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Do fats reduce methane emission by ruminants? - a review

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In recent years, methane has been one of the most discussed and researched subjects due to its effect on global warming and climate change. Approximately 60-65% of methane production is of anthropogenic origin. Considering that half of this volume is generated by livestock breeding, both breeders and nutritionists show significant interest in this matter. Biotechnological and immunological methods as well as genetic improvement studies have the potential to reduce methane emission from ruminants, but as yet they are not commonly applied. For this reason, feeding strategies that are easier to implement in practice are being considered as having the potential to increase the effective usage of consumed energy while decreasing global methane emissions.

Adding fat to the diet of livestock will reduce the amount of carbohydrate consumed. It is known that fats reduce the number of protozoa, while some of the unsaturated fatty acids compete with methanogens for hydrogen. Therefore fats, oilseeds and fatty acids have been intensively studied to see whether they can reduce methane emissions in practice. Although many of these studies have proven that certain fats and fatty acids may be used confidently and effectively, much in vivo research is still needed to clarify the most appropriate diet, which fats are the most effective, and the amount of fat/fatty acids required.

In this review, the effect of using fats, fatty acids and oilseeds in ruminant nutrition is discussed in relation to enteric methane emission, rumen fermentation and the utilization of energy and selected nutrients.

KEYWORDS: methane emission / rumen / fatty acid / oilseed

In September 2013, the Intergovernmental Panel on Climate Change (IPCC) published its highly-anticipated 2200 page report [IPCC 2013]. In this report, carbon dioxide, methane and dinitrogen oxide were shown to be the root causes of global warming and climate change, and were also identified as the major greenhouse gasses. Although, as a gas methane is not found in its free form in the atmosphere for long, its effect on global warming is 21-23 times greater than that of carbon dioxide, although this is countered by the much higher levels of carbon dioxide. For this reason, many national and university laboratories functioning under the World Meteorological Organization (WMO) Global Atmosphere Watch (GAW) programme, have been observing the global distribution of methane [Dlugokencky *et al.* 2011]. Scientists have been conducting scientific research in an internationally coordinated attempt to decrease methane production. In 2003, the government of New Zealand proposed a flatulence tax, but this measure was not adopted as a result of public protests [Silverman 2011].

The release of methane into the atmosphere takes place in two different ways, with natural and anthropogenic origins. Methane that is released from natural wetlands (147 million tons/year), termites (23 million tons/year) and oceans (19 million tons/year) is considered to be natural; while the methane released from waste dumps (55 million tons/year), livestock breeding (90 million tons/year), production processes (rice cultivation: 31 million tons/year, biofuel usage: 12 million tons/year, etc.), transportation and fossil fuel usage (110 million tons/year) is considered to be human induced, or anthropogenic [Bousquet *et al.* 2006].The release of methane as a result of the degradation of organic materials in low-oxygen environments, such as landfill deposition of municipal waste, natural gas usage, etc. increased by 2-2.5 times after the industrial revolution [Anonymous 2013]. Since that time, the indications are that carbon dioxide in the atmosphere has increased by approximately 35% and methane by over 100% [Clark 2013]. According to the IPCC [2013], 45-60% of methane release in the world arises from industrialization, agricultural activities, and the products of fossil fuels (natural gas and petroleum) and from waste materials. It is reported that 25-40% of methane formed as a result of agricultural activities is generated by livestock [Clark 2013]. The highest methane emission from livestock is from ruminants. Over the last 10-15 years, researchers have focused their attention on the reduction of the ruminant source of methane production both through in vivo and in vitro studies. It appears that the administration of feed additives, such as probiotics, organic acids or aromatic plants into ruminant feeds, generally do not provide consistent results, and therefore a definitive conclusion cannot be given [Gorgulu *et al.* 2009]. Among the diet manipulations attempted, it has been recorded that the addition of fat appears to decrease enteric methane release [Boadi *et al.* 2004]. The addition of 1% fat into concentrated feeds decreases methane production in rumen by 5.6% [Beauchemin *et al.* 2007].

In addition to its negative effect on the environment, methane causes the loss of a portion of the energy consumed with feed by ruminants, and hence negatively affects the efficiency of the feed. Attempts to reduce this energy loss have aimed at helping to enhance the feed efficiency, and to increase animal performance while reducing the negative environmental effects. This article examines the addition of fats, fatty acids and/or oilseeds into feed rations of ruminants, and its effect on methane production in the rumen and on rumen fermentation. The aim of the study is to investigate the reduction of methane emission, while the negative effects of methane on both the environment and energy efficiency are also examined.

Methane production in the rumen

One of the end products of nutrient fermentation in the rumen is hydrogen. An excessive accumulation of hydrogen in the rumen negatively affects the digestion of feeds. One of the basic mechanisms that remove the hydrogen is methane production. Methanogens convert the hydrogen plus carbon dioxide into methane and water. For this reason, to reduce methane production, the amount of hydrogen released as a result of fermentation should be decreased, or else the use of the hydrogen in the production of propionic acid should be facilitated. While the acetate and butyrate generated as a result of nutrient fermentation in the rumen support methane production, methane production has been found to decrease as the propionate level increases [Moss *et al*. 2000]. Many years ago researchers determined that fats change the microbial ecosystem in the rumen as they compete for the hydrogen that is used in either methane or propionate production [Demeyer and Henderick 1967, Czerkawski 1972, Fonty and Morvan 1996]. It has been shown that high concentrations of ethanol, acetic acid and butyric acid in the rumen do not affect the activity of the bacteria, but low concentrations of propionic acid can reduce the amount and activity of methanogens (from $6x10^7$ to $0.6\text{-}1x10^7$ mL^{-1}) [Wang *et al*. 2009].

Methane emission from ruminant livestock

Methane release from livestock occurs in two ways, the first of which is as a result of the natural degradation of animal manure (manure originated). The second is from the anaerobic fermentation of organic materials in the reticulo-rumen and large intestine caused by the *Archaea* bacteria (enteric methane). It is indicated that 6-12% of the gross energy of feeds is transformed into methane [Johnson and Johnson 1995]. Methane is also released in indirect ways, such as feed manufacturing processes, fuels used during the manufacture of feeds, the processing of the products obtained, and the usage of generated fertilizers in feed crop production. The most important gas released in the manufacturing and recycling processes is methane. Methane emission directly produced by livestock arises from the ineffective fermentation of nutrients in the rumen and the failure to meet the requirements of the microbial flora adequately and in a balanced manner [Gorgulu *et al.* 2009].

The highest methane production among livestock is seen in ruminants. The Food and Agricultural Organization of the United Nations (FAO) reported that 54.9% of enteric methane release comes from feedlot cattle, 19.64% from dairy cattle, 11.28% from buffalos, 6.48% from sheep and 4.86% from goats [FAO 2010].

Reduction of methane emission through antimethanogenic applications

Numerous factors, such as feed consumption, carbohydrate type used in the ration, feed processing techniques, the addition of fat or ionophores into the diet and changing the rumen microflora, can all affect methane production in cattle [Johnson and Johnson 1995]. It is evident that enteric methane release can be reduced by approaches such as decreasing the ratio of cell wall components in rations, the use of fat, fatty acids and oilseeds in feeds, defaunation, and the addition of monensin, saponin, tannin, essential oil and organic acids into the ration [Monteny *et al.* 2006]. Cieslak *et al.* [2013a] declared that saponins mitigate methanogenesis mainly by reducing the number of protozoa; condensed tannins act both by reducing the number of protozoa and by a direct toxic effect on methanogens, whereas essential oils act mostly by a direct toxic effect on methane producing bacteria.

It is claimed that there is a linear relationship between the consumption of dry matter and methane emission in cattle; as dry matter consumption increases, organic matter fermentation also increases and therefore the levels of volatile fatty acids (VFA) and gasses also increase [Bannink *et al.* 2010]. Additionally, as the ratio of digestible carbohydrates in the feed increases, methane release also increases [Beauchemin *et al.* 2007]. However, it is believed that even within the same animal species there can be differences in terms of methane release, and this difference may be related to the genetic merit of the animal and to the retention of the feeds in the digestive system [Clark 2013].

In recent years, vaccination of animals against methanogens, using anti-bacterial agents known as bacteriocins, the use of genetically improved breeds in terms of methane production, having fewer animals of greater efficiency rather than simply increasing the number of animals, and approaches such as selected feeding have all been employed as methods to reduce the release of methane. In a study conducted by Yurtseven and Öztürk it was shown that methane and carbon dioxide release decrease when sheep are fed a special diet [Yurtseven and Öztürk 2009]. It becomes evident that it is very important to determine the effects of choice feeding on methane production for different species and under different physiological conditions. Some Japanese researchers have found yet another way to reduce methane production in the rumen. A plant derived liquid and a yeast derived surfactant have stimulated a considerable reduction (>70-95%) in methane production in in vitro studies by the production of more propionate through selective anti-bacterial activities [Kobayashi 2010].

The application of these approaches to methane emission reduction has taken different forms. While vaccination, bacteriocin, bacteriophages and chemical inhibitors are directly effective on the methanogens, other manipulations applied to defaunation and rations stimulate the acetogenic population in the rumen and decrease methane production by reducing the amount of hydrogen available to the methanogens [McAllister and Newbold 2008]. It is evident that methanogenesis is directly affected by the presence of protozoa in the rumen [Newbold *et al.* 1995], as some methanogens have a symbiotic relationship with the protozoa [Finlay *et al.* 1994] and thus methane release can be decreased by as much as 20-30% by defaunation of protozoa in the rumen [Kreuzer *et al.* 1986].

On the other hand, there are reasons for limiting the use of the approaches mentioned above. For example, monensin is prohibited in Turkey, similarly as it is in many European countries, and the use of natural additives is becoming more acceptable due to health concerns with regard to antibiotics. More in vivo research is required and there is insufficient scientific data on the optimum use levels and rumen fermentation of materials that can be added to the ration, such as saponin, tannin and organic acids (fumarate, malate, etc.). Furthermore, time is needed for the study of new approaches, such as immunization, while wide spread vaccination and the cost of such approaches is still open to debate.

Fats as antimethanogenic agents

Although methane emission has begun to draw attention, it is recognized that the studies conducted on ruminant source methane release are out of date. The inhibition of methanogenesis in sheep by feeding them polyunsaturated fatty acids and medium chain saturated fatty acids was demonstrated in a study conducted by Blaxter and Czerkawski in the 1960's [1966]. It is thought that studies conducted at that time mostly related to a reduction of the negative effects of methane on energy efficiency in ruminants rather than the environmental effects of methane. In more recent studies, energy efficiency has been considered less important, since reducing the methane released into the atmosphere has become the focus due to its critical role in global warming. The addition of fat into the ruminant rations appears to be an efficient and easy way of reducing methane production. It has been suggested that the effectiveness of fats in methane production takes place in several ways, such as biohydrogenation of unsaturated fatty acids in the rumen, promotion of propionic acid production, and prevention of protozoa activity [Johnson and Johnson 1995]. However, it has been reported that fats do not have any specific effect on methane release, and that the evident decrease reflects a decrease in the digestibility of the ration nutrients [Beauchemin *et al.* 2007].

The use of fat/fatty acids and oilseeds in rations to reduce methane release is preferred over other approaches. Unlike the chemical approaches, fats are of natural origins, they energize raw materials, and change the fatty acid profiles of meat and milk, thereby increasing the efficiency of fat-soluble nutrients, preventing the emission of dust from feed, and enhancing the flavor of the feed. On the other hand, there are some negative aspects that limit the use of fats in ruminant rations despite their positive effects. Over-use of fats in the ration decreases feed consumption [Allen 2000] and therefore cellulolytic activity in the rumen [Palmquist 1984]. In a meta-analysis study, which examined seven different research articles and 37 rations [Giger-Reverdin *et al.* 2003], it was reported that unsaturated fatty acids decreased methane production, but negatively affected feed consumption and cellulose digestion. However, in more recent research it has been shown that some unsaturated fatty acids (especially linoleic acid) increase the number of *ciliate* protozoa and positively affect cellulose digestion and milk quality by increasing the number of cellulotic bacteria [Ivan *et al.* 2013]. A study conducted on goats showed that the decanter cake and palm kernel cake could be used in goats' diets, up to 80%, with improved digestion of fiber; however, the rumen protozoa were reduced [Abubakr *et al.* 2013]. Bettero *et al.* [2013] found that dietary supplementation with ground soybean, cottonseed, soybean oil, and calcium salts of fatty acids did not alter the kinetic parameters of roughage or the concentrate particle passage, or the in vitro NDF degradation. In another study it was concluded that soybean oil of up to 8% in dry matter (DM) can be fed in high fiber diets (50% bermudagrass hay) without depressing DM, organic matter, nitrogen or NDF digestibility [Bateman and Jenkins 1998].These results show that some fats and fatty acids can be safely used in the correct doses in suitable diets. It should be kept in mind that rumen fermentation and nutrient digestibility are affected by many different factors.

The fat source affects methane emission

Different fats and fatty acids affect the microbial population in different ways, for example through protozoan metabolism. Therefore, the effect of fats and fatty acids on methane emission will be described under different headings. Kisidayova et al. [2006] found that rumen ciliates had no uniform response to microbial oil, evening primrose oil, or borage oil. In other studies, pre-fermented cereals containing fungal gamma-linolenic acid [Laho *et al.* 2011] and different forms and concentrations of linoleic acid [Cieslak *et al*. 2009] were also found to have different effects on the rumen ciliate population. These researchers concluded that the responses strongly depended on the composition, form, and concentrations of the oils and fatty acids.

In studies examining the effect of fat on methane emission, coconut oil has frequently been discussed, as its fatty acid concentration is different from that of all other vegetable oils. While some of these studies showed that coconut oil can reduce methane production by up to 70% [Machmüller and Kreuzer 1999], other studies indicated that it reduces methane release without affecting dry matter intake and digestibility if 250 g are given a day [Jordan *et al.* 2006a]. It was also reported that it does not affect the production and quality of milk if added into the ration at a 1.3% level, but when used above this level (2.7-3.3%) it reduces the dry matter intake, milk production and milk fat content [Holmann *et al.* 2012]. In addition, research has shown that medium chain fatty acids, such as C12:0 and C14:0, are particularly effective in reducing methane production [Machmüller 2006]. However, coconut oil, which contains high amounts of these fatty acids, and genetically improved canola oil, are not preferred by breeders due to their high cost [Beauchemin *et al.* 2007].

Some of the studies reported in the literature have explored the use of sunflower, canola, rapeseed and soybean oils to reduce methane emission. It has been reported that oils such as sunflower and canola, which are rich in long-chain fatty acids, reduce methane release in cattle predominantly fed on roughage, and they enhance the efficiency of gross energy by up to 22% [Beauchemin and McGinn2006]. In a study conducted on rapeseed oil, it was determined that methane production decreased by 7.3% (in dry matter) in cattle fed with corn silage or grass silage as roughage; however, feed consumption, organic matter digestibility, and rumen fermentation were not affected, and there was no interaction between the fat and roughage quality [Brask 2013]. In another study conducted with different physical forms of rapeseed (oil, meal, cake, and seed), it was observed that rapeseed can reduce methane release without affecting NDF digestibility and milk production, and that its physical form did not make any difference to the methane production [Brask *et al.* 2013]. Vargas *et al.* [2011] indicated that in the rumen simulating technique, fermentation patterns are affected by olive, sunflower or linseed oil supplementation, mainly by decreasing the acetate to propionate ratio, and that methane production is also affected. In a study conducted on sheep it was reported that sunflower oil added into the ration (6% in dry matter) can decrease the protozoa number and hence decrease the methane production in the rumen [Ivan *et al.* 2001]. Liu *et al.* [2011] determined that 25 g/kg of coconut oil decreases methane production, methanogen bacteria, protozoa number, total VFA quantity, and the number of *Fibrobacter succinogenes* without affecting the performance of the sheep: it does not change the rumen pH, the number of fungi, or the *Ruminococcus albus*. These results were consistent with a previous observation by Mao *et al*. [2010]. In this study, soybean oil was shown to be toxic to fibrolytic microbes, *Fibrobacter succinogenes,* and *Ruminococcus flavefaciens*. However, adding soybean oil did not decrease ruminal fiber fermentability in growing lambs. In a study conducted on goats it was shown that methane production decreased with the addition of 5% of soybean oil; milk yield was not affected, while milk fat and fatty acid composition were improved [Li *et al.* 2009]. Again, after an addition of 3% soybean, coconut or palm oil to the diet of goats, the digestibility of the dry matter and organic matter were not affected, but the methane emission decreased [Jeong *et al.* 2012]. In addition, various studies with cattle have shown that tallow and soybean oil [Johnson and Johnson 1995, Zinn and Plascencia 1996, Lillis *et al.* 2011] and sunflower oil [Beauchemin *et al.*2007] decreased methane emissions.

Besides the common fat sources, we have new alternatives for essential oils or feed containing fat/fatty acids, which may be used in ruminant diets and which may reduce methane emission. For example, in in vitro studies eucalyptus oil (*Eucalyptus globules*) [Ravindra *et al.* 2009], rose seed oil [Szumacher-Strabel *et al.* 2011], garlic and peppermint oil [Patra and Yu 2012], some fruit seed oils, e.g. grape oil or black currant oil [Cieslak *et al.* 2013b], clove oil, and cinnamon oil [Pawar *et al.* 2014], had the potential to inhibit methane production. Cieslak *et al.* [2013b] also demonstrated that the interaction between the diet and the various oil supplements affected rumen methane production and the rumen ciliate species. These findings drew attention to the fact that different forage and feeding systems provided exceptional results in terms of some of the rumen parameters and methane emission.

Fatty acids affect methane emission

In recent years researchers have been conducting studies to determine the effect on methane release of rations that are balanced in terms of the omega-3 and omega-6 fatty acids. In a study examining this issue, it was determined that the addition of 2% fish oil into dairy cattle rations reduces methane production [Anonymous 2009]. In a field study conducted in France it was recorded that feeding balanced in terms of the omega-3 and omega-6 fatty acids decreases the methane release by as much as 20% [Lomas 2013].

Many years ago, free fatty acids were found to have toxic effects on methanogens [Prins *et al.* 1972] and protozoa [Czerkawski *et al.* 1975]. It was shown that lauric (C12:0), myristic (C14:0) and linoleic (C18:2) acids decreased methane release and the number of bacteria producing methane, while lauric acid (C12:0), caprylic acid (C8:0), capric acid (C10:0) and linoleic acid (C18:2) negatively affected the existence of protozoa and medium chain saturated fatty acids (C8:0-C14:0) decreased the digestion of cellulose [Dohme *et al.* 2001]. Zhou et al. [2013] reported that lauric acid has a special ability to reduce cell viability of *Methanobrevibacter ruminantium.* In another study it was shown that adding myristic acid to cows' ration decreases methane release and milk fat by 36% and 2.4% respectively; it increases C14:0 and cis-9 C14:1 fatty acids, and there is a negative correlation between these fatty acids and methane production [Odongo *et al.* 2007]. At the end of this research, it was concluded that myristic acid can be used to prevent methanogenesis as it does not affect the conjugated linoleic acid in milk or the number of trans-10 C18:1 and trans-11 C18:1 isomers. The same researchers showed that the saturated fatty acid ratio in the diet does not affect the methane release, but that the mono-unsaturated and poly-unsaturated fatty acid ratio in the diet decreases methane production and that methane release is affected by the interaction between the fatty acids and the NDF in the ration.

Another study, conducted to determine the effects of fatty acids on methane release, indicated that if stearidonic acid (C18:4 n-3) is used at max. 50 µg/mL it limits methane production without negatively affecting the rumen fermentation [Amaro *et al.* 2013]. It has been found that oleic and linoleic acids, which are unsaturated fatty acids, decrease methane production and the acetate and propionate ratio, but do not change the rumen fermentation parameters such as rumen pH, ammonia nitrogen, acetate, propionate, butyrate, valerate and total VFA concentrations [Wu *et al.* 2013]. The suppressor effect of long chain fatty acids on methane release has not been discussed for a long time, but Giger-Reverdin *et al*. [2003] reported that this effect is possibly related to the degree of unsaturation of fats.

Oil form / derivation methods and oil seeds affect methane emission

Some researchers have conducted studies to determine the effect of the form of the oil and the oil derivation method on methane production. Accordingly, in a study conducted by Getachew *et al.* [2001] it was shown that fats added to the diet in the triglyceride form change the microbial population in the rumen, but do not affect microbial development or cellulose digestion. However, potassium salts of the fats negatively affect rumen fermentation. In another study conducted with aromatic plants it was shown that fats from these plants negatively affect ammonia production and the number and distribution of the *Archaea* bacteria in the rumen. Oregano oil decreases methane release by as much as 87%, but also decreases rumen fermentation and the digestibility of nutrients [Patra and Yu 2012].

The fact that oilseeds ferment more slowly in the rumen than vegetable oils [Dhiman *et al.* 2000] made scientists wonder whether fats can reduce the negative effect on cellulotic bacteria; consequently, investigation of such effects has become the subject of many studies. It has been observed that sunflower seed and canola seed decrease the protozoa number, but do not affect the rumen pH or the total VFA concentration [Beauchemin *et al.* 2009]. Jordan *et al.* [2006b] showed that performance and nutrient digestibility decreased in dairy cows fed with soybean seed. On the other hand, it was reported by Johnson *et al.* [2002] and Grainger *et al.* [2008] that cottonseed and canola seed used in the ration did not affect methane release, but increased the dry matter intake and milk production. Johnson *et al.* [2002] showed that cotton seed and canola seed decreased the C10:0, C12:0, C14:0 and C16:0 fatty acids in milk, and increased the C18:0, C18:1 and trans-C18:1fatty acids. Brask *et al.* [2013] determined that rapeseed did not affect the organic matter and NDF digestibility, but did change the amount of VFA in the rumen and decreased the methane release. Crompton *et al.* [2011] showed that rapeseed decreased the saturated fatty acid ratio in milk and increased the ratio of cis-mono unsaturated fatty acids. It has been recorded that the negative effect on milk efficiency of using flax seed in dairy cattle diets needs to be countered before it could be used to reduce methane production [Martin *et al.* 2008]. Similar criteria have been investigated in some studies conducted with ovine ruminants and positive results have been obtained for the reduction of methane emission. For example, coconut, canola, sunflower and flax seeds have been added into sheep rations and methane release has thereby been decreased by 26, 19, 27 and 10%, respectively. In the same study, no effect was determined on methane release from the addition of protected fat. A decrease in apparent NDF and ADF digestibility with the addition of sunflower seed ($P<0.05$) has been attributed to the negative exposure of cellulose fermentation in rumen. Other fats, excluding protected fat, have decreased the *ciliate* number ($P<0.1$), the total VFA, acetate ($P<0.05$) and butyrate ($P<0.001$) concentrations. Groups of animals that consumed coconut oil and protected fat were found to be similar to the control group in terms of energy efficiency, while a decrease was seen in the ones fed with oilseeds [Machmüller *et al.* 2000]. To the best of my knowledge, limited research has been conducted on by-products from the vegetable industry. Vegetable oil soapstocks, especially those from the sunflower and soybean oil refinery industries, are promising dietary alternatives to reduce ruminal methanogenesis [Blanco *et al.* 2012].

Table 1. Effects of fats and fatty acids on methane production and nutrient digestibility in rumen

Reference	Fat sources	Diets/substrate	Material/dosage	Changes in MO	ND	Changes in FA and VFA	Gas prod./Methane
Getachew *et al.* [2001]	Corn oil (CO)	Forage and concentrate (57:43)	In vitro gas technique / 5, 10, 15, 20, 25%	NA	NE	Total VFA, NE; (-) acetate; (+) propionate	(+) Gas production
	Tallow (TL)				NE	Total VFA, NE; (-) acetate; (+) propionate	Gas production, NE
	Yellow grease (YG)				NE	Total VFA, NE; (-) acetate; (+) propionate	(+) Gas production
	K soaps of CO, TL, YG				(-) TD	(-) Total VFA; (-) acetate; (+) propionate	(-) Gas production
Lovett *et al.* [2003]	Coconut oil	Forage: concentrate 65:35 40:60 10:90	Heifers/350 g/day	-70% protozoa $4.75x10^5$ protozoa $6.97x10^5$ protozoa $4.40x10^5$ protozoa	NA	NA	- 34% 207 l/d 270 l/d 170 l/d
Kisidayova *et al.* [2006]	Microbial oil	Meadow hay and ground barley (60:40)	Rusitec/5%	(-) Eremoplastron and Isotricha spp.	NA	NA	NA
	Borage oil			(-) Eremoplastron and ciliate			
	Evening primrose oil			(+) Polyplastron (-) Dasytricha, Eremoplastron and Isotricha spp. (+) Entodinium spp.			
Beauchemin and McGinn [2006]	Fumaric acid	Barley silage, barley and supplement (75:19:6)	Angus heifers/175 g/d 1g/d 4.6% of DM	NA	NE	(+)Total VFA and propionate; (-) A:P	NE
	Essential oil				NE	Total VFA and propionate, NE; A:P, NE	NE
	Canola oil				(-) DM, NDF and ADF	Total VFA, NE;(+)propionate; (-) A:P	-32%
Beauchemin *et al.*[2007]	Tallow Sunflower oil Sunflower seeds	Barley silage (650 g kg/ DM)	Angus heifers / 34 g fat / kg DM	NA	-15% NDF NE -20% NDF	(+) SFA (-) SFA (-) SFA	-14% -14% -33%
Ravindra *et al.* [2009]	Eucalyptus oil	-	In vitro gas technique/ 0.33 µl/ml 0.66µl/ml 1µl/ml 1.33µl/ml 1.66µl/ml	(-) Holotrichs, spirotrichs	(-) TD (-) TD NE NE NE	Total VFA, NE (+)Total VFA (+)Total VFA (+)Total VFA (+)Total VFA	-10% -17% -35% -46% -56%
Mao *et al.* [2010]	Soybean oil	Chinese wild rye and concentrate(60:40)	Lambs / 3% of DM	(-) Protozoa (-) Methanogens (-) R. flavefaciens (-) F. succinogenes	NA	(+) Total VFA	-13%
Szumacher-Strabel *et al.* [2011]	Rose seeds oil Rose seeds residue	Meadow hay and barley meal (60:40)	In vitro / 5% of DM	(+)Archaea NE	NA	NA	-9% NE
Vargas *et al.* [2011]	Olive oil Sunflower oil Linseed oil	Lucerne hay and concentrate	Rusitec / 50 g oil / kg diet	NA	NA	(+)Propionate;Acetate, NE; (-) A:P (+)Propionate;Acetate, NE; (-) A:P (+)Propionate; Acetate, NE; (-) A:P	-21% -24% -28%
Blanco *et al.* [2012]	Palm soapstock Olive soapstock Soybean soapstock Sunflower soapstock	Barley straw 50 g/kg diet 150 g/kg diet 250 g/kg diet	In vitro/ 30g /kg 60 g/kg	NA	NA	Acetate and propionate, NE (-)Acetate; (+)Propionate (-)Acetate; (+) Propionate Acetate and propionate, NE	Methane, NE (-)Methane (-)Methane (-)Methane

Table 1. Continued

Reference	Fat sources	Diets/substrate	Material/dosage	Changes in MO	ND	Changes in FA and VFA	Gas prod./Methane
Jeong *et al.* [2012]	Soybean oil Coconut oil Palm oil	Tall fescue hay and concentrate (56:44)	Goats / 3%	NA	NE	NA	-22% -33% -29%
Patra and Yu [2012]	Clove oil Eucalyptus oil Garlic oil Origanum oil Peppermint oil	Alfalfa hay and concentrate (50:50)	In vitro/ 0.25, 0.50 and 1.00 g/l	(-) Archaea, protozoa and cellulolytic bacteria	(-) DM,NDF (-) DM,NDF NE (-) DM,NDF (-) DM,NDF	(-)Total VFA Total VFA, NE Total VFA, NE (-)Total VFA Total VFA, NE	-34.4% -17.6% -42.3% -87.0% -25.7%
Abubakr *et al.* [2013]	Palm oil Palm kernel cake Decanter cake	Rice straw and concentrate (50:50)	Goats / 5%	(-)Protozoa (-)Protozoa (-)Protozoa	NE (+)NDF,(+)ADF (-)OM	(-)Total VFA (-)Total VFA	NA
Brask *et al.* [2013]	Rapeseed cake Rapeseed Rapeseed oil	Corn and grass silage and concentrate (50:50)	Dairy cows / 5.5% 6.2% 6.5%	NA	A:P, NE A:P, NE (+) A:P OM and NDF, NE	NA	(-)Methane (-)Methane (-)Methane
Cieslak *et al.* [2013]	Grape oil Black currant oil Grape oil Black currant oil	Lucerne and wheat meal (60:40) Meadow hay and wheat meal (60:40)	In vitro / 50 g/kg DM	(-)Ciliate (-)Ciliate NE NE	DM, NE	Total VFA, acetate and propionate, NE	-21% -23% NE NE
Chuntrakort *et al.* [2014]	Cotton seed Sunflower seed Coconut kernel	Rice straw and concentrate (60:40)	Beef cattle / 197 g/kg of diet 136 g/kg of diet 71 g/ kg of diet	Protozoa, NE Protozoa, NE Protozoa, NE	-9%DM; -12%NDF -14%DM; -20%NDF -19%DM; -30%NDF	Acetate,propionate and A:P,NE Acetate,propionate and A:P,NE Acetate,propionate and A:P,NE	-24% -55% -60%
Fiorentini *et al.* [2014]	Palm oil Linseed oil Protected fat Soybean seed	Maize silage and concentrate (60:40)	Steers / 42 g / kg DM	NA	NA	NA	-55% -57% NE -57%
Pawar *et al.* [2014]	Garlic oil Clove bud oil Clove leaf oil Lemongrass oil Wild turmeric oil Turmeric oil Cinnamon oil	Wheat straw and concentrate (1:1)	In vitro gas technique/ 167, 333, 500, 667, 833 µl/l	NA	-3,-6,-18, -18,-22% OM -11,-20,-30,-40,-40% OM NE,-17,-24,-26,-33% OM NE,-25,-21,-28,-35% OM NE,NE,-31,-23,-36% OM -3,-10,-8,-11, -6 % OM -8,-30,-27,-33,-30% OM	+11,NE,NE,NE,NE%TVFA -14,-12,-11,-10,-2% A:P +6,-6,-10,-20,-32%TVFA +8,+24,+403+67,+62% A:P -12,-16,-28,-36,-38%TVFA NE,+17,+27,+58,+52% A:P NE,-10,-26,-28,-32%TVFA NE,NE,-4,-6,-12% A:P NE,NE,NE,NE,NE,TVFA NE,NE,NE,NE,NE,A:P -6,-6,-10,-8,+2%TVFA NE,NE,NE,NE,NE,A:P -21,-40,-43,-56,-48%TVFA NE,+31,+39,+42,+36% A:P	-37,-41,-41,-54,-70% -11,-14,-55,-55,-55% -10,-21,-40,-40,-46% -6,-12,-58,-83,-93% -14,-14,-18,-25,-48% NE,NE,NE,-11,-13% -36,-86,-86,-99,-100%

A:P – acetate/propionate; DM– dry matter; FA– fatty acid; MO– microorganism; NA– not analyzed; ND– nutrient digestibility; NE– no effect; OM– organic matter; SFA– saturated fatty acid; TD– true digestibility; VFA– volatile fatty acid;(–)decrease; (+)increase.

Conclusion

Several researchers have investigated the effects of fats and fatty acids on rumen fermentation and methane production over the last twenty years due to environmental concerns and the need to improve energy utilization by ruminants. However, we still need further in vivo studies with different feedstock sources to evaluate the effects of oils on both methane production and animal performance. The different fat source effects and recent results are summarized in Table 1.

Next to the rapidly growing world population, developments in production (animal/ vegetable) and production technologies have unfortunately sometimes brought negative consequences. We face irreversible problems, such as an energy crisis, climate change and global warming as a result of overloading our demands on the natural environment. It is crucial to determine the causes and make adjustments to minimize the negative effects of our production processes on the environment. Methane release into the atmosphere can be decreased without affecting the ruminant performance thanks to the use of fats, fatty acids or oilseeds in concentrated feeds. However, it should be noted that the amount of poor quality roughage in the ration, the amount of fat to be added into the feed, the fatty chain length and degree of unsaturation, the structure of the concentrated feed and the fat content are all very important criteria to be ascertained. Moreover, we do not yet know the sustainability of the methane-lowering effect of fats and fatty acids, so we need to investigate this aspect thoroughly.

On the other hand, management applications, such as reduction through genetic selection in herds, feeding strategies, improved quality of grasses, pasture, and other feed sources can all contribute to a decrease in methane emissions. In this context, breeders can reduce methane emission by up to 30% with changes they can make in rations. However, the important point here is how such applications will affect the expense of animal production, because unless they are economically sound, breeders will not adopt these approaches as they need to make their livestock farming financially viable.

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