



Review article

Dietary sources and their effects on animal production and environmental sustainability



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ABSTRACT

Animal agriculture has been an important component in the integrated farming systems in developing countries. It serves in a paramount diversified role in producing animal protein food, draft power, farm manure as well as ensuring social status-quo and enriching livelihood. Ruminants are importantly contributable to the well-being and the livelihood of the global population. Ruminant production systems can vary from subsistence to intensive type of farming depending on locality, resource availability, infrastructure accessibility, food demand and market potentials. The growing demand for sustainable animal production is compelling to researchers exploring the potential approaches to reduce greenhouse gases (GHG) emissions from livestock. Global warming has been an issue of concern and importance for all especially those engaged in animal agriculture. Methane (CH₄) is one of the major GHG accounted for at least 14% of the total GHG with a global warming potential 25-fold of carbon dioxide and a 12-year atmospheric lifetime. Agricultural sector has a contribution of 50 to 60% methane emission and ruminants are the major source of methane contribution (15 to 33%). Methane emission by enteric fermentation of ruminants represents a loss of energy intake (5 to 15% of total) and is produced by methanogens (archae) as a result of fermentation end-products. Ruminants' digestive fermentation results in fermentation end-products of volatile fatty acids (VFA), microbial protein and methane production in the rumen. Rumen microorganisms including bacteria, protozoa and fungal zoospores are closely associated with the rumen fermentation efficiency. Besides using feed formulation and feeding management, local feed resources have been used as alternative feed additives for manipulation of rumen ecology with promising results for replacement in ruminant feeding. Those potential feed additive practices are as follows: 1) the use of plant extracts or plants containing secondary compounds (e.g., condensed tannins and saponins) such as mangosteen peel powder, rain tree pod; 2) plants rich in minerals, e.g., banana flower powder; and 3) plant essential oils, e.g., garlic, eucalyptus leaf powder, etc. Implementation of the -feed-system using cash crop and leguminous shrubs or fodder trees are of promising results.

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1. Introduction

Livestock production is undertaken in a multitude of ways across the planet, providing a large variety of goods and services,

and using different animal species and different sets of resources, in a wide spectrum of agro-ecological and socio-economic conditions (Kearney, 2010). Global livestock systems occupy about 30% of the planet's ice-free terrestrial surface area (Steinfeld et al., 2006) and are a significant global asset with a value of at least \$1.4 trillion (Thornton, 2010). Currently, livestock is one of the fastest growing agricultural subsectors in developing countries. This growth is driven by the rapidly increasing demand for livestock products, this demand being driven by population growth, urbanization and increasing incomes in developing countries (Delgado, 2005). This combination of growing demand in the developing world and stagnant demand in industrialized countries represents a major opportunity for livestock keepers in developing countries,

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where most demand is met by local production, and this is likely to continue well into the foreseeable future (Thornton, 2010). Along with an exploration of food consumption trends and projections to 2050, both globally and for different regions of the world, the drivers largely responsible for these observed consumption trends will be examined (Kearney, 2010). At the same time, the expansion of agricultural production needs to take place in a way that allows the less well-off to benefit from increased demand and that moderates its impact on the environment. Although integral to many farming systems, livestock production is nevertheless associated with many impacts that are deemed socially undesirable (Moran and Wall, 2011). Whereas animal welfare concerns have been documented for centuries, damage attributed to and responsibility for greenhouse gas (GHG) emissions are more recent concerns. Enteric methane (CH₄) emission in ruminants, which is produced via fermentation of feeds in the rumen and lower digestive tract by methanogenic archaea, represents a loss of 2 to 12% of gross energy of feeds and contributes to global greenhouse effects. Globally, about 80 million tonnes of CH₄ is produced annually from enteric fermentation mainly from ruminants. Therefore, CH₄ mitigation strategies in ruminants have been focused on obtaining economic as well as environmental benefits (Patra, 2011).

2. Global animal production systems

Production environments, and the intensities and purposes of production, vary greatly within and across countries (Steinfeld et al., 2006). Animal production systems have been categorised on the basis of agro-ecological opportunities and demand for livestock commodities. In many of these systems, the livestock element is interwoven with crop production, as in the rice/buffalo or cereal/cattle systems of Asia. Animal manure is often essential for maintaining soil fertility, and the role of animals in nutrient cycling is often an important motivation for keeping animals, particularly where this involves a transfer of nutrients from common property resources to private land. Many of these systems that are the result of a long evolution are currently under pressure to adjust to rapidly evolving socio-economic conditions; large intensive livestock production units, in particular for pig and poultry production, have emerged over the last decades in many developing regions in response to the rapidly growing demand for livestock products. Moreover, the degree to which each system is integrated into the market economy varies according to a host of factors, perhaps the most important of which is geographical location. The influence of geographical location on market integration is twofold: partly agro-ecological and partly infrastructural. Some areas may have a higher degree of market integration because rainfall and soil conditions are conducive to cash cropping and the production of surpluses; others may lack one or both of these advantages but are compensated by their relative proximity to urban markets and other facilities. Animal production systems can be described into categories as follows ILRI (1995) and Wanapat (1990, 1999).

2.1. Subsistence animal production systems

For the subsistence-oriented household, land and labour are the principal factors of production. Capital investment is limited to non-monetary self-produced equipment, land improvement and livestock raised through natural reproduction. Increases in production are mainly dependent on the weather and on the quantity and quality of those factors of production controlled by the household. These, for example, may include:

- use of surplus labour for bush clearing and erosion control;
- use of animal manure to raise soil fertility;
- better livestock management practices.

Progress in production is likely to be slow but improvements are possible through farming systems research, education and extension programmes. There are few local off-farm employment opportunities. The monetary circuit plays little role in the economy of the mainly subsistence-oriented household. For the subsistence-oriented farm, output and consumption are identical. Such households thus remain largely (but not wholly) unresponsive to price and market signals. Families living under these conditions rarely aim to maximize production, since this would imply specialization, with its attendant risks. Rather, the goal is to maximize the chances of survival. A mainly subsistence-oriented farmer will be reluctant to shift from a traditional practice to a new technology if doing so incurs greater risk of failure.

2.2. Semi-subsistence animal production systems

A semi-subsistence household produces a considerable proportion of its consumption requirements (60 to 80%). In addition, it will produce cash crops such as vegetables, coffee and tea, and keep livestock for sale. The semi-subsistence producer will therefore be confronted with the risks associated with price fluctuations and with variations in the natural environment. The monetary circuit thus assumes an important role in the semi-subsistence production unit. Such units tend to be more responsive to market and price signals than the subsistence-oriented producers. The higher the share of output being sold on the market, the greater the importance of the monetary circuit in the semi-subsistence production system. The impact of market and price signals will ultimately depend on the degree of market integration.

What are the reasons behind a household's desire to enter the monetary circuit? Answering this question will help us understand the factors which influence production responses. The first step in the transition process from subsistence to more commercialized production may be a need to obtain cash to meet legal or social obligations, such as the payment of school fees or the hosting of a wedding reception. Insofar as such needs are the only purpose of sales, there will be a negative relationship between price and market supply. In other words, the higher the market price, the smaller will be the amounts that need to be sold and vice versa.

As the transition process continues, market supply responses become positive as producers recognize that increasing their cash income enables them to buy other consumer goods which improve their welfare. If these goods are regularly available at local markets, income growth may become an important family goal. Higher income also enables a household to purchase more external inputs (fertilizer, seeds, etc.), thus increasing output still further in the future. Finally, cash can also be used to pay interest and principal on credit, opening up greater opportunities for investment and hence the development of new enterprises. Thus, the transition from pure subsistence, through semi-subsistence to more commercial farming will have two interrelated effects on consumption and production in the rural household, namely:

- The direct acquisition of consumer goods and services.
- The further growth of income through increased use of external inputs.

For families living under these systems, risk aversion remains an important determinant of household decisions. These producers confront the risks associated with price fluctuation as well as those resulting from climate. Sometimes these will offset one

another, as when low yields lead to scarcity, causing market prices to rise, and vice versa. At other times, factors bearing no relationship to yield variations will influence prices. For semi-subsistence producers, innovations with minimal input of external factors of production could be offered.

2.3. Intensive (commercial) animal production systems

In these systems, the monetary circuit becomes more important than the physical one, which may become less complex as a result of specialization. These production units tend to be highly responsive to price and market signals, switching enterprises and increasing or decreasing their market involvement in accordance with them. Increases in production are almost certain to involve the use of external inputs and services. Progress in production can be rapid, but dramatic setbacks may occasionally occur. Off-farm employment opportunities are more common and are found nearer home. For families living under these conditions, the allocation of resources will be determined largely by the profit rather than the survival motive. However, although risk aversion plays a smaller part in decision making, households will tend to refrain from fully commercial production if markets are unreliable or if institutional support (access to credit, price stabilization schemes, animal health services, etc) is inadequate.

The presence of commercial systems is connected to both demand factors and supply determinants; areas with high population density and purchasing power, in particular coastal areas in East Asia, Europe and North America, which also have access to ocean ports, show a high prevalence of industrial systems and import much of the necessary feed (Steinfeld et al., 2006). In contrast, there are areas with ample feed supplies such as the mid-western United States of America (USA) and interior parts of Brazil and Argentina, where industrial systems rely mainly on local feed surpluses. East and Southeast Asia strongly dominate industrial monogastrics' production in the developing regions. Southern Brazil is another industrial production hot spot at world level, while important regional centres of industrial production are found, for example in Mexico, Colombia, Venezuela and Chile. Similarly there are major regional centres for the industrial production of chicken in Nigeria, South Africa and the Middle East.

3. Animal protein products consumption demand for increasing global population

There has been an increasing pressure on the livestock sector to meet the growing demand for high-value animal protein. The world's livestock sector is growing at an unprecedented rate and the driving force behind this enormous surge is a combination of population growth, rising incomes and urbanization. Annual meat production is projected to increase from 218 million tonnes (1997 to 1999) to 376 million tonnes by 2030 (WHO, 2013).

There is a strong positive relationship between the level of income and the consumption of animal protein, with the consumption of meat, milk and eggs increasing at the expense of staple foods. Because of the recent steep decline in prices, developing countries are embarking on higher meat consumption at much lower levels of gross domestic product than the industrialized countries did about 20 or 30 years ago.

Urbanization is a major driving force influencing global demand for livestock products. Urbanization stimulates improvements in infrastructure, including cold chains, which permit trade in perishable goods. Compared with the less diversified diets of the rural communities, city dwellers have a varied diet rich in animal proteins and fats, and characterized by higher consumption of meat, poultry, milk and other dairy products. Table 1 shows

trends in per capita consumption of livestock products in different regions and country groups. There has been a remarkable increase in the consumption of animal products in countries such as Brazil and China, although the levels are still well below the levels of consumption in North American and most other industrialized countries. Consumption of meat in the U.S. were highest when compared to the global average. The countries that consume the least amount of meat are in Africa and South Asia; the lowest ten are Sierra Leone, Democratic Republic of Congo, Mozambique, Sri Lanka, Rwanda, India, Malawi, Guinea, Burundi and Bangladesh. Consumption in these countries is between 3 and 5 kg per capita per year (Speedy, 2003). This is compensated to some extent in Bangladesh by higher fish consumption (17.5 kg) and in India and Sri Lanka by higher milk consumption (47.5 and 35.9 kg, respectively). Milk consumption in the U.S. is 118 kg per capita per year. Many African countries are in the bottom quartile for consumption of meat plus fish combined.

As diets become richer and more diverse, the high-value protein that the livestock sector offers improves the nutrition of the vast majority of the world. Livestock products not only provide high-value protein but are also important sources of a wide range of essential micronutrients, in particular minerals such as iron and zinc, and vitamins such as vitamin A. For the large majority of people in the world, particularly in developing countries, livestock products remain a desired food for nutritional value and taste. Excessive consumption of animal products in some countries and social classes can, however, lead to excessive intakes of fat.

4. Greenhouse gases and animal contribution

The growing demand for livestock products is likely to have an undesirable impact on the environment. For example, there will be more large-scale, industrial production, often located close to urban centres, which brings with it a range of environmental and public health risks (WHO, 2013). Environmental impacts of livestock production have historically been confined to more localized problems of overgrazing, desertification, and water pollution by poor waste handling (Moran and Wall, 2011). Such concerns were often offset by recognition of the cultural significance of livestock and more tangible benefits from the use of animal products and manures in farming systems (Moll, 2005). In developing countries, livestock production provides not only food, but also a wide range of nonfood benefits including income, employment, and many other contributions to rural and social development. The need to respond to global climate change has focused attention on the main sources of emissions with all significant sources coming under scrutiny (World Bank, 2008). This is largely because developed countries have committed themselves to externally defined emissions reductions (mitigation) targets that must somehow be shared amongst polluting industries within their jurisdictional control. Livestock production systems contribute an estimated 18% of global anthropogenic GHG emissions (FAO, 2006). These emissions represent a significant proportion for some countries, including New Zealand, Ireland, and the United Kingdom. The main sources and types of GHG from livestock systems are methane production from animals (25%), carbon dioxide (CO₂) from land use and its changes (32%), and nitrous oxide (N₂O) from manure and slurry management (31%).

5. Strategies in preventing and alleviating greenhouse gases especially from animals

Livestock are already well-known to contribute to GHG emissions and accounting for about 18% of the anthropogenic GHG

Table 1
Protein consumption demand per capita of livestock products.¹

Region	Meat, kg/yr			Milk, kg/yr		
	1964 to 1966	1997 to 1999	2030	1964 to 1966	1997 to 1999	2030
World	24.2	36.4	45.3	73.9	78.1	89.5
Developing countries	10.2	25.5	36.7	28.0	44.6	65.8
Near East and North Africa	11.9	21.2	35.0	68.6	72.3	89.9
Sub-Saharan Africa ²	9.9	9.4	13.4	28.5	29.1	33.8
Latin America and the Caribbean	31.7	53.8	76.6	80.1	110.2	139.8
East Asia	8.7	37.7	58.5	3.6	10.0	17.8
South Asia	3.9	5.3	11.7	37.0	67.5	106.9
Industrialized countries	61.5	88.2	100.1	185.5	212.2	221.0
Transition countries	42.5	46.2	60.7	156.6	159.1	178.7

¹ Source: WHO (2013).

² Excludes South Africa.

emissions (Steinfeld et al., 2006). Among domesticated livestock, ruminant animals (cattle, buffalo, sheep, goats, and camels) produce significant amounts of CH₄ and they are produced in the rumen and hind gut. Fermentation of feeds in the rumen is the largest source of CH₄ from enteric fermentation. Methane production from ruminant is a complex process that involves a group of Archaea known collectively as methanogens, which belong to the phylum *Euryarcheota* (Patra, 2011). During this process, rumen microbes convert ingested organic matter into energy for microbial growth, and into fermentation end-products, including VFA, alcohols, H₂, and CO₂. The major VFA produced in the rumen include acetate (Ac), propionate (Pr) and butyrate (Bu), which generally account for more than 95% of the total VFA production. Excess reducing power generated during conversion of hexose to Ac or Bu is utilized in part by Pr, but mainly by conversion to CH₄ (Moss et al., 2000). Methanogenic archaea are able to take some of these end products and reduce them with H₂ to produce CH₄ and H₂O. Accumulated CH₄ and other volatile gases produced in the rumen are eventually expelled through the mouth into the atmosphere via eructation. Methane emissions in ruminants accounts for 2 to 12% of gross energy loss of feeds depending upon the type of diets (Johnson and Johnson, 1995). Moreover, Leng (2008) reported that CH₄ emitted by the world's farmed ruminant livestock accounts for about one quarter of all anthropogenic CH₄ emission, typically estimated at 80 to 90 Tg/yr (1 Tg = 1 million tonnes) of a total of around 350 Tg/yr. Therefore, lowering global CH₄ emissions from enteric fermentation is an important part of any effort to reduce anthropogenic GHG emissions and ruminant producers are also seeking to identify and promote good management practices. The current approaches for reducing methane production from ruminants are shown in Table 2.

5.1. Feed management

It is well established that increasing the level of concentrate in the diet leads to a reduction in CH₄ emissions as a proportion of energy intake or expressed by unit of animal product (milk and meat) (Matin et al., 2010). A meta-analysis of the bibliography showed that the relationship between concentrate proportion in the diet and CH₄ production is curvilinear (Sauvant and Giger-Reverdin, 2007). Methane losses appear relatively constant (6 to 7% of GE intake) for diets containing 30 to 40% concentrate and then decrease rapidly to low values (2 to 3% of GE intake) for diets containing 80 to 90% concentrate (Martin et al., 2010). Replacing structural carbohydrates from forages (cellulose, hemicellulose) in the diet with non-structural carbohydrates (starch and sugars) contained in most energy-rich concentrates is associated with increases in feed intake, higher rates of ruminal fermentation and accelerated feed turnover, which results in large modifications of

rumen physico-chemical conditions and microbial populations. A shift of VFA production from acetate towards propionate occurs with the development of starch-fermenting microbes. This results in a lower CH₄ production because the relative proportion of ruminal hydrogen sources declines whereas that of hydrogen sinks increases. However, this low acetate to propionate ratio may not be always observed in high-concentrate fed animals, that is, young bulls fed maize grain-based diets containing 30 or 45% starch had a similar ratio (2.50 vs. 2.88, respectively). The lower CH₄ emissions from bulls fed the diet containing 45% starch compared to those fed other two diets containing 30% starch (2.5% vs. 6.9% of GE intake, respectively) could be better explained by a lower ruminal pH (5.06 vs. 5.90, respectively; Martin et al., 2010) and a decrease in protozoal number. The low ruminal pH might also inhibit the growth and/or activity of methanogens (Hegarty, 1999) and of cellulolytic bacteria. A positive correlation between cellulolytic bacteria and methanogens in the rumen of different species (cattle, sheep, llamas, deer) has been shown, except in buffalos. This exception was explained by the fact that *Fibrobacter succinogenes*, a non-hydrogen-producing cellulolytic species, was the major cellulolytic bacteria of this animal species (Matin et al., 2010).

Concerning the effect of the nature of concentrate on methanogenesis, few direct comparisons have been carried out. Concentrates rich in starch (wheat, barley, maize) have a more important negative effect on CH₄ production than fibrous concentrates (beet pulp). Substitution of beet pulp by barley in a high concentrate diet (70%) fed to dairy cows reduced CH₄ emissions by 34%. Lovett et al. (2005) reported that this was not the case when fresh forages were the main ingredients of the basal diet. Beauchemin et al. (2008) measured CH₄ emissions from feedlot cattle fed backgrounding and finishing diets containing maize (slowly degradable starch) or barley grain (rapidly degradable starch). Effect of grain source on CH₄ emissions was conditioned by the production phase. Expressed on the basis of GE intake, CH₄ emissions during the backgrounding phase were not affected by grain source, whereas emissions were surprisingly less for the maize finishing diet than for the barley finishing period. The authors suggested that this was mediated through the lower ruminal pH observed with the maize diet rather than a shift in the site of digestion from the rumen to the intestines (Matin et al., 2010).

5.2. Plant secondary compounds

Plant secondary compounds (condensed tannins and saponins) are important ruminant feed additives, particularly for a methane mitigation strategy because of their natural origin as opposed to chemical additives (Wanapat et al., 2013). Anti-methanogenic

Table 2
Methane abatement strategies, mechanism of abatement, considerations for use and reducing efficiency of CH₄¹.

CH ₄ abatement strategies	Mechanism of abatement	Considerations for use	Reducing efficiency of CH ₄
<ul style="list-style-type: none"> • Feed management <ul style="list-style-type: none"> - Roughage to concentrate ratio, increased hemicellulose/starch, reducing cell wall 	Increased rate of passed; increased C3 to C2 ratio, reduced rumen pH	Shift methanogenesis to hind gut or manure, risk of subacute ruminal acidosis	7 to 90%
<ul style="list-style-type: none"> • Plant Compounds <ul style="list-style-type: none"> - Condensed tannins, saponins, essential oils, organosulfur compound 	Antimicrobial activity; reduced H availability	Optimum dosage unknown; more <i>in vivo</i> research needed; long-term studies needed; may affect digestibility; residues unknown	10 to 96%
<ul style="list-style-type: none"> • Organic Acids <ul style="list-style-type: none"> - Fumarate, malate, nitroethane, nitrate, thiamine, bromochloromethane 	H sink, greater proportion propionate versus acetate <ul style="list-style-type: none"> - Thiamine: inhibits pyruvate oxidative decarboxylation - Bromochloromethane inhibits cobamide-dependent methyl in CH₄ production. 	Varies with diet; more <i>in vivo</i> research needed; long-term studies needed; may affect digestibility	3 to 75%
<ul style="list-style-type: none"> • Ionophore <ul style="list-style-type: none"> - Monensin or rumensin 	Inhibits protozoa and gram-positive bacteria; lack of substrate for methanogenesis	Adaptation of microbiota may occur; varies with diet and animal; banned in the European Union	4 to 76%
<ul style="list-style-type: none"> • Immunisation and biological control <ul style="list-style-type: none"> - Methanogen vaccine, methanotrophs, probiotic, bacteriophages, bacteriocins 	Host immune response to methanogens	Vaccine targets; diet and host geographical location differences	7 to 50%
<ul style="list-style-type: none"> • Defaunation <ul style="list-style-type: none"> - Chemical, feed additives 	Removes associated methanogens; less H for methanogenesis	Adaptation of microbiota may occur; varies with diet; maintenance of defaunated animals	20 to 60%
<ul style="list-style-type: none"> • Lipids <ul style="list-style-type: none"> - Fatty acids, oils, seed oils, taloo 	Inhibition of methanogens and protozoa; greater proportion propionate versus acetate; biohydrogenation	Effect on palatability, intake, performance, and milk components; varies with diet and ruminant species; long-term studies needed	10 to 90%
<ul style="list-style-type: none"> • Genetic selection 	Genetic selection of animals for decreasing methane emissions	Varies with diet and ruminant species; long-term studies needed	

¹ Source: Compiled by Cherdthong (2012).

activity can be attributed to both condensed tannins (CT) and hydrolysable tannins. There are two modes of action of tannins in methanogenesis: a direct effect on ruminal methanogens and an indirect effect on hydrogen production due to lower feed degradation. There is also evidence that some CT can reduce methane emissions while reducing bloat and increasing amino acid absorption in the small intestine. Methane emissions are also commonly lower with higher proportions of forage legumes in the diet, partly due to lower fibre contact, a faster rate of passage and, in some cases, the presence of CT. Supplementation with Phaseolus calcaratus hay at 600 g per animal per year was beneficial for swamp buffaloes fed rice straw as a basal roughage, as it resulted in increased DM intake, reduced protozoal numbers and methane gas production in the rumen, increased N retention as well as improving the efficiency of rumen microbial CP synthesis (Chanthakhoun et al., 2011). Legumes containing CT (e.g., Lotus) are able to lower methane (based on g/kg DMI) by 12 to 15% (Chanthakhoun et al., 2011). Also, some authors have reported that CT can reduce methane production by 13 to 16% (DMI basis), mainly through a direct toxic effect on methanogens. At an appropriate dose, saponins or saponin-containing plants have been shown to suppress the protozoal population, increase the bacteria and fungi population, the production of propionate, the partitioning factor, the yield and efficiency of microbial protein synthesis and to decrease methanogenesis, all of which improve performance in ruminants. Tannins, especially CT, also decrease methane production and increase the efficiency of microbial protein synthesis (Wanapat et al., 2013).

Saponins are natural detergents found in many plants. Interest has increased in using saponin-containing plants as a possible means of suppressing or eliminating protozoa in the rumen. Decreased numbers of ruminal ciliate protozoa may enhance the flow of microbial protein from the rumen, to increase the efficiency of feed utilization and decrease methanogenesis. Saponins are also known to influence both the composition and number of ruminal bacterial species through specific inhibition or selective enhancement of the growth of individual species. Saponins have

been shown to possess strong defaunation properties both *in vitro* and *in vivo* which could reduce methane emissions. While extracts of CT and saponins may be commercially available, their cost is currently prohibitive for their routine use in ruminant production systems. However, research is still required on the optimum sources of CT and saponins, the level of CT astringency (chemical composition) and the feeding methods and dose rates required to reduce methane and stimulate animal production (Wanapat et al., 2013).

Mangosteen peel powder (MP) supplementation both for *in vitro* and *in vivo* trials significantly increased the production of total VFA ($P < 0.05$), as well as propionate production, while acetate, butyrate production and the acetate to propionate ratio were significantly decreased ($P < 0.05$) (Norrakoke et al., 2012). Condensed tannins and saponins contained in MP could contribute to the above effects. These findings showed that MP supplementation did not affect DM intakes, while digestibility and rumen methane production (by estimation using VFA concentration) were significantly decreased ($P < 0.05$). Mangosteen peel powder supplementation reduced rumen protozoa production remarkably, while the numbers of the predominant cellulolytic bacteria increased ($P < 0.05$). In addition, methanogen numbers tended to decrease. However, it was found that mangosteen peel powder significantly increased ($P < 0.05$) the cellulolytic bacteria population. The CT and saponins present in the MP could influence such changes in the rumen (Wanapat et al., 2013).

5.3. Organic acids

Organic acids (malate, fumarate and acrylate) have been assayed as diet additives (Morgavi et al., 2010). Fumarate and acrylate have been shown to be the most effective *in vitro*. In contrast to the well-documented CH₄ production response to organic acids *in vitro*, responses to dietary supplementation *in vivo* remain inconclusive and highly variable. For example, no changes were reported in beef heifers (Beauchemin et al., 2008), whereas up to 16% decreases were reported in beef cattle (Foley et al.,

2009), although in this last study feed intake for organic acid-supplemented animals was also reduced. An exceptional decrease in CH₄ production, up to 75%, has been shown with 10% encapsulated fumarate in the diet of lambs without negative effect on animal growth (Wallace et al., 2006). In contrast, encapsulated fumarate had no significant effect in another trial in dairy cows (McCourt et al., 2008). Further research is needed with such a product as additive. 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 microbial fermentation (Matin et al., 2010).

5.4. Ionophores

Ionophore antibiotics such as monensin are usually used in ruminants to improve the efficiency of meat and milk production (Morgavi et al., 2010). Ionophores do not alter the quantity and diversity of methanogens (Hook et al., 2011), but they change the bacterial population from Gram-positive to Gram-negative organisms with a concomitant change in the fermentation from acetate to propionate. This fermentation shift lowers the availability of H₂ for CH₄ production by methanogens. They might also reduce ruminal protozoal numbers. Relatively high-dose levels might be required to lessen CH₄ compared with doses needed to improve feed efficiency. Monensin included in diets at a dose of < 20 mg/kg diet may not always have profound effect on CH₄ production (Beauchemin et al., 2008). Higher doses (24 to 35 mg/kg diet) decreased CH₄ production by 4 to 10% (Odongo et al., 2007) with short-term decreases in CH₄ up to 30% at a dose level of 33 mg/kg diet (Guan et al., 2006). Unfortunately, some long-term trials suggest that the inhibition of methanogenesis by ionophores may not persist over time (Guan et al., 2006). It appears that monensin can be used for short-term decreases in CH₄ emissions, which can also improve efficiency of feed utilization in ruminants. However, the use of ionophores as feed additives has been banned in the European Union and is restricted in some other countries as feed additives (Matin et al., 2010).

5.5. Immunisation and biological control

Several biotechnological strategies are currently being explored (Matin et al., 2010). A vaccine against three selected methanogens decreased CH₄ production by nearly 8% in Australian sheep (Wright et al., 2004). However, vaccines prepared with a different set of methanogen species or tested in other geographical regions did not elicit a positive response (Wright et al., 2004). The highly diverse methanogenic community present in animals reared under different conditions (Wright et al., 2007) and the replacement of the ecological niche left by the targeted species by another methanogens (Williams et al., 2009) might account for immunisation failures. The recent completion of the complete genome sequence of *Methanobrevibacter ruminantium* by New Zealand scientists (<http://www.pggc.co.nz>) opens the way for the identification of specific immunological targets that could be common to other methanogens found in the rumen. This information could be used for the development of second-generation vaccines (Attwood and McSweeney, 2008). Passive immunisation was also recently assayed using antibodies, which were produced in laying hens, against three common methanogens present in the digestive tract of animals. Treatments using whole eggs decreased transiently CH₄ production *in vitro* but the effect was lost at the end of the 24-h incubation (Cook et al., 2008). Up to now, immunisation has not delivered a clear, positive answer in reducing CH₄ emissions by ruminants, highlighting the difficulties of this approach (Morgavi et al., 2010).

5.6. Defaunation

Defaunation, which is the removal of protozoa from the rumen, has been used to investigate the role of protozoa in rumen function, and also to study the effect on methane production (Hook et al., 2011). Rumen protozoa, as stated previously, share a symbiotic relationship with methanogens, participating in interspecies hydrogen transfer, which provides methanogens with the hydrogen they require to reduce carbon dioxide to methane. It has been estimated that the methanogens associated with the ciliate protozoa, both intracellularly and extracellularly, are responsible for 9 to 37% of the methane production in the rumen (Newbold et al., 1995). For this reason, treatments that decrease the protozoal population of the rumen, may also decrease the protozoa-associated methanogen population and therefore, decrease the methane production within the rumen. Treatments that have been used include copper sulphate, acids, surface-active chemicals, triazine, lipids, tannins, ionophores, and saponins. It has been suggested that the effect of defaunation on methane output is diet dependent. Hegarty (1999) found that defaunation reduced methane output 13%, but the magnitude of reduction varied with diet. The greatest reduction in methane production with defaunation was measured on a high-concentrate diet, likely because protozoa are the predominant source of hydrogen for methanogenesis on starch-based diets. Although, Hegarty et al. (2007) also found that there was no main effect of protozoa on rumen methane production, when investigated in chemically-defaunated, defaunated from birth, and faunated lambs. Another consideration is whether there are long-term effects of defaunation on methanogenesis. Morgavi et al. (2010) found methane reductions due to defaunation to last more than two years, but a study of ionophore supplementation by Guan et al. (2006) found that reductions in rumen methanogenesis were short-lived and hypothesized this was due to adaptation of ciliate protozoa. Finally, maintenance of defaunated animals can be difficult. A recent study found that transfer of viable protozoa to defaunated animals does not occur readily through contact with feed or feces of faunated animals, nor with direct contact with faunated animals, but does occur through contaminated water (Hook et al., 2011).

5.7. Lipids

Dietary fat seems a promising nutritional alternative to depress ruminal methanogenesis without affecting other ruminal parameters (Wanapat et al., 2013). There are five possible mechanisms by which lipid supplementation reduces methane: reducing fibre digestion (mainly in long chain fatty acids); lowering DMI (if total dietary fat exceeds 6 to 7%); suppression of methanogens (mainly in medium chain fatty acids); suppression of rumen protozoa and to a limited extent through biohydrogenation. 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 animal production. Oils may act as hydrogen sinks but medium chain length oils appear to act directly on methanogens and reduce the numbers of ciliate protozoa. However, Kongmun et al. (2010) reported that supplementation of coconut with garlic powder improved *in vitro* ruminal fluid fermentation in terms of the VFA profile, reduced methane losses and reduced protozoal population. 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 the increased demand for food and industrial use. Few reports cover the effect of oil supplementation on methane emissions from dairy cows, where its impact on milk fatty acid composition and overall milk

fat content would need to be carefully studied. Recent strategies, based on processed linseed, turned out to be very promising in both respects. Most importantly, a comprehensive whole system analysis needs to be carried out to assess the overall impact on global GHG emissions (Wanapat et al., 2013).

Manh et al. (2012) reported that supplementation with Eucalyptus leaf meal at 100 g/d for ruminants could be an alternative feed enhancer: it reduces the production of rumen methane gas in cattle, while the digestibility of nutrients was unchanged. Conversely, Pilajun and Wanapat (2011) reported that increasing the coconut oil and mangosteen peel pellets (Mago-pel) levels decreased proportion of methane production, and that a suitable level should not exceed 6% for coconut oil and 4% DM for Mago-pel supplementation. In the future, comprehensive research into the individual components of essential oils, the physiological status of animals, the nutrient composition of diets and their effects on the rumen microbial ecosystem and metabolism of essential oils will be required to obtain consistent beneficial effects. Moreover, previous work, based on using plant secondary compounds and oils in both *in vitro* and *in vivo* trials, concerning rumen microorganisms, methane production and their impact on the mitigation of methane in the rumen, shows great potential for improving rumen ecology in the study of ruminant productivity (Wanapat et al., 2013).

5.8. Genetic selection

Recently, it has been studied that CH₄ production from different animals under same feeding conditions shows significant variation among animals (Patra, 2011). In trials with grazing sheep, Pinares-Patiño et al. (2003) identified some animals as high and low CH₄ emitters on the basis of CH₄ output per unit of feed intake and noted that these differences persisted all the four measurement periods of 5 months when the same type of diet was fed. Although the reason is not clear, it might be due to variations of methanogen numbers among animals (Zhou et al., 2009). This finding suggests the possibility of genetic differences between animals in CH₄ production, which could be utilized for genetic selection for low CH₄ production. Recent research has demonstrated that ruminants with low residual feed intake (RFI; i.e., the difference between actual feed intake and the expected feed requirements for maintenance and production) emit less CH₄ than the animals with high RFI (Hegarty et al., 2007). This may offer an opportunity for genetic selection for this trait and it can be selected without compromising the production traits. For instance, Hegarty et al. (2007) reported that CH₄ emission was lower in Angus steers selected based on low RFI than in steers having high RFI (142 vs. 192 g CH₄ per day or 132 vs. 173 g CH₄ per kg daily gain) and daily gain was similar in both groups. The low CH₄ emissions by cattle with low RFI might be due to lower methanogen numbers in low RFI cattle than in high RFI cattle (Zhou et al., 2009). It has also been suggested that the greater suppression of CH₄ could be achieved on low digestibility diets, when animals are selected based on low RFI (Hegarty et al., 2007). Thus, this strategy could be more advantageous for the tropical countries where low-quality feeds are fed to ruminants.

6. Conclusions

Livestock production is essential for food security and for bringing millions of people out of poverty and starvation to build and maintain a stable society. The world is facing major challenges, from feeding the growing population to tackling severe environmental crises including natural resource degradation and catastrophic climate change. The management strategies to mitigate

methane emissions from ruminant not only will enhance utilization of dietary, improve feed efficiency and animal productivity, but also a decrease in methane emissions will reduce the contribution of ruminant livestock to the global methane inventory.

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