Iranian Journal of Applied Animal Science

Recent Nutritional Advances to Mitigate Methane Emission in Cattle: A Review

Review Article

A. Hadipour[1], A. Mohit[1*], H. Darmani Kuhi[1] and F. Hashemzadeh[2]

[1] Department of Animal Science, Faculty of Agricultural Science, University of Guilan, Rasht, Iran
[2] Department of Animal Science, Faculty of Agriculture, Isfahan University of Technology, Isfahan, Iran

Received on: 15 Feb 2020
Revised on: 15 May 2020
Accepted on: 31 May 2020
Online Published on: Mar 2021

*Correspondence E-mail: ar_mohit@guilan.ac.ir

ABSTRACT

Climate change and preventative regulations on greenhouse gas (GHG) emissions have forced countries to focus on reducing the emission of GHG by the causative factors. The rapid increase in the world population, the culture of urbanization and enhanced income of human societies over the past few decades have raised concerns about more effective and sustainable ways of the food supply with minimum adverse effects on the environment. The livestock sector is very important in terms of meat, milk, and eggs, that all of them are important and high-quality constituents of human nutrition. Despite the value of these products, livestock and poultry have not ever been without a detrimental effect on the environment, and the challenge for researchers and scientists in this field has tried to minimize these adverse effects. GHGs such as CH_4, CO_2 and N_2O, and nitrogen and phosphorus disposal are some of them, which affect both the livestock and poultry sector. About 14.5% of total global anthropogenic GHG per year has been attributed to the domestic animal production sector, which is equal to 7.1 gigatonnes of the annual CO_2 equivalent (CO_{2equ}) of GHG. Approximately, 44%, 29% and 27% of the sector's emissions are CH_4, N_2O, and CO_2, respectively. Methane production and N_2O emission in ruminants are not only effective on the environment but also on animal performance, so the use of multipurpose strategies to reduce the emission of these compounds can improve livestock performance in addition to positive environmental impacts. Since more than 54% of the annual production of CO_{2equ} has been accounted for beef cattle, using different mitigation strategies in this section is more essential. The present review aimed to summarize the current knowledge and findings of the influencing factors on GHG emissions from beef cattle.

KEY WORDS beef cattle, emission, greenhouse gas, methane.

INTRODUCTION

Climate change, besides environmental degradation, population growth, widespread poverty and increasing food insecurity, are considered as the most important challenges of the 21st century. Unfortunately, the effects of climate change such as rising sea levels, increasing flood risks and changing climate patterns will be irreparable (FAO and GDP, 2018). Forecasts suggest that the world population will reach from 7.6 to 9.8 billion in 2050 but the food demand will double, mainly due to increasing urbanization and income level (FAOSTAT, 2020) .Therefore, agriculture, and especially the livestock sector, will play a very critical and challenging role in meeting the rising demand for this growing population. Iran, as one of the largest countries in the Middle East, plays a key role in the region's economy, especially agriculture and livestock production. According to the FAOSTAT (2020) and the Statistical Center of Iran (2017), there were more than 4.8 million cattle in Iran producing more than 6.8 million tons of milk and

477000 tons of meat annually. In addition to being economically important, the profession has also employed over 3.1 million people (about 3.8% of the population) in the country. Because of significant differences in the number of livestock between Iran compared to United States, Brazil, China, Turkey, and European Union (EU) (Table 1), the contribution of Iran to greenhouse gas (GHG) emission from livestock production appears to be less. However, since Iran is located in a hot and dry region will affect more than other regions and will not be safe from climate change. Therefore, to the goal of "sustainability" of global food system, any effort to minimize the adverse impact of ruminant husbandry on the environment will be valuable. "Sustainability" is more than environmental impacts and balances environmental, social concerns and economic conditions (Flachowsky *et al*. 2018; Gleason and White, 2019; Lan and Yang, 2019).

A significant source of greenhouse gas (GHG) emissions is the agricultural sector (Burney *et al*. 2010). According to FAO (2018), the three main GHGs emitted from agriculture activities are CH_4, CO_2, and N_2O. The GHGs emission sources remarked including Enteric fermentation and manure management; Application of fertilizers and associated products; Energy consumption (directly or indirectly like livestock production, farm facilities and feed manufacturing and processing practice); and Land use changes. Generally, it is estimated that ruminants contribute around 80% of the total global livestock emissions and recognized as major contributors through the production of methane (Gerber *et al*. 2013). According to EPA (2018), beef cattle were predominant contributors to CH_4 emissions and were responsible for 71% of total enteric CH_4 emissions from livestock in 2016. In addition, as described by Mitloehner (2018) and White and Hall (2017) United States beef cattle enterprises account for 52% and 25% of emissions from animal agriculture and of all agricultural emissions, respectively. The magnitude of the impact of each GHGs on global warming is calculated using a conversion factor as CO_2 equivalent, which is 1, 34 and 298 for CO_2, CH_4 and N_2O, respectively (FAO, 2018).

The environmental impact of animal-derived foods are currently quantified by so-called CO_{2equ} footprints (CFs) (Flachowsky and Hachenberg, 2009). The CFs for animal originated food depends on numerous of affecting factors like animal species, type of production, feeding of animals, level of animal performance, system boundaries, and output/endpoints of production (Flachowsky and Kamphues, 2012). Edible protein from ruminants is mainly defined by a higher CFs because of the high GHGs potential of CH_4 produced in the rumen. In addition, the energy and protein conversion efficiency from feed into food of animal origin is low and may vary between 3% (energy-beef) and up to 40% (energy-dairy; protein-chicken for fattening); (Cassidy *et al*. 2013; Flachowsky *et al*. 2018). However, CFs for beef cattle husbandry usually extend from the inputs to the harvesting system through the feedlot or slaughterhouse gates. GHG emissions from beef cattle rearing are including CO_2 emissions from commercial fertilizer synthesis, herbicides, seeds and other inputs to the farm system; CO_2 emissions from field management and transportation; CH_4 emissions from enteric fermentation and manure storage. Direct and indirect N_2O emissions from manure management; CO_2 emissions from infrastructure upkeep; and other sources (Gleason and White, 2019). For most beef cattle producers in the United State, the cow-calf operation contributes the greatest to the whole-system emission primarily because of enteric fermentation from the herd level of cow (Beauchemin *et al*. 2007; Asem-Hiablie *et al*. 2019).

According to Opio *et al*. (2013), cattle annually emitted 4.6 gigatonnes CO_{2equ}, of which 46% derived from dairy and 54% from beef cattle. However, buffalos and small ruminants released only 0.62 and 0.47 gigatonnes CO_{2equ}, respectively. In addition, enteric CH_4 contributed almost 45% of the combined CO_{2equ} emissions from dairy and beef cattle. It is reported the meat production by beef cattle systems is about 35 million tonnes/year, while by dairy cattle systems is only 27 million tonnes/year. GHG emission intensity of meat protein from beef cattle, and integrated milk and meat protein intensity from dairy cattle differ from about 200-1100, and 50-350 kg CO_{2equ}/kg edible protein, respectively, related to the region of the world (Opio *et al*. 2013).

Feed, as the major variable inputs cost, plays a critical role in cattle production, and a cattle operation can be profitable when the feed used efficiently to meet nutrient requirement (Johnson *et al*. 2019). Determining efficient beef cattle breeds and their adoptability to suitable production systems is a major challenge of meat production around the world, with the raising concern about the environmental effects of beef productions (Rowntree *et al*. 2016). Recently, the EPA (2018) and Rotz *et al*. (2019) reported that beef cattle have emitted about between 132 to 142 Tg CO_{2equ}/year through enteric fermentation and manure management.

Anaerobic digestion and microbiology of methanogenesis

Anaerobic digestion is a very complicated process of dissociation of organic compounds including a sequence of biochemical processes, consisting of hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Due to the complexity of this digestion process, a specific group of microorganisms performs each step with different rates; for instance, the most critical of them are hydrolytic-fermentative, acetoclastic and hydrogenotrophic methanogenic archaea, proton-reducing acetogenic and their metabolic intermediates (Zabranska and Pokorna, 2018). Since methanogenesis, the process of CH_4 formation, has the slowest rate, the balance among different steps of anaerobic digestion is required to achieve the optimum process efficiency (Demirel and Scherer, 2008) (Table 2). Briefly, the complex organic compounds are enzymatically metabolized by all mentioned groups of microorganisms through series of metabolic intermediates like CO_2, H_2, alcohols, and low fatty acids, especially volatile fatty acids (VFA) such as propionic and butyric acids.

Then, propionic and butyric acids are hydrolysed by syntrophic acetogens into direct and simpler precursors of methanogenesis such as CH_3-COOH (acetate), CO_2, and H_2. Finally, CH_4 be generated by methanogenic archaea from a limited number of substrates, CO_2 and H_2, acetic acid, C1-compounds, and methyl group donors (e.g. methanol, methylamines, and methylsulfides) (Costa and Leigh, 2014; Zabranska and Pokorna, 2018).

Methanogens are a specific community of microorganisms, which are exclusively producing CH_4 through the methanogenesis and belongs to domain archaea. Despite their division and taxonomy are included to four classes (*Methanobacteria*, *Methanococci*, *Methanomicrobia*, and *Methanopyri*).

These microorganisms have living conditions requirements and greatly specific substrates and become frequently the restrictive community of the completely anaerobic digestion. The principal specifications of given methanogenic archaea, particular and limited precursors, as shown in Figure 1, (H_2, CO_2, formate, methanol, acetate, and methylamines), and requirements for the cultivation conditions like optimal temperature (30-83 ˚C) and optimal pH ranges (5-8.5) (Zabranska and Pokorna, 2018; De la Fuente *et al.* 2019). Hydrogenotrophic methanogens use H_2 and CO_2 or formic acid to generate CH_4. In addition, acetotrophic methanogens produce methane from acetic acid, but methylotrophic methanogens only use C1- and methylated as precursor compounds (Demirel and Scherer, 2008). Interestingly, *Methanosarcina* spp. are the only methanogens, which are capable to utilize all the substrates mentioned above and metabolize up to nine several different substrates (Galagan *et al.* 2002). Furthermore, it should be considered that until now only around 10% of rumen microbes are known and there are undetected rumen microbial genera and species especially involving on methanogenesis (Pers-Kamczyc *et al.* 2011). Fortunately, findings have detected new rumen microbial species through molecular biology techniques like Real-time PCR, polymerase chain reaction and denaturing gradient gel electrophoresis (PCR-DGGE), and fluorescence *in situ* hybridization (FISH) (Mohammed *et al.* 2011; Szumacher-Strabel *et al.* 2011).

It should be noted that enteric CH_4 emission in ruminants along with being an environmental negative impacts leading to a loss of 10–11% of the total gross energy (GE) intake of the animal (Flachowsky and Brade, 2007; Tamminga *et al.* 2007; Valli, 2020). Therefor, suppress CH_4 emission from ruminant is crucially required (Lan and Yang, 2019). In recent decades, various strategies and intensive research have been developed to mitigate enteric CH_4 emissions without negatively effect on animal productivity. For example, nutritional strategies, rumen manipulations as well as management or breeding techniques can be mentioned. Feeding and nutritional strategies are more practical and conventional approaches to reduce enteric CH_4 emissions and can be more easily practiced under field conditions by farmers. Furthermore, to the direct relationship between enteric CH_4 production and dry matter intake, total methane emission of high-producing cattle will be higher than low-producing animals. However, the amount of CH_4 intensity (g/kg of meat or milk) from higher dry matter intake of the high-yielding animals will be reduced. In other words, despite higher GHGs emissions, the main advantages of raising high producing, more health and fertile, and longer life expectancy animals ultimately reduce the GHGs intensity per unit of products (milk/meat) (Özkan *et al.* 2015; Özkan *et al.* 2018; Von Soosten *et al.* 2020).

Various strategies, which manipulate rumen conditions and subsequently reduce enteric CH_4 emissions are increasing of concentrate to forage ratio, increasing levels of fatty acids and lipid supplementation, plant secondary metabolites, bacteriocins, ionophores, probiotics, halogenated CH_4 analogues, nitroxy compounds, fungal metabolite, and microalgae.

Dietary strategies to mitigate CH_4 emissions

Various methods and strategies have been proposed to reduce enteric CH_4 production in ruminants, such as dietary modification, manipulation of ruminal fermentation, and preventing methanogenic archaea using specific inhibitors. Methanogenesis inhibitors might be potentially efficient reducing agents if they apply the evolutionary determined of methanogenic archaea (Moate *et al.* 2016). In addition, archaea are evolutionarily distinct from other rumen microorganisms (including bacteria, protozoa, fungi, and viruses), and all methanogenic archaea contribute a similar biochemical pathway of methanogenesis (Hedderich and Whitman, 2013). Hence, the preventers of the methanogenesis pathway may exclusively prevent only methanogens without directly affecting other useful rumen microorganisms (Moate *et al.* 2016; Patra, 2016).

Table 1 Statics data of cattle production in Iran comparing to other countries in 2017 (FAOSTAT, 2017)

Country	Cattle Qty. (×10^6)	Meat production (ton)	Milk production (ton)
Iran	4.879	477887	6811482
China	83.355	6911741	30772422
United States	93.705	11907239	97734736
Brazil	214.890	9550000	33490810
Turkey	14.080	987482	18762319
European Union	121.396	10504465	221362061

Table 2 Reactions of methanogenesis (Demirel and Scherer, 2008; Zabranska and Pokorna, 2018)

$4H_2+CO_2 \rightarrow CH_4 + 2H_2O$

$CH_3COOH \rightarrow CH_4 + CO_2$

$4HCOOH \rightarrow CH_4+ 3CO_2 + 2H_2O$

$4CH_3OH \rightarrow 3CH_4 + CO_2 + 2H_2O$

$4CO + 5H_2O \rightarrow CH_4 + 3H_2CO_3$

$4(CH_3)_3N + 6H_2O \rightarrow 9CH_4 + 3CO_2 + 4NH_3$

$2(CH_3)_2NH + 2H_2O \rightarrow 3CH_4 + CO_2 + 2NH_3$

$4(CH_3)NH_2 + 2H_2O \rightarrow 3CH_4 + CO_2 + 4NH_3$

$2(CH_3)_2S + 2H_2O \rightarrow 3CH_4 + CO_2 + H_2S$

$4Me^0 + 8H^+ + CO_2 \rightarrow 4Me^{++} + CH_4 + 2H_2O$

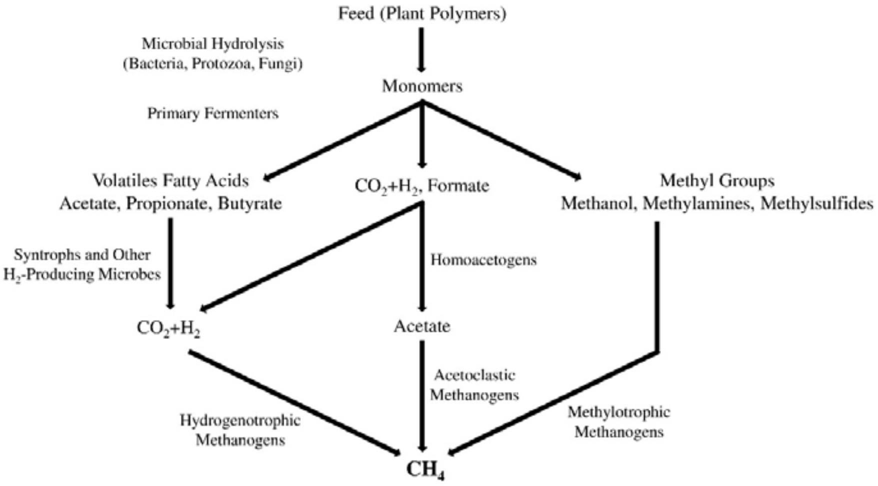

Figure 1 Schematic anaerobic fermentation of organic matter to methane
The main substrates and microbial groups catalyzing the reactions are indicated (De la Fuente *et al.* 2019)

Several reviews on CH_4 reduction approaches and options have been published previously (Patra, 2016; Knapp *et al.* 2014; Cottle *et al.* 2011). In this section, further recent advances in nutritional CH_4 mitigation strategies are mentioned.

Increasing concentrate:forage ratio

One of the most reliable strategies to reduce CH_4 emissions in dairy and beef cattle is using higher level of concentrate (Knapp *et al.* 2014).

Providing higher amounts of concentrate is mitigated gross energy (GE) loss dramatically (Johnson and Johnson, 1995) and is decreased CH_4 emissions by 3-6.5% (Beauchemin *et al.* 2007). Increased percentage of concentrate in diets consequently decrease fiber levels (cellulose and hemicellulose) and increase starch levels caused widespread physiological changes in the rumen environment. These changes are due to changes in microbial populations such as amylolytic bacteria, increasing in the production of VFAs, enhancing the ratio of propionate to acetate, which reduces CH_4 production by reducing the availability of H_2 in the rumen (Ribeiro Pereira *et al.* 2015).

Altogether, the effects of increasing the amount of concentrate on CH_4 production depend on several factors. The most important factors are the type and quality of forage and the level of supplementation of concentrate or forage. In general, these effects are exacerbated when the amount of concentrate in low quality forage diets increases from zero to around 50% or from 70-75% to more than 90%. Conversely, there were at least changes in CH_4 emission when a moderate amount of concentrate in higher quality forages (such as grass silage) diets included (increase from 25-30% to 70-75%) (Huhtanen and Huuskonen, 2020). The type of grains used in the concentrate has shown that can change the CH_4 production too. For example, when the main grain source of concentrate was corn, 30% greater decrease in CH_4 production was shown compared to barley. Also, the reduction of CH_4 emission has been dramatically increased when optimum dietary balance and high digestible and nutritive ingredients were used in grazing cows fed with the high amount of concentrate (Beauchemin and McGinn, 2005).

It should be noted, providing a higher ratio of concentrate in cattle diet to reduce CH_4 emission has special considerations and limitations. High levels of concentrate could decrease the ruminal pH, increase the production of lactic acid and subsequently promote ruminal acidosis and shorten the productive life span of animals. Furthermore, the economic explainability of concentrate supplementation should be considered. Increasing the concentrate to forage ratio will negatively affect the digestibility of crude fiber which could lead to loss of productivity potential and will also result in increased concentration of fermentable organic matter in manure and is presumably to increase CH_4 emissions from manure management (Lee *et al.* 2012).

The increased price of forage in Iran as a result of consecutive droughts has been makes beef cattle operators to include more concentrate in the ration (Statistical Center of Iran, 2017).

Supplementation of lipid and fatty acid

Supplementation of lipid, oils and fatty acids is considered as reliable solution to mitigate enteric methane emission of dairy and beef cattle (Beauchemin *et al.* 2007; Patra and Yu, 2013a; Bayat *et al.* 2018). More recent studies have also proven that supplementation of plant oils, fats or fatty acid supplementation in beef cattle diets can effectively decrease enteric CH_4 emissions (Aviles-Nieto *et al.* 2019; Winders *et al.* 2019). According to Patra and Yu, (2013b), each 1% increase in dietary fat supplementation decreases CH_4 emission by 4.30%. In addition, in a meta-analysis using 33 treatments (Beauchemin *et al.* 2007), each 1 percentage of dietary fat addition resulted in a 5.6% mitigation in CH_4 (g/kg of dry matter intake (DMI)) maximum to 36%. In general, there are three ways that dietary lipids reduce methane: 1) biohydrogenation of fatty acids, 2) increased propionate production from lipolysis converting triglycerides to glycerol, which is then converted to propionate by *Anaerovibrio lipolytica* bacteria, and 3) reduction in available fermentable substrate in the rumen as fatty acids are not fermentable (Winders *et al.* 2019). Dietary supplementation of different type of lipids might decrease dry matter intake in many kinds of diets, eventually can indirectly influence on enteric CH_4 emission (Eugène *et al.* 2008; Rabiee *et al.* 2012; Hristov *et al.* 2013). It should be considered that the physical form of lipid (free oils comparing oilseeds) could affect its potential to reduce enteric CH_4 emissions. For example, supplementation of whole sunflower seeds has been mitigated CH_4 more than it’s free oil (Beauchemin *et al.* 2007). In contrast, in further studies by Brask *et al.* (2013) and Fiorentini *et al.* (2014) were not found any positive impact of the physical form of lipids on CH_4 emissions when cattle fed total mixed rations. A recent *in vitro* research (Beck *et al.* 2018) has shown that supplementation of whole cottonseed to grazing beef cattle is an efficient solution to reduce enteric CH_4 emission intensity.

In addition, Beck *et al.* (2019) reported fat supplements varying in physical form (whole cotton seed meal, bypass fat and soybean oil) can improve beef cattle performance and reduce methane emission divergently. In summary, using unsaturated fatty acid sources (soybean oil and whole cottonseed) has reduced approximately 12% of methane production (g/d) comparing control and bypass fat powder. Although, dietary fat supplementation has emitted CH_4 emission (g/kg average daily gain (ADG)) nearly 50%. However, it seems differences in oil and fat source can shift the rumen microbial communities (Wang *et al.* 2017). Alternatively, supplementation of oilseeds may be gradually released or only be partially available to the rumen (Beck *et al.* 2019).

Plant secondary metabolites

Antibiotics are widely supplemented to beef cattle rations in order to their ability as rumen modulators, optimizing animal productivity (D’Aurea *et al.* 2019; Vieco-Saiz *et al.* 2019) and decreasing enteric CH_4 production (Bodas *et al.* 2012). However, present regulations by health organizations have been banned or limited antibiotic usage in animal husbandry. This issue has forced different workers looking for antibiotics alternatives such as natural feed additives or plant secondary metabolites (Ornaghi *et al.* 2019). Several plant secondary metabolites, such as saponins, tannins, and essential oils (EO), in different forages and plant extracts have been proven to be efficient for enteric CH_4 reduction

(Hristov *et al*. 2013; Knapp *et al*. 2014; Patra, 2016). Plants contain a high amount of tannins and saponins have reported being potential to mitigate CH_4 emission in cattle (Suybeng *et al*. 2019; Wu *et al*. 2019). As recently reviewed by Aboagye and Beauchemin (2019), tannins play as rumen modifiers and able to influence methanogenesis although their mechanism is still unclear.

Nevertheless, various theories have been reported that how tannins reduce CH_4 emission in ruminants: (a) tannins can directly impact on methanogens; (b) they influence protozoa that are related to methanogens; (c) tannins effect on fibrolytic bacteria and decrease rumen fiber digestibility, and (d) they act as an H_2 sink.

Probably, the tannin type (molecular weight, source or subunit), concentration, dietary substrate, and animal type are the most significant factors can affect CH_4 production and might be divers in an extensive range (*in vivo*=6.0% to 68% and *in vitro*=4.3% to 70%). In beef cattle, supplementation of hydrolysable tannin subunit (i.e. gallic acid) has the potential to reduce the environment impact of cattle husbandry (lower CH_4, N_2O and ammonia emissions), without affecting animal productivity (Aboagye *et al*. 2019).

In a recent *in vitro* study, using different levels of eucalyptus oil (2, 4, 6, 8, and 10 mL.kg^{-1} DM) and a high-protein diet has decreased the CH_4 emission even with minimum oil amounts (Abdelrahman *et al*. 2019). Eucalyptus oil acts a definitive role in CH_4 reduction in order to it's highly desaturation point, which led to toxicity for methanogenic archaea (Prins *et al*. 1972).

Recent *in vitro* study demonstrated that using a basal dietary plant-like alfalfa silage (rich in secondary metabolites, especially saponins) can reduce enteric CH_4 emission and methanogens counts (Kozłowska *et al*. 2020). This kind of investigation can more feasible and acceptable for farmers to use inexpensive and more available compound instead of saponins rich sources.

The good potential of garlic and citrus extracts (15 g.d^{-1}.animal^{-1}) has been showed to mitigate CH_4 production and yield in Angus × Hereford feedlot cattle (Roque *et al*. 2019). Allicin, a biologically active compound in garlic extracts, can affect CH_4 emission through reductions in on methanogenic archaea and protozoa populations (Ma *et al*. 2016) with it's highly permeable potential through cell membranes (Miron *et al*. 2000). According to Eger *et al*. (2018) a blend of citrus and garlic extracts may decreased CH_4 production by changing the population of methanogenic archaea such that the proportion of *Methanobacteriaceae* was emitted without affecting negative impacts on rumen fermentation.

Dietary supplementation of a mixture of natural additives (1.5, 3.0, 4.5, or 6.0 g.d^{-1}.animal^{-1}, containing 37.5% each of clove essential oil (vanillin, eugenol and thymol) plus 12.5 % of castor and cashew oils) linearly reduced CH_4 production (76%) in cross-bred Angus × Nellore beef cattle. Moreover, measurement of abundance of Archaeal community demonstrated a reduction (79%) in the main CH_4 producing genera including: Ferroplasma, Halorhabdus, Methanoplanus, and Picrophilus. The greatest generators of acetate in the rumen, *Fibrobacter* and *Lactobacillus*, have been declined by 71% leading to inhibition of H_2 production and reduction of CH_4 formation (Ornaghi *et al*. 2019).

Berry fruits and their by-products contain several biologically active compounds like tannins, saponins, flavones, phenolic acids, ellagic acid, vitamins C and E, folic acid, and ß-sitosterol that can be applied in animal nutrition (Roj *et al*. 2009). Supplementation of hemp and blueberry oils (as unconventional oils high in polyunsaturated fatty acids, (PUFA)) has been showed which can reduce enteric CH_4 emission by 10-16% without compromising effect on rumen fermentation and degradability (Embaby *et al*. 2019). Adding of berry seed residues showed profitable economically and nutritionally for dairy cattle production and but reduced CH_4 emission numerically (Bryszak *et al*. 2019).

The effect of bioactive compounds and secondary plant metabolites on CH_4 mitigation may also depend on the basic nutrient components (like crude protein and crude fiber) (Patra and Saxena, 2009; Cieslak *et al*. 2013; Cieslak *et al*. 2014). There are some evidences that basic nutrient components can interact with bioactive compounds and consequently the bioactive compounds become physically less available for microbiota. For instance, increasing the amount of NDF and ADF inhibits microbial activity through a reduction in the availability of slowly fermented carbohydrates (Wilson and Hatfield, 1997). In addition, variations in the chemical composition of the herbs (such as Neutral detergent fiber (NDF), acid detergent fiber (ADF), crude protein (CP) can affect the concentration of short chain fatty acids (Njidda and Nasiru, 2010) and the ruminal pH and can suppress methanogen growth, hence mitigating CH_4 production per unit of fermented organic matter (Van Kessel and Russell, 1996). Furthermore, the results confirmed that fumarate supplementation with herbal mixture in high concentrate diet can reduce *in vitro* CH_4 emission by 10-11% and increase propionate ranging from 5 to 13%; however, it's effect depends on many parameters, such as the type or nature of diet, fumarate concentration, ruminal pH, and different microbial community in batch culture (Pisarčíková *et al*. 2016).

Nitrate supplementation

Researchers suggested that nitrate (NO_3^-) acts as a CH_4 inhibitor by changing the population of rumen microbiome in the following two methods: a) toxicity by nitrite (NO_2^-), an intermediate of nitrate reduction; b) competition for H_2 (Zhao *et al.* 2015). In the other word, nitrate prevents methanogenesis playing as H_2 alternative sinks and directly preventing the methanogenic archaea. As described by Patra (2016) two benefits are introduced for nitrate supplementation: (a) reducing of CH_4 production, as mentioned above, and (2) providing ammonia to growth of rumen microbial community resulting in reduced dietary protein inclusion. Therefore, nitrate can influence as an efficient CH_4 suppressor and a possible non-protein nitrogen (NPN) resource for beef cattle, playing as an electron sink and adding NH_4-based N to the rumen (Nolan *et al.* 2010; Zhao *et al.* 2015).

Encapsulation of nitrate (NO_3) has been investigated to make sure nitrate slowly release inside the rumen environment and enhance the efficiency of microbial community to reduce NO_3 to NH_4 completely, hence keeping down the risk of NO_3/NO_2 toxicity (Alemu *et al.* 2019). Feeding slow release nitrate (encapsulation nitrate (EN), 2.5% encapsulated calcium ammonium nitrate (NO_3^-)) in feedlot cattle fed high-grain finishing diets reduced CH_4 yield (10.06%), dry matter intake and slaughter weight without affecting ADG; however, more days on-feed may be required to reach slaughter weight which may compensate some of the benefits of improved G:F (9.7%) and reduced CH_4 emissions (Romero-Pérez *et al.* 2018). Supplementation of NE in substitution of urea mitigated enteric CH_4 emissions (13%) although has not been shown positive impact on beef cattle performance (Alemu *et al.* 2019).

In grazing steers, NO_3 encapsulation can positively influence enteric CH_4 emission, thereby reducing *Methanobrevibacter* abundance in the rumen. Moreover, EN supplementation can stimulate the growth of fumarate-reducer and lactate generator bacteria, thereby increasing propionate: acetate ratio through rumen fermentation (Granja-Salcedo *et al.* 2019). Finally, information about the factors affecting the efficiency of nitrate reduction in the rumen is scarce. Encapsulation nitrate, amount of nitrate consumed and the rate of nitrate intake as well as the type of diet (e.g., concentrate:forage ratio, nitrogen and sulfur concentrations) and the type of animal affect the ruminal nitrate consumption, and subsequently, the reduction of CH_4 emissions. In addition, the period time of a dietary nitrate added may influence its efficacy in decreasing CH_4 emission over time (Alemu *et al.* 2019).

Lactic acid bacteria (LAB) supplementation

Sustainable food production can be achieved when innovative and creative strategies are used to reduce CH_4 emissions from livestock. One of these recent strategies is the application of LAB (Vieco-Saiz *et al.* 2019).

This kind of microorganisms are suitable probiotics and gram-positive bacteria producing lactic acid, as a main end product of carbohydrates fermentation. In addition, LAB-probiotics are intrinsic inhabitants of the mammalian gut microbiome and are among the most relevant microorganisms used in food fermentation. Lactic acid bacteria are simply isolated from the digestive tract of ruminants and used in various forms of direct-fed microbials or silage inoculants (Doyle *et al.* 2019). In addition, it has been suggested that LAB can be used to decrease CH_4 production in ruminant livestock (Haque, 2018).

The researchers examined 45 bacterial strains, including strains of LAB, *Propionibacteria*, and *Bifidobacteria*, for their potential to reduce methanogenic archaea (Jeyanathan *et al.* 2016). They suggested that LAB could stimulate the growth of lactic acid-consuming bacteria, which would increase propionic acid production and subsequently reduce hydrogen availability for methane production. On the contrary, it should be noted that the subsequent work of these researchers (Jeyanathan *et al.* 2019) using similar strains had no effect on reducing methane emissions. However, LAB supplementation can be an effective, viable and intrinsic solution for reducing enteric CH_4 production (Doyle *et al.* 2019), although reliable research and data in this area are still scarce to promote these strategies.

Hydrogen-utilizing bacteria

Hydrogen is recognized as the major substrate for ruminal methanogenesis. There is a closely relevant between H_2 metabolism, its related microbiome and methane producing archaea (Figure 2) (Russell and Wallace, 1997; Lourenço *et al.* 2010). Specific microbes can compete with methanogenic archaea and could convey H_2 apart from methanogenesis consequently reduce enteric CH_4 emission. This strategy may inhibit detrimental effects of chemical additives like microbial resistance or toxicity and increase the availability of feed gross energy of the animal (Lan and Yang, 2019). To explore this method of CH_4 mitigation different types of bacteria have been introduced; e.g., propionate producing bacteria (PPB), sulphate (SO_4^{2-})-reducing bacteria (SRB), nitrate/nitrite-reducing bacteria (NRB) or the homoacetogens. Thermodynamically, PPB, SRB and NRB groups have some special benefits compared to methanogenic archaea when using H_2 as an electron sink. However, their metabolism would be limited in normal ruminal environment due to their low abundance or lack of essential substrates (Lan and Yang, 2019).

Recently, two reliable strategies have been developed to improve the propionate production pathway in the rumen, including the use of propionate precursors such as malate or fumarate or supplementation of propionate-producing bacteria.

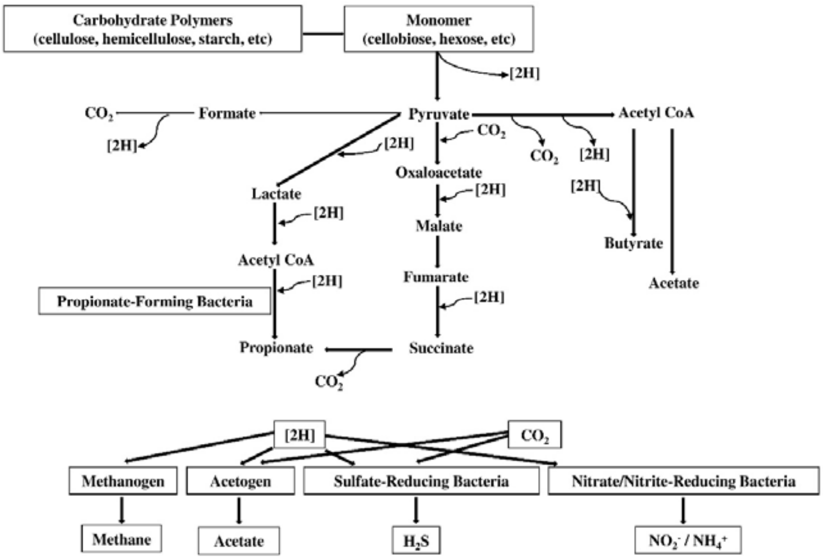

Figure 2 Feed fermentation and H_2 disposal pathways in the rumen (Lan and Yang, 2019)

Because of the small concentration of NO_3^- and SO_4^{2-} in the rumen medium, the use of SO_4^{2-} or nitrate as additives is a preferred approach to stimulate SO_4^{2-} and nitrate reducing bacteria. In order to prevent the toxic effects of these compounds in the rumen, the use of SO_4^{2-} or nitrate/nitrite reducing bacteria is recommended. Despite the dynamic nature of rumen microorganisms, the development and generalization of these methods will require more extensive research on methane emission reduction, both *in vivo* and in larger scale studies (Lan and Yang, 2019).

Nitrooxy compounds

3-nitrooxypropanol (3-NOP) is a recently developed compound that have particular anti-methanogenic effects and can mitigate enteric CH_4 production by 25 to 45% in several studies while maintaining animal performance (Romero-Perez *et al*. 2014; Hristov *et al*. 2015; Vyas *et al*. 2016; Vyas *et al*. 2018). In addition, McGinn *et al*. (2019) indicated that there was a large CH_4 emission reduction of about 70% (±18%) because of 3 nitrooxypropanol dietary adding. This additive has been demonstrated to exclusively target the nickel enzyme methyl-coenzyme M reductase (*mcr*) in methanogenic archaea, thereby preventing the final phase of CH_4 production by reversibly oxidizing the nickel enzyme cofactor from Ni(I) to Ni(II) (Duin *et al*. 2016). Furthermore, dietary adding 3-NOP at 100 $mg.kg^{-1}$ DM decreased CH_4 yield by 18% when beef steers were fed a low concentrate diet but no reduction was reported when a high concentrate diet was fed (Kim *et al*. 2019).

There are some inconsistencies between methane mitigation studies when 3-NOP was fed, although the reasons are still unclear. However, animal type and variation, experimental design and duration, dietary composition, and methane measurement technique may have attributed to the variability (Huhtanen *et al*. 2019). As described by Vyas *et al*. (2016) the rumen concentration of *mcr* may be decreased for a high grain comparing to low grain diet, resulting in greater efficacy of 3-NOP in CH_4 reduction. In addition, Kim *et al*. (2019) reported that by preventing of rumen CH_4 production, fermentation process shifts from acetate to propionate production for $2H^+$ removal. Valerate, as an alternative sink for $2H^+$ in the rumen, has increased when 3-NOP was fed too.

Fungal metabolites

Lovastatin is known as a secondary fungal metabolite that inhibits the activity of a critical enzyme in cholesterol synthesis, 3-hydroxy-3-methyl glutaryl coenzyme A (HMG-CoA) reductase (Jahromi *et al*. 2013; Candyrine *et al*. 2018). Researches have shown that the use of fungal strain *Aspergillus terreus* containing lovastatin as well as fungal strain *Mortierella wolfii* reduced the ruminal population of methanogenic archaea and methane production (Cosgrove *et al*. 2012).

In addition, other fungal metabolites such as “mevastatin” and “pravastatin” also increased the proportion of propionate to acetate and thereby reducing the production of enteric CH_4 production (Morgavi *et al*. 2013).

Microalgae

Studies using microalgae, as methane reducing agents, have shown that CH_4 production is reduced by 99% even with 2% Asparagopsis supplementation *in vitro* condition (Machado *et al.* 2014). Use of algae *Chlorella vulgaris* improved rumen bacterial growth as well as increased total VFAs and enhanced milk production in dairy cows (Anele *et al.* 2016; Kholif *et al.* 2017; Tsiplakou *et al.* 2017). This strain of algae has also been identified as a reliable candidate for reducing methane emissions (Bohutskyi *et al.* 2014; Tsiplakou *et al.* 2017; Wild *et al.* 2019). Furthermore, *Oedogonium*, a member of *Filamentous* microalgae, was reported to reduce enteric methane production (Machado *et al.* 2014). *Cystoseira trinodis* and *Dictyota bartayresii* members of brown algae can inhibit methane production *in vitro* conditions. In addition, Sucu (2019) reported that careful selection and combination of substrate and algae (*Chlorella vulgaris* and *C. variabilis*) may positively manipulate rumen fermentation and may inhibit CH_4 production.

CH_4 inhibitors

Monensin has been widely investigated and accounted to enhance the productivity of beef cattle (Pancini *et al.* 2020). This ionophoric antibiotic isolated from *Streptomyces cinnamonensis* and has antifungal and antiprotozoal (anticoccidial) characteristics. Monensin is commonly utilized in different commercial livestock production, as a growth promotor or improving the ruminal fermentation, body weight gain (BWG) and FCR or as a coccidiostat (Ipharraguerre and Clark 2003; Mimouni *et al.* 2014). Monensin can reduce acetate to propionate proportion, enteric CH_4 and NH_4^+ production, thereby improving efficiency of energy metabolism, feed efficiency and BWG (Hemphill *et al.* 2018; Gupta *et al.* 2019).

In a meta-analysis study by Appuhamy *et al.* (2013), monensin remarkably reduced CH_4 emissions in beef steers and dairy cows (-19 and -6 $g.day^{-1}$, respectively). The reducing impact of monensin on methanogenesis is because of preventive effect on protozoa and gram-positive bacteria, which promote propionate formation and reduce acetate, butyrate and formate production, leading to lower substrate availability for methanogenic archaea and subsequent CH_4 production.

Combination use of CH_4 inhibitors

In recent years, a large number of CH_4 inhibitors have been investigated, mainly individually. However, these compounds usually have special effects on nutrient digestibility and ruminal fermentation, especially if supplemented at high concentration levels for greater inhibition effect on methane emission (Patra, 2016). Some of these compounds also lead to animal toxicity when used at high doses (Patra, 2012). Supplementation of lower doses of CH_4 inhibitors can compensate for the toxicity problems but the methanogenesis inhibition effect is not highlighted at low doses. However, combinations of inhibitors with a supplementary mode of actions may mitigate CH_4 emission synergistically and improve their efficiency without using any harmful impact on rumen fermentation or nutrient digestion at low levels (Patra and Yu, 2013a; Narvaez *et al.* 2013). Recently, it has been demonstrated that combinations of two relevant CH_4 inhibitors (saponin with nitrate) can be more effective and practical than individual inhibitors (reduced 32.92% and 25.04% with nitrate and nitrate+saponin, respectively). Different mechanisms have been reported for these inhibitors such as antimethanogenic actions or inhibit different microbial communities involved in CH_4 production or SO_4-reduction (Wu *et al.* 2019).

Genetic control of GHGs

Nowadays, the mitigation of enteric CH_4 of cattle has critical importance. In general, there are four main methane-controlling parameters: 1) rumen microbial community, 2) dry matter intake and feed composition, 3) host physiological conditions, and 4) host genetics (De Haas *et al.* 2016). Recent studies have shown that genetic factors in which controlling enteric CH_4 is a heritable trait with a high correlation with dry matter intake (De Haas *et al.* 2016; Garnsworthy *et al.* 2019). Different studies have illustrated that intrinsic variation between cattle exists in enteric methane emission and there is a possibility to decrease CH_4 production ranging from 10 to 20% by breeding (Waghorn and Woodeward, 2006; Grainger *et al.* 2007). However, it should be considered that nutritional and management strategies to mitigate enteric CH_4 emission leading to short-term reduction, but breeding and genetic strategies can provide long-term and persistence reduction in order to their improvement are cumulative and permanent (Garnsworthy *et al.* 2019). It should be stressed that the genetic control of GHGs are mainly focused on dairy cattle and information from beef cattle are scarce (Barwick *et al.* 2019; Fennessy *et al.* 2019).

Regardless of the reduction approaches, measurement methods of enteric CH_4 emission are critically essential to achieve a highly accurate and precise date. In addition, measuring CH_4 on a large quantity of cattle is a strict challenge. However, different scientists around the world have tried to focus on efficient measurement methods to achieve a highly accurate date with a large number of animals (Jonker *et al.* 2020). However, recent findings confirmed that there is a sufficient correlation among different direct and indirect methods measuring enteric methane emission (Garnsworthy *et al.* 2019).

CONCLUSION

Practical strategies to reduce enteric CH_4 emission in ruminants can be effective both in achieving international commitments due to climate change and in improving gross energy efficiency and livestock performance. Increasing livestock productivity through production systems improves the livelihoods of livestock farmers and ensures food security. Although innovative and novel strategies to reduce CH_4 emissions have been explored, only a few of them have been developed due to efficiency, feasibility, and cost-effectiveness, which will subsequently be developed on farms. It seems that combining several strategies to reduce CH_4 production at the farm level would significantly reduce the rate of CH_4 emit from cows to a considerable extent compared to using a single or an individual strategy. Therefore, CH_4 reduction strategies that show both nutritional and environmental benefits are likely to be better accepted by farmers. For example, increasing the level of concentrate and fat and oil supplements can reduce the production of CH_4 as well as improve animal productivity. Likewise, dietary nitrate supplementation can reduce crude protein levels in the diet and ultimately reduce methane emissions and enhance productivity. Future research, however, on reducing greenhouse gas emissions, particularly methane and N_2O, should focus on achieving both environmental and nutritional approaches to sustainable development.

ACKNOWLEDGEMENT

The authors would like to express special thanks to Aida Jafari- Sayadi for her contribution to this review.

REFERENCES

Abdelrahman S.M., Li R.H., Elnahr M., Farouk M.H. and Lou Y. (2019). Effects of different levels of eucalyptus oil on methane production under *in vitro* conditions. *Polish J. Environ. Stud.* **28(3),** 1031-1042.

Aboagye I.A. and Beauchemin K.A. (2019). Potential of molecular weight and structure of tannins to reduce methane emissions from ruminants: A review. *Animals.* **9(11),** 856-874.

Aboagye I.A., Oba M., Koenig K.M., Zhao G.Y. and Beauchemin, K.A. (2019). Use of gallic acid and hydrolyzable tannins to reduce methane emission and nitrogen excretion in beef cattle fed a diet containing alfalfa silage. *J. Anim. Sci.* **97(5),** 2230-2244.

Alemu A.W., Romero-Pérez A., Araujo R.C. and Beauchemin K.A. (2019). Effect of encapsulated nitrate and microencapsulated blend of essential oils on growth performance and methane emissions from beef steers fed backgrounding diets. *Animals.* **9(1),** 21-38.

Anele U.Y., Yang W.Z., McGinn P.J., Tibbetts S.M. and McAllister T.A. (2016). Ruminal *in vitro* gas production, dry matter digestibility, methane abatement potential, and fatty acid biohydrogenation of six species of microalgae. *Canadian J. Anim. Sci.* **96(3),** 354-363.

Appuhamy J.R.N., Strathe A.B., Jayasundara S., Wagner-Riddle C., Dijkstra J., France J. and Kebreab E. (2013). Anti-methanogenic effects of monensin in dairy and beef cattle: A meta-analysis. *J. Dairy Sci.* **96(8),** 5161-5173.

Asem-Hiablie S., Battagliese T., Stackhouse-Lawson K.R. and Rotz C.A. (2019). A life cycle assessment of the environmental impacts of a beef system in the USA. *Int. J. Life Cycle Assess.* **24(3),** 441-455.

Aviles-Nieto J., Marquez-Mota C., Romero-Pérez A., Talamantes-Gómez J., Castillo-Gallegos E., Jarillo J. and Corona L. (2019). PSXIV-12 effect of the addition of canola oil on digestibility, rumen fermentation and methane emissions in beef cattle in the Mexican tropic. *J. Anim. Sci.* **97(3),** 440-441.

Barwick S.A., Henzell A.L., Herd R.M., Walmsley B.J. and Arthur P.F. (2019). Methods and consequences of including reduction in greenhouse gas emission in beef cattle multiple-trait selection. *Genet. Sel. Evol.* **51(1),** 18-26.

Bayat A.R., Tapio I., Vilkki J., Shingfield K.J. and Leskinen H. (2018). Plant oil supplements reduce methane emissions and improve milk fatty acid composition in dairy cows fed grass silage-based diets without affecting milk yield. *J. Dairy Sci.* **101(2),** 1136-1151.

Beauchemin K.A. and McGinn S.M. (2005). Methane emissions from feedlot cattle fed barley or corn diets. *J. Anim. Sci.* **83(3),** 653-661.

Beauchemin K.A., McGinn S.M. and Petit H.V. (2007). Methane abatement strategies for cattle: Lipid supplementation of diets. *Canadian J. Anim. Sci.* **87(3),** 431-440.

Beck M.R., Thompson L.R., White J.E., Williams G.D., Place S.E., Moffet C.A., Gunter S.A. and Reuter R.R. (2018). Whole cottonseed supplementation improves performance and reduces methane emission intensity of grazing beef steers. *Prof. Anim. Sci.* **34(4),** 339-345.

Beck M.R., Thompson L.R., Williams G.D., Place S.E., Gunter S.A. and Reuter R.R. (2019). Fat supplements differing in physical form improve performance but divergently influence methane emissions of grazing beef cattle. *Anim. Feed Sci. Technol.* **254,** 114210.

Bodas R., Prieto N., García-González R., Andrés S., Giráldez F.J. and López S. (2012). Manipulation of rumen fermentation and methane production with plant secondary metabolites. *Anim. Feed Sci. Technol.* **176(1),** 78-93.

Bohutskyi P., Betenbaugh M.J. and Bouwer E.J. (2014). The effects of alternative pretreatment strategies on anaerobic digestion and methane production from different algal strains. *Bioresour. Technol.* **155,** 366-372.

Brask M., Lund P., Weisbjerg M.R., Hellwing A.L.F., Poulsen M., Larsen M.K. and Hvelplund T. (2013). Methane production and digestion of different physical forms of rapeseed as fat supplements in dairy cows. *J. Dairy Sci.* **96(4),** 2356-2365.

Bryszak M., Szumacher-Strabel M., El-Sherbiny M., Stochmal A., Oleszek W., Roj E., Patra A.K. and Cieslak A. (2019). Effects of berry seed residues on ruminal fermentation, methane concentration, milk production, and fatty acid proportions in the rumen and milk of dairy cows. *J. Dairy Sci.* **102(2),** 1257-1273.

Burney J.A., Davis S.J. and Lobell D.B. (2010). Greenhouse gas mitigation by agricultural intensification. *Proc. Natl. Acad. Sci.* **107(26),** 12052-12057.

Candyrine S.C.L., Mahadzir M.F., Garba S., Jahromi M.F., Ebrahimi M., Goh Y.M., Samsudin A.A., Sazili A.Q., Li Chen W., Ganesh S., Ronimus R., Muetzel S. and Liang J.B. (2018). Effects of naturally-produced lovastatin on feed digestibility, rumen fermentation, microbiota and methane emissions in goats over a 12-week treatment period. *PLoS One*. **13(7),** e0199840.

Cassidy E.S., West P.C., Gerber J.S. and Foley J.A. (2013). Redefining agricultural yields: From tonnes to people nourished per hectare. *Environ. Res. Lett.* **8(3),** 034015.

Cieslak A., Szumacher-Strabel M., Stochmal A. and Oleszek W. (2013). Plant components with specific activities against rumen methanogens. *Animal*. **7(2),** 253-265.

Cieslak A., Zmora P., Stochmal A., Pecio L., Oleszek W., Pers-Kamczyc E., Szczechowiak J., Nowak A. and Szumacher-Strabel M. (2014). Rumen antimethanogenic effect of *Saponaria officinalis* phytochemicals *in vitro*. *J. Agric. Sci.* **152(6),** 981-993.

Cosgrove G.P., Muetzel S., Skipp R.A. and Mace W.J. (2012). Effects of endophytic and saprophytic fungi on *in vitro* methanogenesis. *New Zealand J. Agric. Res.* **55(3),** 293-307.

Costa K.C. and Leigh J.A. (2014). Metabolic versatility in methanogens. *Curr. Opin. Biotechnol*. **29,** 70-75.

Cottle D.J., Nolan J.V. and Wiedemann S.G. (2011). Ruminant enteric methane mitigation: A review. *Anim. Prod. Sci.* **51(6),** 491-514.

D'Aurea A.P., Fernandes L.B., Oliveira A.P., Ferreira L.E., Lima M.M., Limede A.C. and Silva M.F. (2019). Natural additives can replace the conventional growth promoters in cattle feedlot diet. *EAAP Sci. Ser*. **138,** 175-176.

De Haas Y., Garnsworthy P.C., Kuhla B., Negussie E., Pszczola M., Wall E. and Lassen J. (2016). Genetic control of greenhouse gas emissions. *Adv. Anim. Biosci.* **7(2),** 196-199.

De la Fuente G., Yañez-Ruiz D.R., Seradj A.R., Balcells J. and Belanche A. (2019). Methanogenesis in animals with foregut and hindgut fermentation: A review. *Anim. Prod. Sci.* **59(12),** 2109-2122.

Demirel B. and Scherer P. (2008). The roles of acetotrophic and hydrogenotrophic methanogens during anaerobic conversion of biomass to methane: A review. *Rev. Environ. Sci. Biotechnol.* **7(2),** 173-190.

Doyle N., Mbandlwa P., Attwood G.T., Li Y., Ross P., Stanton C. and Leahy S.C. (2019). Use of lactic acid bacteria to reduce methane production in ruminants, a critical review. *Front. Microbiol.* **10,** 2207-2215.

Duin E.C., Wagner T., Shima S., Prakash D., Cronin B., Yáñez-Ruiz D.R., Duval S., Rumbeli R., Stemmler R.T., Thauer R.K. and Kindermann M. (2016). Mode of action uncovered for the specific reduction of methane emissions from ruminants by the small molecule 3-nitrooxypropanol. *Proc. Natl Acad. Sci.* **113(22),** 6172-6177.

Eger M., Graz M., Riede S. and Breves G. (2018). Application of mootral TM reduces methane production by altering the archaea community in the rumen simulation technique. *Front. Microbiol.* **9,** 2094-2109.

Embaby M.G., Günal M. and AbuGhazaleh A. (2019). Effect of Unconventional oils on *in vitro* rumen methane production and fermentation. *Cie. Invest. Agr.* **46(3),** 276-285.

Environmental Protection Agency (EPA). (2018). Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2016. Available at: https://www.epa.gov/sites/production/files.

Eugène M., Massé D., Chiquette J. and Benchaar C. (2008). Meta-analysis on the effects of lipid supplementation on methane production in lactating dairy cows. *Canadian J. Anim. Sci.* **88(2),** 331-337.

FAO. (2018). Global Livestock Environmental Assessment Model. Rome, Italy.

FAO and GDP. (2018). Climate Change and the Global Dairy Cattle Sector – The Role of the Dairy Sector in a Low-Carbon Future. Rome, Italy.

FAOSTAT. (2020). Database of the Food and Agricultural Organization (FAO) of the United Nations. Availabe at: http://www.fao.org/faostat/en/#home.

Fennessy P.F., Byrne T.J., Proctor L.E. and Amer P.R. (2019). The potential impact of breeding strategies to reduce methane output from beef cattle. *Anim. Prod. Sci.* **59(9),** 1598-1610.

Fiorentini G., Carvalho I.P.C., Messana J.D., Castagnino P.S., Berndt A., Canesin R.C., Frighetto R.T.S. and Berchielli T.T. (2014). Effect of lipid sources with different fatty acid profiles on the intake, performance, and methane emissions of feedlot Nellore steers. *J. Anim. Sci.* **92(4),** 1613-1620.

Flachowsky G. and Brade W. (2007). Potenziale zur reduzierung der mmethan-emissionen bei Wiederkäuern. *Züchtungskunde*. ***79*(6),** 417-465.

Flachowsky G. and Hachenberg S. (2009). CO_2-footprints for food of animal origin–present stage and open questions. *J. Verbrauch. Lebensm.* **4(2),** 190-198.

Flachowsky G. and Kamphues J. (2012). Carbon footprints for food of animal origin: What are the most preferable criteria to measure animal yields? *Animals*. **2(2),** 108-126.

Flachowsky G., Meyer U. and Südekum K.H. (2018). Invited review: Resource inputs and land, water and carbon footprints from the production of edible protein of animal origin. *Arch. Tierz.* **61(1),** 17-27.

Galagan J.E., Nusbaum C., Roy A., Endrizzi M.G., Macdonald P., FitzHugh W., Calvo S., Engels R., Smirnov S., Atnoor D. and Brown A. (2002). The genome of M. acetivorans reveals extensive metabolic and physiological diversity. *Genome Res.* **12(4),** 532-542.

Garnsworthy P.C., Difford G.F., Bell M.J., Bayat A.R., Huhtanen P., Kuhla B., Lassen J., Peiren N., Pszczola M., Sorg D. and Visker M.H. (2019). Comparison of methods to measure methane for use in genetic evaluation of dairy cattle. *Animals*.

9(10), 837-851.

Gerber P.J., Steinfeld H., Henderson B., Mottet A., Opio C., Dijkman J., Falcucci A. and Tempio G. (2013). Tackling climate change through livestock. Pp. 51-57 in A Global Assessment of Emissions and Mitigation Opportunities, Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.

Gleason C.B. and White R.R. (2019). Beef species-ruminant nutrition cactus beef symposium: A role for beef cattle in sustainable US food production. *J. Anim. Sci.* **97(9),** 4010-4020.

Grainger C., Clarke T., McGinn S.M., Auldist M.J., Beauchemin K.A., Hannah M.C., Waghorn G.C., Clark H. and Eckard R.J. (2007). Methane emissions from dairy cows measured using the sulfur hexafluoride (SF6) tracer and chamber techniques. *J. Dairy Sci.* **90(6),** 2755-2766.

Granja-Salcedo Y.T., Fernandes R.M., Araujo R.C.D., Kishi L.T., Berchielli T.T., Resende F.D.D., Berndt A. and Siqueira G.R. (2019). Long-term encapsulated nitrate supplementation modulates rumen microbial diversity and rumen fermentation to reduce methane emission in grazing steers. *Front. Microbiol.* **10,** 614-625.

Gupta S., Mohini M., Malla B.A., Mondal G. and Pandita S. (2019). Effects of monensin feeding on performance, nutrient utilisation and enteric methane production in growing buffalo heifers. *Trop. Anim. Health Prod.* **51(4),** 859-866.

Haque M.N. (2018). Dietary manipulation: A sustainable way to mitigate methane emissions from ruminants. *J. Anim. Sci. Technol.* **60(1),** 15-22.

Hedderich R. and Whitman W.B. (2013). Physiology and biochemistry of the methane-producing archaea. Pp. 635-662 in The Prokaryotes, E. Rosenberg, E.F. DeLong, S. Lory, E. Stackebrandt and F. Thompson, Eds. Springer Berlin Heidelberg, Germany.

Hemphill C.N., Wickersham T.A., Sawyer J.E., Brown-Brandl T.M., Freetly H.C. and Hales K.E. (2018). Effects of feeding monensin to bred heifers fed in a drylot on nutrient and energy balance. *J. Anim. Sci.* **96(3),** 1171-1180.

Hristov A.N., Oh J., Firkins J.L., Dijkstra J., Kebreab E., Waghorn G., Makkar H.P.S., Adesogan A.T., Yang W., Lee C. and Gerber P.J. (2013). Special topics—Mitigation of methane and nitrous oxide emissions from animal operations: I. A review of enteric methane mitigation options. *J. Anim. Sci.* **91(11),** 5045-5069.

Hristov A.N., Oh J., Giallongo F., Frederick T.W., Harper M.T., Weeks H.L., Branco A.F., Moate P.J., Deighton M.H., Williams S.R.O. and Kindermann M. (2015). An inhibitor persistently decreased enteric methane emission from dairy cows with no negative effect on milk production. *Proc. Natl. Acad. Sci.* **112(34),** 10663-10668.

Huhtanen P. and Huuskonen A. (2020). Modelling effects of carcass weight, dietary concentrate and protein levels on the CH4 emission, N and P excretion of dairy bulls. *Livest. Sci.* **232,** 103896-103906.

Huhtanen P., Ramin M. and Hristov A.N. (2019). Enteric methane emission can be reliably measured by the Green Feed monitoring unit. *Livest. Sci.* **222,** 31-40.

Ipharraguerre I.R. and Clark J.H. (2003). Usefulness of ionophores for lactating dairy cows: A review. *Anim. Feed Sci. Technol.* **106(1),** 39-57.

Jahromi F.M., Liang J.B., Ho Y.W., Mohamad R., Goh Y.M., Shokryazdan P. and Chin J. (2013). Lovastatin in Aspergillus *terreus*: Fermented rice straw extracts interferes with methane production and gene expression in *Methanobrevibacter smithii*. *Biomed. Res. Int*. 2013, 604721-604732.

Jeyanathan J., Martin C. and Morgavi D.P. (2016). Screening of bacterial direct-fed microbials for their antimethanogenic potential *in vitro* and assessment of their effect on ruminal fermentation and microbial profiles in sheep. *J. Anim. Sci.* **94(2),** 739-750.

Jeyanathan J., Martin C., Eugène M., Ferlay A., Popova M. and Morgavi D.P. (2019). Bacterial direct-fed microbials fail to reduce methane emissions in primiparous lactating dairy cows. *J. Anim. Sci. Biotechnol.* **10(1),** 41-49.

Johnson J.R., Carstens G.E., Krueger W.K., Lancaster P.A., Brown E.G., Tedeschi L.O., Anderson R.C., Johnson K.A. and Brosh A. (2019). Associations between residual feed intake and apparent nutrient digestibility, *in vitro* methane-producing activity, and volatile fatty acid concentrations in growing beef cattle. *J. Anim. Sci.* **97(8),** 3550-3561.

Johnson K.A. and Johnson D.E. (1995). Methane emissions from cattle*. J. Anim. Sci.* **73(8),** 2483-2492.

Jonker A., Green P., Waghorn G., van der Weerden T., Pacheco D. and de Klein C. (2020). A meta-analysis comparing four measurement methods to determine the relationship between methane emissions and dry-matter intake in New Zealand dairy cattle. *Anim. Prod. Sci.* **60(1),** 96-101.

Kholif A.E., Morsy T.A., Matloup O.H., Anele U.Y., Mohamed A.G. and El-Sayed A.B. (2017). Dietary *Chlorella vulgaris* microalgae improves feed utilization, milk production and concentrations of conjugated linoleic acids in the milk of Damascus goats. *J. Agric. Sci.* **155(3),** 508-518.

Kim S.H., Lee C., Pechtl H.A., Hettick J.M., Campler M.R., Pairis-Garcia M.D., Beauchemin K.A., Celi P. and Duval S.M. (2019). Effects of 3-nitrooxypropanol on enteric methane production, rumen fermentation, and feeding behavior in beef cattle fed a high-forage or high-grain diet. *J. Anim. Sci.* **97(7),** 2687-2699.

Knapp J.R., Laur G.L., Vadas P.A., Weiss W.P. and Tricarico J.M. (2014). Invited review: Enteric methane in dairy cattle production: Quantifying the opportunities and impact of reducing emissions. *J. Dairy Sci.* **97(6),** 3231-3261.

Kozłowska M., Cieślak A., Jóźwik A., El Sherbiny M., Stochmal A., Oleszek W. and Szumacher Strabel M. (2020). The effect of total and individual alfalfa saponins on rumen methane production. *J. Sci. Food Agric.* **100(5),** 1922-1930.

Lan W. and Yang C. (2019). Ruminal methane production: Associated microorganisms and the potential of applying hydrogen-utilizing bacteria for mitigation. *Sci. Total Environ.* **654,** 1270-1283.

Lee C., Hristov A.N., Dell C.J., Feyereisen G.W., Kaye J. and Beegle D. (2012). Effect of dietary protein concentration on ammonia and greenhouse gas emitting potential of dairy manure. *J. Dairy Sci.* **95(4),** 1930-1941.

Lourenço M., Ramos-Morales E. and Wallace R.J. (2010). The role of microbes in rumen lipolysis and biohydrogenation and their manipulation. *Animal*. **4(7),** 1008-1023.

Ma T., Chen D., Tu Y., Zhang N., Si B., Deng K. and Diao Q. (2016). Effect of supplementation of allicin on methanogenesis and ruminal microbial flora in Dorper crossbred ewes. *J. Anim. Sci. Biotechnol.* **7(1),** 1-11.

Machado L., Magnusson M., Paul N.A., de Nys R. and Tomkins N. (2014). Effects of marine and freshwater macroalgae on *in vitro* total gas and methane production. *PLoS One.* **9(1),** e85289.

McGinn S.M., Flesch T.K., Beauchemin K.A., Shreck A. and Kindermann M. (2019). Micrometeorological methods for measuring methane emission reduction at beef cattle feedlots: Evaluation of 3-nitrooxypropanol feed additive. *J. Environ. Qual.* **48(5),** 1454-1461.

Mimouni M.F.Z.K., Khardli F.Z., Warad I., Ahmad M., Mubarak M.S., Sultana S. and Hadda T.B. (2014). Antimicrobial activity of naturally occurring antibiotics monensin, lasalocid and their metal complexes. *J. Mater. Environ. Sci.* **5(1),** 207-214.

Miron T., Rabinkov A., Mirelman D., Wilchek M. and Weiner L. (2000). The mode of action of allicin: Its ready permeability through phospholipid membranes may contribute to its biological activity. *Biochim. Biophys. Acta.* **1463(1),** 20-30.

Mitloehner F. (2018). Livestock and climate change: Facts and fiction. Pp. 27-30 in The Welfare of Cattle. T. Engle, D.J. Klingborg and B.E. Rollin, Eds. CRC Press, Florida, US.

Moate P.J., Deighton M.H., Williams S.R.O., Pryce J.E., Hayes B. J., Jacobs J.L., Eckard R.J., Hannah M.C. and Wales W.J. (2016). Reducing the carbon footprint of Australian milk production by mitigation of enteric methane emissions. *Anim. Prod. Sci.* **56(7),** 1017-1034.

Mohammed R., Zhou M., Koenig K.M., Beauchemin K.A. and Guan L.L. (2011). Evaluation of rumen methanogen diversity in cattle fed diets containing dry corn distillers grains and condensed tannins using PCR-DGGE and qRT-PCR analyses. *Anim. Feed Sci. Technol.* **166,** 122-131.

Morgavi D.P., Martin C. and Boudra H. (2013). Fungal secondary metabolites from *Monascus* spp. reduce rumen methane production *in vitro* and *in vivo*. *J. Anim. Sci.* **91(2),** 848-860.

Narvaez N., Wang Y. and McAllister T. (2013). Effects of extracts of *Humulus lupulus* (hops) and *Yucca schidigera* applied alone or in combination with monensin on rumen fermentation and microbial populations *in vitro*. *J. Sci. Food Agric.* **93(10),** 2517-2522.

Njidda A.A. and Nasiru A. (2010). *In vitro* gas production and dry matter digestibility of tannin-containing forages of semi-arid region of north-eastern Nigeria. *Pakistan J. Nutr.* **9(1),** 60-66.

Nolan J.V., Hegarty R.S., Hegarty J., Godwin I.R. and Woodgate R. (2010). Effects of dietary nitrate on fermentation, methane production and digesta kinetics in sheep. *Anim. Prod. Sci.* **50(8),** 801-806.

Opio C., Gerber P., Mottet A., Falcucci A., Tempio G., MacLeod M., Vellinga T., Henderson B. and Steinfeld H. (2013). Greenhouse gas emissions from ruminant supply chains. Pp. 101-107 in A Global Life Cycle Assessment, Food Agriculture organization of the United Nations, Rome, Italy.

Ornaghi M., do Prado R., Oyama L., Huws S. and do Prado I. (2019). Investigating methane mitigation in beef cattle fed with natural additives. *Access Microbiol.* **1,** 1-10.

Özkan Ş.Ö., Ahmadi B.V. and Stott A.W. (2018). Impact of subclinical mastitis on greenhouse gas emissions intensity and profitability of dairy cows in Norway. *Prev. Vet. Med.* **150,** 19-29.

Özkan Ş.O., Ahmadi B.V., Bonesmo H., Østerås O., Stott A. and Harstad O.M. (2015). Impact of animal health on greenhouse gas emissions. *Adv. Anim.Biosci.* **6(1),** 24-25.

Pancini S., Cooke R.F., Brandão A.P., Dias N.W., Timlin C.L., Fontes P.L.P., Sales A.F.F., Wicks J.C., Murray A., Marques R.S., Pohler K.G. and Mercadante V.R.G. (2020). Supplementing a yeast-derived product to feedlot cattle consuming monensin: Impacts on performance, physiological responses, and carcass characteristics. *Livest. Sci.* **232,** 103907-1039017.

Patra A.K. (2012). Enteric methane mitigation technologies for ruminant livestock: a synthesis of current research and future directions. *Environ. Monit. Assess.* **184(4),** 1929-1952.

Patra A.K. (2016). Recent advances in measurement and dietary mitigation of enteric methane emissions in ruminants. *Front. Vet. Sci.* **3,** 39-50.

Patra A.K. and Saxena J. (2009). Dietary phytochemicals as rumen modifiers: A review of the effects on microbial populations. *Antonie van Leeuwenhoek.* **96(4),** 363-375.

Patra A.K. and Yu Z. (2013a). Effective reduction of enteric methane production by a combination of nitrate and saponin without adverse effect on feed degradability, fermentation, or bacterial and archaeal communities of the rumen. *Biores. Technol.* **148,** 352-360.

Patra A.K. and Yu Z. (2013b). Effects of gas composition in headspace and bicarbonate concentrations in media on gas and methane production, degradability, and rumen fermentation using *in vitro* gas production techniques. *J. Dairy Sci.* **96(7),** 4592-4600.

Pers-Kamczyc E., Zmora P., Cieślak A. and Szumacher-Strabel M. (2011). Development of nucleic acid based techniques and possibilities of their application to rumen microbial ecology research. *J. Anim. Feed Sci.* **20(3),** 315-337.

Pisarčíková J., Váradyová Z., Mihaliková K. and Kišidayová S. (2016). Quantification of organic acids in ruminal *in vitro* batch culture fermentation supplemented with fumarate using a herb mix as a substrate. *Canadian J. Anim. Sci.* **96(1),** 60-68.

Prins R.A., Van Nevel C.J. and Demeyer D.I. (1972). Pure culture studies of inhibitors for methanogenic bacteria. *Antonie van Leeuwenhoek*. **38(1),** 281-287.

Rabiee A.R., Breinhild K., Scott W., Golder H.M., Block E. and Lean I.J. (2012). Effect of fat additions to diets of dairy cattle on milk production and components: A meta-analysis and meta-regression. *J. Dairy Sci.* **95(6),** 3225-3247.

Ribeiro Pereira L.G., Machado F.S., Campos M.M., Guimaraes Júnior R., Tomich T.R., Reis L.G. and Coombs C. (2015). Enteric methane mitigation strategies in ruminants: A review. *Rev. Colomb. Cienc. Pec.* **28(2),** 124-143.

Roj E., Dobrzynska-Inger A., Kostrzewa D., Kolodziejczyk K., Sojka M., Krol B., Miszczak A. and Markowski J. (2009). Extraction of berry seed oils with supercritical CO_2. *Przem. Chem.* **88(12),** 1325-1330.

Romero-Pérez A., Alemu A., Araujo R. and Beauchemin K. (2018). Effect of slow release nitrate and essential oil on animal performance and methane emissions from feedlot cattle fed high-grain finishing diets. *J. Anim. Sci.* **96(3),** 409-409.

Romero-Perez A., Okine E.K., McGinn S.M., Guan L.L., Oba M., Duval S.M., Kindermann M. and Beauchemin K.A. (2014). The potential of 3-nitrooxypropanol to lower enteric methane emissions from beef cattle. *J. Anim. Sci.* **92(10),** 4682-4693.

Roque B.M., Van Lingen H.J., Vrancken H. and Kebreab E. (2019). Effect of mootral—a garlic-and citrus-extract-based feed additive—on enteric methane emissions in feedlot cattle. *Transl. Anim. Sci.* **3(4),** 1383-1388.

Rotz C.A., Asem-Hiablie S., Place S. and Thoma G. (2019). Environmental footprints of beef cattle production in the United States. *Agric. Syst.* **169,** 1-13.

Rowntree J.E., Ryals R., DeLonge M.S., Teague W.R., Chiavegato M.B., Byck P., Wang T. and Xu S. (2016). Potential mitigation of midwest grass-finished beef production emissions with soil carbon sequestration in the United States of America. *J. Food Agric. Soc.* **4(3),** 31-38.

Russell J.B. and Wallace R.J. (1997). Energy-yielding and energy-consuming reactions. Pp. 246-282 in The Rumen Microbial Ecosystem. P.N. Hobson and C.S. Stewart, Eds. Blackie Academic and Professional, London, United Kingdom.

Statistical Center of Iran. (2017). Statical Details of Animal Husbandry, in Persion. Available at: https://www.amar.org.ir.

Sucu E. (2019). Effects of microalgae species on *in vitro* rumen fermentation pattern and methane production. *Ann. Anim. Sci.* **2019,** 1-20.

Suybeng B., Charmley E., Gardiner C.P., Malau-Aduli B.S., and Malau-Aduli A.E. (2019). Methane emissions and the use of desmanthus in beef cattle production in Northern Australia. *Animals*. **9(8),** 542-556.

Szumacher-Strabel M., Zmora P., Roj E., Stochmal A., Pers-Kamczyc E., Urbańczyk A., Oleszek W., Lechniak W. and Cieślak A. (2011). The potential of the wild dog rose (Rosa canina) to mitigate *in vitro* rumen methane production. *J. Anim. Feed Sci*. **20(2),** 285-299.

Tamminga S., Bannink A., Dijkstra J. and Zom R.L.G. (2007). Feeding Strategies to Reduce Methane Loss in Cattle. Wageningen UR, Lelystad, the Netherlands.

Tsiplakou E., Abdullah M.A.M., Skliros D., Chatzikonstantinou M., Flemetakis E., Labrou N. and Zervas G. (2017). The effect of dietary *Chlorella vulgaris* supplementation on micro organism community, enzyme activities and fatty acid profile in the rumen liquid of goats. *J. Anim. Physiol. Anim. Nutr.* **101(2),** 275-283.

Valli C. (2020). Mitigating enteric methane emission from livestock through farmer-friendly practices. Pp. 257-273 in A Global Climate Change and Environmental Policy, Springer, Singapore.

Van Kessel J.A.S. and Russell J.B. (1996). The effect of pH on ruminal methanogenesis. *FEMS Microbiol. Ecol.* **20(4),** 205-210.

Vieco-Saiz N., Belguesmia Y., Raspoet R., Auclair E., Gancel F., Kempf I. and Drider D. (2019). Benefits and inputs from lactic acid bacteria and their bacteriocins as alternatives to antibiotic growth promoters during food-animal production. *Front. Microbiol.* **10,** 57-69.

Von Soosten D., Meyer U., Flachowsky G. and Dänicke S. (2020). Dairy Cow Health and Greenhouse Gas Emission Intensity. *Dairy*. **1(1),** 3-29.

Vyas D., Alemu A.W., McGinn S.M., Duval S.M., Kindermann M. and Beauchemin K.A. (2018). The combined effects of supplementing monensin and 3-nitrooxypropanol on methane emissions, growth rate, and feed conversion efficiency in beef cattle fed high-forage and high-grain diets. *J. Anim. Sci.* **96(7),** 2923-2938.

Vyas D., McGinn S.M., Duval S.M., Kindermann M. and Beauchemin K.A. (2016). Effects of sustained reduction of enteric methane emissions with dietary supplementation of 3-nitrooxypropanol on growth performance of growing and finishing beef cattle. *J. Anim. Sci.* **94(5),** 2024-2034.

Waghorn G.C. and Woodward S.L. (2006). Ruminant Contributions to Methane and Global Warming-A New Zealand Perspective. Pp. 233-260 in Climate Change and Managed Ecosystems,J.S. Bhatti, R. Lal, M.J. Apps and M.A. Price, Eds. CRC Press, New York.

Wang S., Giller K., Kreuzer M., Ulbrich S.E., Braun U. and Schwarm A. (2017). Contribution of ruminal fungi, archaea, protozoa, and bacteria to the methane suppression caused by oilseed supplemented diets. *Front. Microbiol.* **8,** 1864-1874.

White R.R. and Hall M.B. (2017). Nutritional and greenhouse gas impacts of removing animals from US agriculture. *Proc. Natl. Acad. Sci.* **114(48),** 10301-10308.

Wild K.J., Steingaß H. and Rodehutscord M. (2019). Variability of *in vitro* ruminal fermentation and nutritional value of cell disrupted and nondisrupted microalgae for ruminants. *GCB Bioenergy*. **11(1),** 345-359.

Wilson J.R. and Hatfield R.D. (1997). Structural and chemical changes of cell wall types during stem development: Consequences for fibre degradation by rumen microflora. *Australian J. Agric. Res.* **48(2),** 165-180.

Winders T.M., Boyd B.M., Hilscher H.F., Fernando S.C., Stowell R.R. and Erickson G.E. (2019). Corn oil supplementation on performance and methane production in finishing steers. *Nebraska Beef Cattle Rep*. **103,** 60-62.

Wu H., Meng Q., Zhou Z. and Yu Z. (2019). Ferric citrate, nitrate, saponin and their combinations affect *in vitro* ruminal fermentation, production of sulphide and methane and abundance of select microbial populations. *J. Appl. Microbiol.* **127(1),** 150-158.

Zabranska J. and Pokorna D. (2018). Bioconversion of carbon dioxide to methane using hydrogen and hydrogenotrophic methanogens. *Biotechnol. Adv.* **36(3),** 707-720.

Zhao L., Meng Q., Ren L., Liu W., Zhang X., Huo Y. and Zhou Z. (2015). Effects of nitrate addition on rumen fermentation, bacterial biodiversity and abundance. *Asian-Australasian J. Anim. Sci.* **28,** 1433-1441.