall components and that within non cell wall components soluble sugars are more methanogenic than starch. All carbohydrate fractions yielded CH₄, but the highest contribution to CH₄ losses came from sugars (Tamminga *et al.*, 2007). Maheri-Sis *et al.* (2008b) reported that variety and type of legume grain can be affect *in vitro* gas production volume. Different gas production can be due to different chemical constituents of legume variety and type, animal types and breeds and quality of inoculums source. There was a positive correlation between NFC content of feeds and total gas production, but feed CP, NH₃-N and NDF levels were negatively correlated with total gas production. It is well know that increasing gas production essentially not to meaning increasing the methane production.

Sejian *et al.* (2011) indicated that adding flax seed to the diet of dairy cattle can be an effective means of reducing CH₄ emissions. However, over supplement of flax seed may reduce CH₄ but at the expense of diet digestibility in addition to possible negative effects on milk production of high-producing dairy cows. This critical point should not be overlooked while targeting reduction of enteric CH₄ emission.

Concentrate level: Lovett *et al.* (2006) examined the effect on-farm and off-farm emissions of increasing concentrate feeding from 376 to 810 and 1540 kg/cow/lactation. Total emissions (both on and off-farm) were 1.149, 1.103 and 1.040 kg CO₂ equivalents per kg milk respectively, for low, medium and high concentrate levels, i.e. a decrease of 9.5% between the extremes. The financial cost to the producer of implementing the measure depended on the pedigree index of the cows. With low or medium index cows, costs were higher. With high index cows, it was profitable to go to the higher concentrate level (Rowlinson *et al.*, 2008).

Digestibility of feeds: Pelchen and Peters (1998) saw, when comparing 89 references from literature concerning methane emissions from sheep that an increasing intake of digestible energy, crude fibre and N-free extracts also increased the amount of CH₄ emitted. On the other hand, an increasing intake of crude protein and a higher energy density of the diet decreased the emissions. Increasing digestibility of rations heightens the methane emissions, but at digestibility above around 72% the increasing effect on the emissions faded out. As the digestibility of a feed increases, the amount energy available to the animal also increases and therefore the methane emitted per kg of production for example growth decreases. Therefore, increased digestibility of diets often means less methane emissions per unit of production (Allard, 2009).

Level of feeding: The digestibility of a feed usually decreases when the feeding level increases. Feeding level is defined as the amount of feed consumed, divided with the feed requirements for maintenance. In an experiment the same types of feed were fed to several sheep but in diets with varying degrees of covering the maintenance requirements. The feed was given covering 0.9, 1.7 and 2.3 of the requirements and the proportions energy lost as methane of gross energy were 10.8, 9.3 and 8.2% (Allard, 2009). Pelchen and Peters (1998) also found that higher levels of feeding decreased the percentage of gross energy lost as methane, supporting the results methane production (g/day) increases but methane yield (% of gross energy) decreases with an increasing feeding level. The amount of methane increases because of the higher energy intake, but the percentage of gross energy lost as methane produced decreases, as less of the energy contained in the feed is available for digestion at high feeding levels. Therefore the percentage energy lost as methane of the total gross energy also decreases. This change in emissions is smaller for feeds of lower quality which have lower digestibility (Allard, 2009).

Feeding systems: Feeding systems that allow choice may provide one mechanism by which ruminants can select optimum feed ingredients to balance ruminal fermentation in favor of the propionic acid (Yurtseven and Ozturk, 2009). Yurtseven *et al.* (2009) were studied different feeding systems (choice feeding and conventional system) on performance and emission of carbon dioxide and enteric methane and indicated that the choice feeding system may be a potential mitigating effect on enteric emission of CH₄ and CO₂. Because choice feeding create a less favorable rumen environment for methanogenesis through an increased rate of passage and rate of digestion, depression of rumination and depression of rumen pH. This system, may avor

propionate-producing bacteria over acetate producers, making less hydrogen available to methanogens. Sejian *et al.* (2011) reported that Total mixed ration (TMR) feeding leads to decrease methane production vs. separate forage-concentrate feeding.

By-products: Many by-products have a substantial potential nutritional value as animal feedstuffs. Most Ruminants, especially, have the unique capacity to utilize fibrous by-products because of their rumen microbes (Mirzaei-Aghsaghali and Maheri-Sis, 2008). It is well known that amount of ruminal gas produced from various by-products may be different due to their variable cell wall and cell content (Maheri-Sis *et al.*, 2007; Aghajanzadeh-Golshani *et al.*, 2010; Mirzaei-Aghsaghali *et al.*, 2011). Structural carbohydrates (cellulose and hemicelluloses) ferment at slower rates than non structural carbohydrates (starch and sugars) and yield more CH₄ per unit of substrate fermented due to greater acetate: propionate ratio. It has also been suggested that non-structural carbohydrates should be further subdivided as soluble sugars have a higher methanogenic potential than starch. This suggests that cereal feedstuffs will result in lower emissions than by-product feedstuffs with higher fibre levels. However, if looking at a systems analysis, GHG emissions associated with the cultivation and subsequent processing of starch-based animal feeds will have to be fully attributed to the animal feed whereas the emissions associated with cultivation and processing of by-products (e.g. sugar beet pulp) have to be divided between the waste product (beet pulp) and the main product (sugar) (Johnson and Johnson, 1995; Rowlinson *et al.*, 2008).

Plant secondary components: In recent years, there is growing interest in the use of plant secondary compounds (tannins and saponins) as a CH₄ mitigation strategy because of their natural origin in opposition to chemicals additives. Most trials with plant extracts have been done in vitro and the response of these molecules on methanogenesis is highly variable. For tannin containing plants, the antimethanogenic activity has been attributed mainly to condensed tannins. There are two modes of action of tannins on methanogenesis: a direct effect on ruminal methanogens and an indirect effect on hydrogen production due to lower feed degradation. Also, there is evidence that some Condensed Tannins (CT) can reduce CH₄ emissions. CTs are flavonoid polymers which complex with soluble protein and render them insoluble in the rumen yet release them under the acidic conditions found in the small intestine, reducing bloat and increasing amino acid absorption. Legumes containing condensed tannin (e.g., *Lotuses*) are able to lower methane (g kg⁻¹ DM intake) by 12-15% (Beauchemin *et al.*, 2008; Rowlinson *et al.*, 2008). Also, some authors reported that condensed tannins to reduce CH₄ production by 13 to 16% (DMI basis) (Grainger *et al.*, 2009; Woodward *et al.*, 2004), mainly through a direct toxic effect on methanogens. However, high CT concentrations (>55 g CT/kg DM) may reduce voluntary feed intake and digestibility (Beauchemin *et al.*, 2008; Grainger *et al.*, 2009). Waghorn *et al.* (2002) reported a 16% depression in CH₄ emissions kg⁻¹ DMI (from 13.8 to 11.5 g kg⁻¹ DMI) due to the presence of CT in a diet of *Lotus pedunculatus* fed to sheep housed indoors. More recently (Woodward *et al.*, 2004) carried out a similar trial with cows fed *Lotus corniculatus*, containing a lower concentration of CT in the DM (2.62 g/100 g) compared to 5.3% in the *L. pedunculatus* fed to sheep. This trial comprised four treatments, ryegrass/white clover without and with PEG and *L. corniculatus* without and with PEG. Methane was 24.2, 24.7, 19.9 and 22.9 g kg⁻¹ DMI for the respective treatments. The CT in *lotus* reduced methane kg⁻¹ DMI by 13% and the cows fed *lotus* produced 32% less methane kg⁻¹ milk solids (fat+protein) compared to those fed good quality ryegrass. Puchala *et al.* (2005) have reported low CH₄ emissions from goats fed *Serecia lespedeza* (*Lespedeza cuneata*) containing 6% CT

in the DM, compared to grass dominant forage (6 vs. 14.1 g kg⁻¹ DMI for the respective diets). CT inhibit microbial activity in vitro and in vivo but proportions of VFA are unchanged, so there will be a similar yield of hydrogen with or without CT. Mechanisms by which polyphenolics affect a reduction in methanogenesis are speculative (Waghorn and Woodward, 2004). Such plants offer the prospect of methane reduction in the grazing environment (Ulyatt and Lassey, 2001). In New Zealand, research has been conducted on examining the mitigation potential of condensed tannin forage species, such as sulla (*Hedysarum coronarium*) and birdsfoot trefoil (*Lotus corniculatus*) (Woodward *et al.*, 2002, 2004). Results from Woodward *et al.* (2002) observed a 25% reduction per kg of DM intake in CH₄ emissions from dairy cows grazing the legume sulla compared to perennial ryegrass. Similar results were also observed by Woodward *et al.* (2001 and 2004) when birdsfoot trefoil was grazed verses perennial ryegrass-based pastures. McAllister and Newbold (2008) reported that extracts from plants such as rhubarb and garlic could decrease CH₄ emissions. While there is insufficient evidence to conclude on the potential of plant secondary compounds or extracts as mitigation strategies, this is likely to be an area of significant research over the coming years. An approach of current interest, supported by some promising initial findings, is the use of tannin containing forages and breeding of forage species with enhanced tannin content. Forage legumes such as *Lotus corniculatus* (*Birdsfoot trefoil*) and *L. uliginosus* (greater trefoil) possess secondary metabolites known as condensed tannins (CTs) in their leaves. They are not present in the leaves of white or red clover but are present in the inflorescences. Recent studies have shown that methane production values were lower in sheep fed on red clover and birdsfoot trefoil than on a ryegrass/white clover pasture. The extent of variation in CT content between and within varieties of *Lotus corniculatus* and *L. uliginosus* has been recently confirmed (Rowlinson *et al.*, 2008).

Saponins are natural detergents found in many plants. Saponins have detergent or surfactant properties because they contain both water-soluble and fat-soluble components. They consist of a fat-soluble nucleus, having either a steroid or triterpenoid structure, with one or more side chains of water-soluble carbohydrates. The two major commercial sources of saponins are *Yucca schidigera* which grows in the arid Mexican desert and *Quillaja saponaria*, a tree that grows in arid areas of Chile (Pen, 2007). There has been increased interest in saponin-containing plants as possible means of suppressing or eliminating protozoa in the rumen. A decrease in protozoa numbers has been reported in the rumen of sheep infused with saponins or fed on saponin-containing plants. Decreased numbers of ruminal ciliate protozoa may enhance the flow of microbial protein from the rumen, increase efficiency of feed utilization and decrease methanogenesis. Saponins are also known to influence both ruminal bacterial species composition and number through specific inhibition, or selective enhancement, of growth of individual species. Additional research *in vivo* is required to determine the optimal dose of the active compounds, to consider the potential adaptation of the microbes, the presence of residues in animal products as well as the potential anti-nutritional side-effects of such molecules (Calsamiglia *et al.*, 2007; Pen, 2007). *Yucca* extract has been reported to reduce ruminal NH₃-N concentrations *in vitro* (Takahashi *et al.*, 2000) and *in vivo* (Santoso *et al.*, 2004) which might be attributed to its NH₃-binding properties or its inhibitory effects on ciliate protozoa in the rumen (Pen, 2007). Saponins have been shown to possess strong defaunating properties both *in vitro* and *in vivo* which could reduce CH₄ emissions (Rowlinson *et al.*, 2008). Beauchemin *et al.* (2008) recently reviewed literature related to their effect on CH₄ and concluded that there is evidence for a reduction in CH₄ from at least some sources of saponins, but that not all are effective (Rowlinson *et al.*, 2008). While extracts of CT and saponins may be commercially available, their cost is currently prohibitive for routine use in ruminant

production systems. However, still required on the optimum sources, level of CT astringency (chemical composition), plus the feeding methods and dose rates required to reduce CH₄ and stimulate production.

Dietary supplements and additives: Dietary supplements offer potential to profitably reduce CH₄ emissions from intensive ruminant production systems, with many strategies already available for implementation on-farm. Such as, yeast cultures of *Saccharomyces cerevisiae* potentially stimulate acetogenic microbes in the rumen, consuming H₂ to form acetate, thus potentially reducing CH₄ production. However, results appear to be strain dependent and variable in their impact on CH₄ production in the rumen (Chaucheyras *et al.*, 1995; McGinn *et al.*, 2004).

Probiotics: There is extensive literature concerning the impact of feed additives on methanogenesis (Moss *et al.*, 2000; Klieve and Joblin, 2007), so a brief summary of viable options is presented here. Feed additives may be hydrogen sinks, influence the rumen microflora to lower hydrogen production or influence the methanogenic archaea directly. Antibiotics, bacteriocins and probiotics seem to have short-term effectiveness (Moss *et al.*, 2000) and all need to be evaluated *in vivo*. Consistent responses are essential for commercial application. Products must be acceptable to consumers and increased use of antibiotics is likely to be restricted by legislation (Waghorn and Woodward, 2004). Treatment of animals with growth promoting substances can result in increased efficiency of production. An example, Bauman *et al.* (1985) based on bovine somatotrophin (bST) treatment of milking cows showed that as bST dose was increased, milk production per unit intake (efficiency) increased and methane emitted per kg milk was calculated to decrease. Growth stimulants such as steroids would be expected to have a similar effect: less feed and methane overall to achieve the same level of production. All these techniques use dilution of maintenance requirements to achieve reduced methane emission.

The use of probiotics or the stimulation of rumen microbial populations capable to decrease methane emissions potentially remains an interesting approach. Diverting hydrogen from methanogenesis towards acetogenesis has been assayed by several authors. The final product of the reaction, acetate, has the additional advantage of being a source of energy for the animal. However, in the rumen environment, acetogens are less efficient than methanogens in the competition for reducing equivalents and attempts to boost their activity had been so far unsuccessful. The recent isolation of new, high hydrogen utilizing species from diverse gut environments could offer a better alternative than previously tested acetogens. Methanotrophy, i.e., the oxidation of methane, was reported to be less than 0.5% *in vitro*. However, it has not been quantified *in vivo* where conditions at the rumen epithelium may favour aerobic oxidation of methane. Capnophily, i.e., the ability to use CO₂, is also present in the rumen. Capnophilic bacteria also use hydrogen to produce organic acids as final products but the influence that they have on hydrogen balance is not known (Kajikawa *et al.*, 2003; Klieve and Joblin, 2007).

Ionophores: Ionophores (e.g. monensin) are antibiotics produced by bacteria (*Streptomyces* spp.). Several ionophores have been licensed for use in beef cattle in many countries and dairy cows in some countries (e.g. Australia, Mexico and Brazil). The review of National Research Council (2001) outlined increases in milk production, better feed conversion efficiency, reduced acidosis, ketosis and bloat resulting from the feeding of ionophores. In the rumen, they increase the proportion of gram positive bacteria, resulting in a shift in fermentation acids from acetate and butyrate to propionate,

consequently methane production is reduced (National Reserch Council, 2001). Intake is also reduced in many experiments, with O'Kelly and Spiers (1992) calculating that this is responsible for 0.55 of the decline in methane emissions following monensin application. However, researchers have reported that the effects on methane production are transient indicating that microbial adaptation occurs (O'Mara, 2004). Monensin is available in a slow release (100 day) formulation and is used to reduce the risk of bloat in cattle and can lower methane emissions. Clark *et al.* (2005) reported emissions of 158 and 179 g CH₄ day⁻¹ from cows fed ryegrass based pasture with and without monensin treatment. Intakes were not affected by monensin and there was a significant reduction in methane kg⁻¹ milk solids (milk fat+protein) for monensin (375 g kg⁻¹) vs. control (420 g kg⁻¹) cows. In that study the monensin treatment continued to lower methane emission after 60 days but persistence of methane suppression by ionophors is variable and often not sustained (Waghorn and Woodward, 2004).

Among feed additives, ionophore antibiotics such as monensin, typically used to improve efficiency of animal production, are known to decrease methane production (Beauchemin *et al.*, 2008). This is due to a shift of fermentation towards propionogenesis, but these additives are now forbidden in the European Union. Other chemical additives, of which neither the efficiency nor the innocuity has been proven, are not described here. Monensin should reduce CH₄ emissions because it reduces DMI and because of a shift in rumen VFA proportions towards propionate and a reduction in ruminal protozoa numbers. *In vivo* studies have shown that animals treated with monensin emit reduced levels of CH₄ (McGinn *et al.*, 2004) but others have reported no significant effect (Waghorn, 2008). Van Nevel and Demeyer (1996) reviewed 9 experiments and concluded that on average monensin reduces CH₄ production as a proportion of gross energy intake by 0.18, with the extent of the reduction being related to the dose and type of diet. Some work has suggested that the monensin induced reduction in CH₄ production may be transitory with CH₄ emissions returning to pre-treatment levels in a period as short as 14 days. This is despite the changes in VFA proportions persisting. Not all long term studies have shown that the effect is transitory. The reason for the differences between studies is not clear and further work is needed to determine the reduction potential, particularly in dairy cow feeding where the supplementation is long term. But even if the response is transitory, the impact on DMI persists and should reduce CH₄ emissions by up to 5%, due to the strong relationship between CH₄ production and DMI. However, there are regulations to prevent the use of ionophores as a dietary (Rowlinson *et al.*, 2008).

Dietary oils: Assuming that most forages have some fat content and that DMI may be suppressed at fat intakes above 6 to 7%, CH₄ abatements of 10-25% are possible from the addition of dietary oils to the diet of ruminants (Beauchemin *et al.*, 2008). There are five possible mechanisms by which lipid supplementation reduces CH₄: reducing fibre digestion (mainly in long chain fatty acids); lowering DMI (if total dietary fat exceeds 6-7%); suppression of methanogens (mainly in medium chain fatty acids); suppression of rumen protozoa and to a limited extent through biohydrogenation (McGinn *et al.*, 2004; Beauchemin *et al.*, 2008; Johnson and Johnson, 1995).

The inclusions of unsaturated fatty acids in ruminant diets depress protozoal numbers and the use of lipids as a defaunating agent has been suggested. Fat inclusion in the diet causes a marked decrease in methane production by rumen fluid with the effect being at least partly governed by the fat source used. However, the effects of fat on methane production are not limited to those mediated via the rumen protozoa. Lipids have also been shown to inhibit methanogenesis even in the absence of rumen protozoa, possibly due to the toxicity of long chain fatty acids to

methanogenic bacteria. However, as with defaunation, the effect of fat supplementation cannot be viewed in isolation (GHADS, 2005; Gworgwor *et al.*, 2006).

As outlined above, defaunation or removal of protozoa from the rumen is one method which could reduce methane emissions. One method by which defaunation can be brought about is the addition of certain oils/fats. In the absence of protozoa, rumen CH₄ output is reduced by 0.13 on average, although this varies with diet. The magnitude of reduction in CH₄ output following dietary supplementation of fats/oils is source dependent, with coconut oil identified as being very effective (O'Mara, 2004; GHADS, 2005). Recent studies with beef cattle have shown it to be effective in reducing methane emissions at 0.045 of DM intake (Lovett *et al.*, 2003) and also that the response is linear from low to moderate levels (Jordan *et al.*, 2004). There are reductions in intake and diet digestibility, but in two growth studies (Lovett *et al.*, 2003); these were compensated for by the increased dietary energy density and the reduced energy loss as methane (O'Mara, 2004).

Oils offer a practical approach to reducing methane in situations where animals can be given daily feed supplements, but excess oil is detrimental to fibre digestion and productions. Oils may act as hydrogen sinks but medium chain length oils appear to act directly on methanogens and reduce numbers of ciliate protozoa (Machmuller *et al.*, 2000). In contrast, Johnson *et al.* (2002) and (2008) found no response to diets containing 2.3, 4.0 and 5.6% fat (cottonseed and canola) fed over an entire lactation.

Oils containing C12 (lauric acid) and C14 (myristic acid) are particularly toxic to methanogens (Rowlinson *et al.*, 2008). The addition of FA to the diet, particularly those of medium (C12-C16) and unsaturated long (>C16) carbon chain length have also been shown to depress CH₄ production. These longer chains FA have the capacity to hold more H₂ atoms and thus may be more able to influence the H₂ balance in the rumen when large quantities are included in the diet compared to shorter chain FA (Ellis *et al.*, 2008). Jouany *et al.* (2008) showed that utilization of polyunsaturated fatty acids, especially from linseed, to decrease rumen methanogenesis may be a practical abatement technology in ruminant production. The use of products from linseed is interesting owing to a simultaneous enhancement of the nutritional value of milk and ruminant meat, provided that linseed supply does not decrease overall fermentation and thus does not impair animal performance. Beauchemin *et al.* (2008) recently reviewed the effect of level of dietary lipid on CH₄ emissions over 17 studies and reported that with beef cattle, dairy cows and lambs, there was a proportional reduction of 0.056 in CH₄ (g kg⁻¹ DM intake) for each 10 g kg⁻¹ DM addition of supplemental fat. While this is encouraging, many factors need to be considered such as the type of oil, the form of the oil (whole crushed oilseeds vs. pure oils), handling issues (e.g., coconut oil has a melting point of 25°C) and the cost of oils which has increased dramatically in recent years due to increased demand for food and industrial use. In addition, there are few reports of the effect of oil supplementation on CH₄ emissions of dairy cows, where the impact on milk fatty acid composition and overall milk fat content would need to be carefully studied. Strategies based on processed linseed turned out to be very promising in both respects recently. Most importantly, a comprehensive whole system analysis needs to be carried out to assess the overall impact on global GHG emissions (Rowlinson *et al.*, 2008).

Enzymes: Enzymes in the form of cellulases and hemicellulases, added to the diet of ruminants, have been shown to improve ruminal fibre digestion and productivity and, perhaps through reducing the acetate-to-propionate ratio, reduced CH₄ by 28% *in vivo* and 9% *in vivo*. These

enzymes are widely used in the food processing, textile and paper industries, with potential for large quantities to be available at reasonable cost. Further research is still required to screen a large number of enzymes to isolate those with both a production benefit and significant CH₄ abatement potential (O'Mara, 2004; Beauchemin *et al.*, 2008).

Organic acids (Dicarboxylic acids): Dicarboxylic acids, like fumarate, malate and acrylate, are precursors to propionate production in the rumen and can act as an alternative H₂ sink restricting methanogenesis. McAllister and Newbold (2008) studies showed that between 0 and 75% reductions in CH₄ from feeding fumaric acid. However, at the relatively high dose rates required, dicarboxylic acids would be prohibitively expensive as an abatement strategy. Khampa and Wanapat (2007) reviewed that supplementation of ruminant diets with organic acids could improve rumen efficiency by maintaining higher pH, optimum ammonia-nitrogen (NH₃-N), thus reducing methane (CH₄) and increasing microbial protein synthesis and essential volatile fatty acid (VFAs), for enhancing ruminant productivity.

Methane is formed as a result of the need to remove hydrogen from the rumen. Propionate formation also utilizes hydrogen. Therefore if precursors of propionate are added to the diet, they should reduce methane production by removing some of the hydrogen produced during ruminal fermentation. The organic acids such as malate, fumarate, citrate, succinate, etc are propionate precursors and it has been demonstrated both *in vitro* and *in vivo* that their addition to the diet reduces methane production, with the response being dose dependent. Their use as dietary supplements is likely to be limited by their costs, but they are found in significant quantities in forages where they are intermediates in the citric acid cycle (O'Mara, 2004). Furthermore, assuming an increased concentration of malate up to 3% of DMI, the decrease in CH₄ observed with the lucerne might also be explained by this organic acid. This effect on methanogenesis is not a characteristic of all legumes; for instance, clover (white and red) did not differ from ryegrass on CH₄ emissions of growing cattle (Beever *et al.*, 1985) or dairy cows (Van Dorland *et al.*, 2007). Callaway *et al.* (1997) reported much higher malate concentrations in alfalfa (2.9-7.5% of DM) than Muck *et al.* (1991) reported for permanent pasture grass (less than 0.6% of DM), although extraction method which can have an effect, differed between the studies. There is less information on concentrations among different varieties/cultivars of the same plant, although some differences have been reported for alfalfa and tall fescue. If these differences are at least partly under genetic control (i.e., are not influenced totally by environmental factors), then there may be scope to breed cultivars with high contents of organic acids which would reduce methane production. This would be extremely valuable in regions where production systems have a substantial grazing component which often does not lend itself to other mitigation strategies (that involve delivering some product/supplement to the animal in the diet) because concentrates are often not fed in these situations (O'Mara, 2004).

It has been suggested by Martin (1998) that the high malate content in fresh forages at early growth stage, especially lucerne, could lead to significant changes in rumen fermentation. Assuming an increase in dietary malate of 3%, the decrease in methane could be explained by this organic acid (McCaughy *et al.*, 1999). However, other factors may be involved such as the high intake and a high rate of passage out of the rumen for lucerne and presence of saponins.

Newbold *et al.* (2005) reported fumarate and acrylate to be the most effective in batch culture and artificial rumen. Wallace *et al.* (2006) described a proportional reduction of 0.4-0.75 when encapsulated fumaric acid (0.1 of diet) was fed to sheep. On the other hand, others (McGinn *et al.*,

2004) reported no or small reductions in CH₄ (l/kg DM intake) when beef cattle received were fed malate. While the level of reduction in CH₄ emissions that could be achieved is somewhat uncertain, the main impediment to this strategy is the current cost of organic acids which makes their use uneconomical.

CONCLUSION

Because of the importance of reducing production of GHGs including methane from ruminants, it is necessary to emphasize different strategies to controlling methane emission in ruminant production systems. Although nutritional and feeding strategies can play important role on mitigating methane production, it should be use the other technologies such as management, biotechnology and microbiology. In further papers we emphasized on the effects of these technologies on controlling greenhouse gases especially methane production from ruminant animals.

REFERENCES

- Aghajanzadeh-Golshani A., N. Maheri-Sis, A. Mirzaei-Aghsaghali and A. Baradaran-Hasanzadeh, 2010. Comparison of nutritional value of tomato pomace and brewer's grain for ruminants using *in vitro* gas production technique. *Asian J. Anim. Vet. Adv.*, 5: 43-51.
- Allard, H., 2009. Methane Emissions from Swedish Sheep Production. Swedish University of Agricultural Sciences, SLU, Uppsala, Sweden.
- Bannink, A., H. De Visser, A. Klop, J. Dijkstra and J. France, 1997. Impact of diet-specific input parameters on simulated rumen function. *J. Theor. Biol.*, 184: 371-384.
- Bauman, D.E., P.J. Eppard, M.J. DeGeeter and G.M. Lanza, 1985. Responses of high-producing dairy cows to long-term treatment with pituitary somatotrophin and recombinant somatotrophin. *J. Dairy Sci.*, 68: 1352-1362.
- Beauchemin, K.A., M. Kreuzer F. O'Mara and T.A. McAllister, 2008. Nutritional management for enteric methane abatement: A review. *Aust. J. Exp. Agric.*, 48: 21-27.
- Beever, D.E., D.J. Thomson, M.J. Ulyatt, S.B. Camell and M.C. Spooner, 1985. The digestion of fresh perennial ryegrass (*Lolium perenne* L. cv. *Melle*) and white clover (*Trifolium repens* L. cv. *Blanca*) by growing cattle fed indoors. *Br. J. Nutr.*, 54: 763-775.
- Benchaar, C., C. Pomar and J. Chiquette, 2001. Evaluation of dietary strategies to reduce methane production in ruminants: A modelling approach. *Can. J. Anim. Sci.*, 81: 563-574.
- Blaxter, K.L. and J.L. Clapperton, 1965. Prediction of the amount of methane produced by ruminants. *Br. J. Nutr.*, 19: 511-522.
- Boadi, D., C. Benchaar, J. Chiquette and D. Masse, 2004. Mitigation strategies to reduce enteric methane emissions from dairy cows: Update review. *Can. J. Anim. Sci.*, 84: 319-335.
- Brouwer, E., 1965. Report of subcommittee on constants and factors. Proceedings of the 3rd EAAP Symposium on Energy Metabolism, (EM'65), Academic Press, London, pp: 441-443.
- CAT, 2010. Biogas-in developing countries and the UK. Information Service, Center for Alternative Technology, Mashynlleth, Powys, UK. <http://www.cat.org.uk/information/pdf/Biogas.pdf>.
- Callaway, T.R., S.A. Martin, J.L. Wampler, N.S. Hill and G.M. Hill, 1997. Malate content of forage varieties commonly fed to cattle. *J. Dairy Sci.*, 80: 1651-1655.
- Calsamiglia, S., M. Busquet, P.W. Cardozo, L. Castillejos and A. Ferret, 2007. Invited review: Essential oils as modifiers of rumen microbial fermentation. *J. Dairy Sci.*, 90: 2580-2595.

- Chaucheyras, F., G. Fonty, G. Bertin and P. Gouet, 1995. *In vitro* H₂ utilization by a ruminal acetogenic bacterium cultivated alone or in association with an archaea methanogen is stimulated by a probiotic strain of *Saccharomyces cerevisiae*. *Applied Environ. Microbiol.*, 61: 3466-3467.
- Clark, H., C. Pinares and C. de Klein, 2005. Methane and Nitrous Oxide Emissions from Grazed Grasslands. In: *Grassland-A Global Resource*, McGilloway, D. (Ed.). Wageningen Academic Publishers, Wageningen, The Netherlands, pp: 279-293.
- Ellis, J.L., J. Dijkstra, E. Kebreab, A. Bannink, N.E. Odongo, B.W. McBride and J. France, 2008. Aspects of rumen microbiology central to mechanistic modeling of methane production in cattle. *J. Agric. Sci.*, 146: 213-233.
- FAO, 2010. Greenhouse gas emissions from the dairy sector-a life cycle assessment. Animal Production and Health Division, Food and Agriculture Organization of the United Nations. pp: 94.
- GHADS, 2005. Field measurement procedures for carbon accounting. Green House Accounting Decision Support Framework (GHADS), Australia.
- GHGMP, 2005. Good management practice-greenhouse gas emissions. GHGMP for Canadian Agriculture and AAFC, Canada.
- Giger-Reverdin, S., D. Sauvant, M. Vermorel and J.P. Jounay, 2000. Empirical modeling on methane losses from ruminants. *Rencontres Rech. Rumin.*, 7: 187-190.
- Grainger, C., T. Clarke, M.J. Auldist, K.A. Beauchemin, S.M. McGinn, G.C. Waghorn and R.J. Eckard, 2009. Mitigation of greenhouse gas emissions from dairy cows fed pasture and grain through supplementation with *Acacia mearnsii* tannins. *Can. J. Anim. Sci.* (In Press).
- Gworgwor, Z.A., T.F. Mbahi and B. Yakubu, 2006. Environmental implications of methane production by ruminants: A review. *J. Sustainable Dev. Agric. Environ.*, 2: 1-14.
- Hopkins, A. and M. Lobley, 2009. A scientific review of the impact of UK ruminant livestock on greenhouse gas emissions. CRPR Research Report No. 27, Centre for Rural Policy Research, University of Exeter, UK. <https://eric.exeter.ac.uk/repository/handle/10036/65855>.
- Jemmett, R., 2006. Methane, biogas, production guide. Version 1.0., UK., pp: 1-15. <http://www.small-farm-permaculture-and-sustainable-living.com/support-files/methane-1.pdf>.
- Joblin, K.N., 1999. Ruminant acetogens and their potential to lower ruminant methane emissions. *Aust. J. Agric. Res.*, 50: 1307-1313.
- Johnson, K.A. and D.E. Johnson, 1995. Methane emissions from cattle. *J. Anim. Sci.*, 73: 2483-2492.
- Johnson, K.A., R.L. Kincaid, H.H. Westberg, C.T. Gaskins, B.K. Lamb and J.D. Cronrath, 2002. The effects of oil seeds in diets of lactating cows on milk production and methane emissions. *J. Dairy Sci.*, 85: 1509-1515.
- Johnson, I.R., D.F. Chapman, V.O. Snow, R.J. Eckard, A.J. Parsons, M.G. Lambert and B.R. Cullen, 2008. DairyMod and EcoMod: Biophysical pastoral simulation models for Australia and New Zealand. *Aust. J. Exper. Agric.*, 48: 621-631.
- Jordan, E., D.K. Lovett, M. Hawkins and F.P. O'Mara, 2004. The effect of varying levels of coconut oil on methane output from continental cross beef heifers. *Proceeding of the International Conference Greenhouse Gas Emissions from Agriculture-Mitigation Options and Strategies*, Feb. 10-12, Leipzig, Germany, pp: 317-318.

- Jouany, J.P., Y. Papon, D.P. Morgavi and M. Doreau, 2008. Linseed oil and a combination of sunflower oil and malic acid decrease rumen methane emissions *in vitro*. Proceedings of the International Conference Livestock and Global Climate Change, May 17-20, Hammamet, Tunisia, pp: 140-143.
- Kajikawa, H., C. Valdes, K. Hillman, R.J. Wallace and C.J. Newbold, 2003. Methane oxidation and its coupled electron-sink reactions in ruminal fluid. *Lett. Applied Microbiol.*, 36: 354-357.
- Kebreab, E., J. France, B.W. McBride, N. Odongo, A. Bannink, J.A.N. Mills and J. Dijkstra, 2006. Evaluation of Models to Predict Methane Emissions from Enteric Fermentation in North American Cattle. In: *Nutrient Digestion and Utilization in Farm Animals: Modelling Approaches*, Kebreab, E., J. Dijkstra, J. France, A. Bannink and W.J.J. Gerrits (Eds.). CAB International, Wallingford, UK., ISBN-13: 9781845930059, pp: 299-313.
- Khampa, S. and M. Wanapat, 2007. Manipulation of rumen fermentation with organic acids supplementation in ruminants raised in the tropics. *Pak. J. Nutr.*, 6: 20-27.
- Kingeston-Smith, A.H., J.E. Edwards, S.A. Huws, E.J. Kim and M. Abberton, 2010. Plant-based strategies towards minimising livestock's long shadow. *Proc. Nutr. Soc* 69: 613-620.
- Klieve, A. and K. Joblin, 2007. Comparison in Hydrogen Utilisation of Ruminal and Marsupial Reductive Acetogens. In: *5 Year Research Progress Report 2002-2007*, Kennedy, R. (Ed.). The Pastoral Greenhouse Gas Research Consortium, Wellington, New Zealand, pp: 34-35.
- Kumar, A., G.N. Tiwari, S. Kumar and M. Pandey, 2006. Role of greenhouse technology in agricultural engineering. *Int. J. Agric. Res.*, 1: 364-372.
- Kurihara, M., T. Magner, R.A. Hunter and G.J. McCrabb, 1997. Methane emissions of cattle fed on tropical forage and high grain diets. *Proc. Nutr. Soc. Aust.*, 21: 169-169.
- Lana, R.P., J.B. Russell and M.E. Van Amburgh, 1998. The role of pH in regulating ruminal methane and ammonia production. *J. Anim. Sci.*, 76: 2190-2196.
- Leahy, S.C., W.J. Kelly, E. Altermann, R.S. Ronimus and C.J. Yeoman *et al.*, 2010. The genome sequence of the rumen methanogen *Methanobrevibacter ruminantium* reveals new possibilities for controlling ruminant methane emissions. *PLoS ONE*, 5: e8926-e8926.
- Lovett, D.K., D. McGilloy, A. Bortolozzo and F.P. O'Mara, 2003. *In vitro* methane production of different cultivars of perennial ryegrass. *British Society of Animal Science*, York, UK., pp: 162. <http://www.bsas.org.uk/downloads/annlproc/Pdf2003/162.pdf>.
- Lovett, D.K., A. Bortolozzo, P. Conaghan, P. O'Kiely and F.P. O'Mara, 2004. *In vitro* total and methane gas production as influenced by rate of nitrogen application, season of harvest and perennial ryegrass cultivar. *Grass Forage Sci.*, 59: 227-232.
- Lovett, D.K., L. Shalloo, P. Dillon and F.P. O'Mara, 2006. A systems approach to quantify greenhouse gas fluxes from pastoral dairy production as affected by management regime. *Agric. Syst.*, 88: 156-179.
- Machmuller, A., D.A. Ossowski and M. Kreuzer, 2000. Comparative evaluation of the effects of coconut oil, oilseeds and crystalline fat on methane release, digestion and energy balance in lambs. *Anim. Feed Sci. Technol.*, 85: 41-60.
- Maheri-Sis, N., M. Chamani, A.A. Sadeghi, A. Mirza-Aghazadeh and A.A. Safaei, 2007. Nutritional evaluation of chickpea wastes for ruminants using *in vitro* gas production technique. *J. Anim. Vet. Adv.*, 6: 1453-1457.
- Maheri-Sis, N., A. Mirzaei-Aghsaghali, A.R. Safaei, A. Mirza-Aghazadeh and G.H. Bibalani, 2008a. Quack grass (*Agropyron repens* L.): As ruminant feed. *Res. J. Environ. Sci.*, 2: 228-233.

- Maheri-Sis, N., M. Chamani, A.A. Sadeghi, A. Mirza-Aghazadeh and A. Aghajanzadeh-Golshani, 2008b. Nutritional evaluation of kabuli and desi type chickpeas (*Cicer arietinum* L.) for ruminants using *in vitro* gas production technique. *Afr. J. Biotechnol.*, 7: 2946-2951.
- Margan, D.E., N.M. Graham, D.J. Minson and T.W. Searle, 1988. Energy and protein values of four forages, including a comparison between tropical and temperate species. *Aust. J. Exper. Agri.*, 28: 729-736.
- Martin, S.A., 1998. Manipulation of ruminal fermentation with organic acids: A review. *J. Anim. Sci.*, 76: 3123-3132.
- Martin, C., H. Dubroeuq, D. Micol, J. Agabriel and M. Doreau, 2007. Methane output from beef cattle fed different high-concentrate diets. Proceedings of the British Society of Animal Science, April 2-4, Southport, UK, pp: 46-46.
- Martin, C., D.P. Morgavi and M. Doreau, 2010. Methane mitigation in ruminants: From microbe to the farm scale. *Animal*, 4: 351-365.
- McAllister, T.A., E.K. Okine, G.W. Mathison and K.J. Cheng, 1996. Dietary, environmental and microbiological aspects of methane production in ruminants. *Can. J. Anim. Sci.*, 76: 231-243.
- McAllister, T.A. and C.J. Newbold, 2008. Redirecting rumen fermentation to reduce methanogenesis. *Aust. J. Exper. Agri.*, 48: 7-13.
- McCaughy, W.P., K. Wittenberg and D. Corrigan, 1999. Impact of pasture type on methane production by lactating beef cows. *Can. J. Anim. Sci.*, 79: 221-226.
- McGinn, S.M., K.A. Beauchemin, T. Coates and D. Colombatto, 2004. Methane emissions from beef cattle: Effects of monensin, sunflower oil, enzymes, yeast and fumaric acid. *J. Anim. Sci.*, 82: 3346-3356.
- Minson, D.J., 1990. Forages in Ruminant Nutrition. Academic Press, New York, pp: 350.
- Mirzaei-Aghsaghali, A. and N. Maheri-Sis, 2008. Nutritive value of some agro-industrial by-product for ruminants-a review. *World J. Zool.*, 3: 40-46.
- Mirzaei-Aghsaghali, A., N. Maheri-Sis, A. Mirza-Aghazadeh, Y. Ebrahimnezhad, M.R. Dastouri and A. Aghajanzadeh-Golshani, 2008. Estimation of methane production in sheep using nutrient composition of the diet. *J. Anim. Vet. Adv.*, 7: 765-770.
- Mirzaei-Aghsaghali, A., N. Maheri-Sis, H. Mansouri, M.E. Razeghi, J. Shayegh and A. Aghajanzadeh-Golshani, 2011. Evaluating nutritional value of apple pomace for ruminants using *in vitro* gas production technique. *Ann. Biol. Res.*, 2: 100-106.
- Moe, P.W. and H.F. Tyrell, 1979. Methane production in dairy cows. *J. Dairy Sci.*, 62: 1583-1586.
- Moss, A.R., J.P. Jouany and J. Newbold, 2000. Methane production by ruminants: Its contribution to global warming. *Ann. Zootech.*, 49: 231-253.
- Muck, R.E., R.K. Wilson and P. O'Kiely, 1991. Organic acid content of permanent pasture grasses. *Irish J. Agri. Res.*, 30: 143-152.
- National Research Council, 2001. Nutrient Requirements of Dairy Cattle. 7th Rev. Edn., National Academy of Sciences, Washington, DC.
- Newbold, C.J., S. Lopez, N. Nelson, J.O. Ouda, R.J. Wallace and A.R. Moss, 2005. Propionate precursors and other metabolic intermediates as possible alternative electron acceptors to methanogenesis in ruminal fermentation *in vitro*. *Br. J. Nutr.*, 94: 27-35.
- O'Kelly, J.C. and W.G. Spiers, 1992. Effect of monensin on methane and heat production of steers fed lucerne hay either *ad libitum* or at the rate of 250 g/h. *Aust. J. Agric. Res.*, 43: 1789-1793.
- O'Mara, F., 2004. Greenhouse gas production from dairying: Reducing methane production. *Adv. Dairy Technol.*, 16: 295-309.

- Offner, A. and D. Sauvant, 2006. Thermodynamic modelling of ruminal fermentations. *Anim. Res.*, 55: 343-365.
- Ovenell-Roy, K.H., M.L. Nelson, H.H. Westburg and J.A. Froseth, 1998. Effects of barley cultivar on energy and nitrogen metabolism of lambs. *Can. J. Anim. Sci.*, 78: 389-397.
- Pelchen, A. and K.J. Peters, 1998. Methane emissions from sheep. *Small Rumin. Res.*, 27: 137-150.
- Pen, 2007. Studies on manipulation of ruminal fermentation and methanogenesis by natural products. Ph.D. thesis, United Graduate School of Agricultural Sciences, Iwate University.
- Pinares-Patino, C.S., G.C. Waghorn, A. Machmuller, B. Vlaming, G. Molano, A. Cavanagh and H. Clark, 2007. Methane emissions and digestive physiology of non-lactating dairy cows fed pasture forage. *Can. J. Anim. Sci.*, 87: 601-613.
- Puchala, R., B.R. Min, A.L. Goetsch and T. Sahlu, 2005. The effect of a condensed tannin-containing forage on methane emission by goats. *J. Anim. Sci.*, 83: 182-186.
- Rowlinson, P., M. Steele and A. Nefzaoui, 2008. Livestock and global climate change. Proceedings of the International Conference in Hammamet, May 17-20, Cambridge University Press, pp: 216-216.
- Santoso, B., B. Mwenya, C. Sar, Y. Gamo and T. Kobayashi *et al.*, 2004. Effects of supplementing galacto-oligosaccharides *Yucca schidigera* or nicin on rumen methanogenesis, nitrogen and energy metabolism in sheep. *Livest. Prod. Sci.*, 91: 209-217.
- Sauvant, D. and S. Giger-Reverdin, 2007. Energy and Protein Metabolism and Nutrition. Wageningen Academic Publishers, EAAP Publication, The Netherlands, pp: 124-561.
- Sejian, V., J. Lakritz, T. Ezeji and R. Lal, 2011. Forage and flax seed impact on enteric methane emission in dairy cows. *Res. J. Vet. Sci.*, 4: 1-8.
- Sommer, S.G., 2005. Greenhouse gas emission from manure and livestock. NJF Seminar 372. Manure-an agronomic and environmental challenge, pp: 26-36.
- Takahashi, J., T. Miyagawa, Y. Kojima, K. Umetsu, 2000. Effects of *Yucca schidigera* extract, probiotics, monensin and L-cysteine on rumen methanogenesis. *Asian-Aus. J. Anim. Sci.*, 13: 499-501.
- Tamminga, S., A. Bannink, J. Dijkstra and R. Zom, 2007. Feeding strategies to reduce methane loss in cattle. Report 34, Animal Science Group. <http://edepot.wur.nl/28209>.
- The Kyoto Protocol, 2001. Kyoto protocol: Ensuring our future. Consultation Paper Ministry of the Environment. New Zealand.
- Ulyatt, M.J. and K.R. Lassey, 2001. Methane emissions from pastoral systems: The situation in New Zealand. *Arch. Latinoam. Prod. Anim.*, 9: 118-126.
- Ulyatt, M.J., K.R. Lassey, I.D. Shelton, C.F. Walker, 2002. Methane emission from dairy cows and wether sheep fed subtropical grass-dominant pastures in midsummer in New Zealand. *New Zealand J. Agric. Res.*, 45: 227-234.
- Van Dorland, H.A., H.R. Wettstein, H. Leuenberger and M. Kreuzer, 2007. Effect of supplementation of fresh and ensiled clovers to ryegrass on nitrogen loss and methane emission of dairy cows. *Livestock Sci.*, 111: 57-69.
- Van Nevel, C.J. and D.I. Demeyer, 1996. Influence of antibiotics and a deaminase inhibitor on volatile fatty acids and methane production from detergent washed hay and soluble starch by rumen microbes *in vitro*. *Anim. Feed Sci. Technol.*, 37: 21-31.
- Van Soest, P.J., 1982. Nutritional Ecology of the Ruminant. O and B Books Inc., Corvallis.
- Van Soest, P.J., 1994. Nutritional Ecology of the Ruminant. 2nd Edn., Cornell University Press, Ithaca, New York, pp: 373.

- Waghorn, G.C., M.H. Tavendale and D.R. Woodfield, 2002. Methanogenesis from forages fed to sheep. *Proc. N.Z. Grass Assoc.*, 64: 167-171.
- Waghorn, G.C. and S.L. Woodward, 2004. Ruminant contribution to methane and global warming- A New Zealand perspective. *The Science of Changing Climates-Impact on Agriculture, Forestry and Wetlands*. pp: 1-51.
- Waghorn, G., 2008. Beneficial and detrimental effects of dietary condensed tannins for sustainable sheep and goat production-Progress and challenges. *Anim. Feed Sci. Technol.*, 147: 116-139.
- Wallace, R.J., T.A. Wood, A. Rowe, J. Price, D.R. Yanez, S.P. Williams, C.J. Newbold, 2006. Encapsulated Fumaric Acid as a Means of Decreasing Ruminal Methane Emissions. In: *Greenhouse Gases and Animal Agriculture: An Update*, Soliva, C.R., J. Takahashi and M. Kreuzer, (Eds.). Elsevier, Amsterdam, The Netherlands, pp. 148-151.
- Woodward, S.L., G.C. Waghorn, M.J. Ulyatt and K.R. Lassey, 2001. Early indications that feeding *Lotus* will reduce methane emissions from ruminants. *Proceedings of the New Zealand Society of Animal Production*, (NZSOAP'01), New Zealand Society of Animal Production, pp: 23-26.
- Woodward, S.L., G.C. Waghorn, K.R. Lassey and P.G. Laboyrie, 2002. Does feeding sulla (*Hedysarum coronarium*) reduce methane emissions from dairy cows? *Proc. N.Z. Soc. Anim. Prod.*, 62: 227-230.
- Woodward, S.L., G.C. Waghorn, P. Laboyrie, 2004. Condensed tannins in birdsfoot trefoil (*Lotus corniculatus*) reduced methane emissions from dairy cows. *Proc. N. Z. Soc. Anim. Prod.*, 64: 160-164.
- Yan, T., R.E. Agnew, F.J. Gordon and M.G. Porter, 2000. Prediction of methane energy output in dairy and beef cattle offered grass silage-based diets. *Livest. Prod. Sci.*, 64: 253-263.
- Yurtseven, S. and I. Ozturk, 2009. Influence of two sources of cereals (corn or barley), in free choice feeding on diet selection, milk production indices and gaseous products (CH₄ and CO₂) in lactating sheep. *Asian J. Anim. Vet. Adv.*, 4: 76-85.
- Yurtseven, S., M. Cetin, I. Ozturk, A. Can, M. Boga, T. Sahin and H. Turkoglu, 2009. Effect of different feeding method on methane and carbon dioxide emissions milk yield and composition of lactating awassi sheep. *Asian J. Anim. Vet. Adv.*, 4: 278-287.