Proceedings of the 2nd International Conference on Environmental Geoscience and Earth Ecology
DOI: 10.54254/2753-8818/48/20240219

Effects of different dietary modifications on carbon emissions of dairy cows based on mathematical modeling

Shenghao Wang

Nanjing Foreign Language School, Nanjing, 210000, China

2430669859@qq.com

Abstract. With the expansion of the dairy farming industry, the phenomenon of methane emissions has also increased year by year. To reduce the greenhouse effect problems caused by methane emissions, this article lists several measures to improve the diet of dairy cows to reduce methane emissions: increasing the forage quality, replacing the grass silage with the maize silage and fat supplementation. Based on the basic principles of methane production in dairy cows, we further explained the basic reasons why the three methods can reduce methane emissions in dairy cows. Later, we integrated the information of some statistical data and confirmed the validity of the three methods through the statistical code analysis through Jupyter Notebook. At the end of the paper, we pointed out the weakness: our paper neglected the difference between different kinds of dairy cows, the potential harm caused by fat supplementation, the interaction between three kinds of dietary modification and potential economic cost. We hope future researchers will limit pastures to regional analysis and consider the disadvantages of the model.

Keywords: Methane emission, Dairy cows, Maize silage, Forage quality, Fat supplementation

1. Introduction

In recent years, global warming has intensified, with methane emissions playing a significant role in this escalation. Methane is a potent greenhouse gas, exhibiting a global warming potential of approximately 20 to 25 times greater than that of carbon dioxide [1]. This potency is attributed to methane's ability to effectively trap long-wavelength radiation emitted from the Earth, thereby exacerbating the greenhouse effect. Notably, enteric fermentation, particularly in dairy cattle, accounts for approximately 27% of total methane emissions [2]. During the digestive process in dairy cattle, ingested feed undergoes fermentation in the rumen (a specialized compartment of the bovine stomach), facilitated by resident microbes. This fermentation process, essential for converting plant materials into digestible forms, inadvertently produces methane. The quantity of methane generated is directly proportional to the amount of roughage in the cattle feed; higher roughage content necessitates more extensive fermentation, leading to increased methane production. Consequently, the implementation of appropriate feeding strategies is crucial in mitigating methane emissions from dairy cattle.

As one of the world's largest dairy farming nations, China has experienced a significant surge in milk demand, leading to a marked increase in the dairy cattle population. From a modest count of approximately 100,000 dairy cattle in 1949, the number escalated to 2.945 million by 1991 and further rose to over 14 million by 2018. This rapid growth in dairy cattle populations has correspondingly increased methane emissions, contributing to the intensification of global warming effects.

2. Mechanism of CH4 production in dairy cows

Methane in the cows' stomach is produced by the methanogens while digesting food. When food, mainly carbohydrate polymers, flows into dairy cows' stomachs, it first faces microbial hydrolysis and is converted into monomers. Then the monomer will endure microbial fermentation and is converted into acetate, propionate and butyrate. Hydrogen and carbon dioxide are the by-products of this process, and they are also raw materials used to produce methane. For the production of methane, archaea methanogens promote the reduction of carbon dioxide with the help of hydrogen, letting methane become the final product through a dynamic process (a complicated process with all kinds of microorganisms interdependent).

However, the methane produced through the reaction of carbon dioxide and hydrogen by methanogens just accounts for 80% of total methane production. Besides that, formate can be used as a substitute for hydrogen to produce methane and this accounts for 18% of the total production. Other substrates, like methylamine, methanol, and acetate may account for the remaining 2%. Most of these substrates have small amounts. Although acetate is highly available in the rumen, the methanoscarcinales that make use of acetate grow too slowly to be kept in ruminants' digestive system. Acetogens also have a low affinity to hydrogen. These factors all contribute to the low amount of methane production.

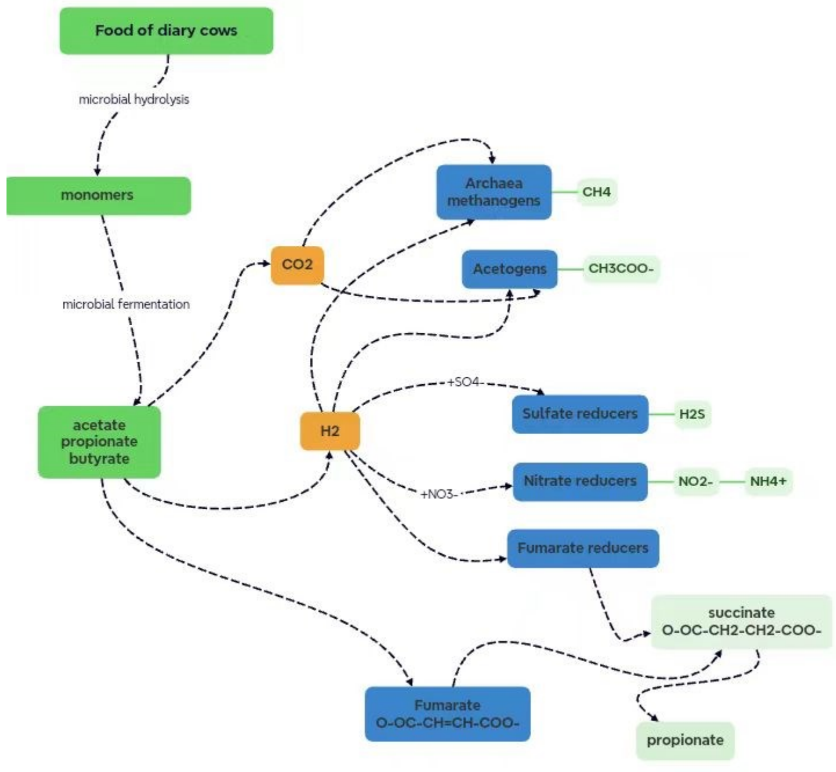

Figure 1. The graph about chemical reactions that happen after dairy cows digest the food.

3. Three diet modifications reduces methane emission

To reduce the methane production from cows, some diet modifications can be used. These methods are all based on the mechanism of how the cows digest the foods in Fig. 1 above. The methods mentioned

DOI: 10.54254/2753-8818/48/20240219

in this part can be concluded in 2 sectors: reducing the ferment of methanogens and making the cow produce propionate as a substitute for producing methane.

3.1. Increase the forage quality

Usually, the forage plants of higher quality (like the young plants) are more beneficial in reducing methane production. These plants have more fermentable carbohydrates and less NDF, which means the proportion of carbon is lower and the proportion of nitrogen is higher compared with the matured grass [3]. The digestibility and passage rate will increase, which means the microbial fermentation will form fewer by-products like carbon dioxide and hydrogen. The methane produced from these gases will decrease. By contrast, matured grass has a higher C: N ratio. These kinds of plants are harder for dairy cows to digest, thus the methane emissions could increase [4].

While choosing the forage with higher quality, farmers should also consider the type of the plant. This is because the variation in plants' chemicals can alter the amount of methane produced by animals greatly. For example, legume plant has lower methane emissions while being consumed by dairy cows because of the high pass rate and high digestibility. The same mechanism as the young plants [5].

3.1.1. Verification of the theory

The concept of quality is difficult to quantify, but we develop three quality levels to quantify the quality. The quality level is generally divided into three types, excellent(1), good(2), and poor(3). Each one is allocated with a factor. The good level is set as one to serve as a benchmark. The poor quality forage would increase methane emission with a factor over one, while excellent quality forage would decrease methane emission with a factor below. Then judge the impact of the increase in forage quality on methane emission by calculating the weight ratio and forage quality feed intake and other methods. Here, we introduce 400,500,600 indicators to judge the vertical range values by the input function and thus draw conclusions.

Code:

```
clc
clear
mass=input("cow mass (kg) =");
quality=input("1 for excellent, 2 for good, 3 for poor =");
DMI=[3 2.5 1.5];
dmi=DMI(quality);
data=[12 15 18; 10 12.5 15; 6 7.5 9];
if mass<=450
      crop=data(quality,1);
else
      if mass>450&&mass<=550
            crop=data(quality,2);
      else
            crop=data(quality,3);
      end
end
display(crop);
display(dmi);
```

3.1.2. Result analysis

Keep the mass of the diary cow at 500 kilograms.

When the "mass=500 kg, quality=3", the results are "crop yield=7.5, DMI=1.5"

When the "mass=500 kg, quality=3", the results are "crop yield=12.5, DMI=2.5"

When the "mass=500 kg, quality=1", the results are "crop yield=15, DMI=3"

From the result, we can conclude that an increase in the quality of the feed will elevate the DMI value. When DMI increases, it shows that the digestibility of the dairy cows will increase. Higher digestibility contributes to reducing methane production.

3.2. Replace the grass silage with maize silage

Silage is a common method to preserve the feed for dairy cows. It involves compressing the fresh plant material into a container with limited oxygen [3]. This process can promote the fermentation of lactic acid bacteria. During this process, lactic acid bacteria can decompose the sugar into the lactic acid. The pH value will be lower to exhibit the growth of some harmful bacteria. For grass silage, it is usually matured at a later stage of maturity, the concentration of digestible organic matter, sugar and nitrogen will decrease [6]. As a consequence, methane emissions will be high. By contrast, maize silage has a larger proportion of dry matter and digestible carbohydrates. A higher starch environment makes propionate more likely to be produced than acetate. What's more, maize silage can elevate the total level of DMI and increase the passage rate, which means the time foods stay in the rumen and produce methane will decrease, and methane production will be low as well. The low pH value of propionate can also exhibit some methanogens from producing methane [7].

3.2.1. Verification of the theory

This method is for ingredient substitution. Maize and grass silage differ mainly by the fraction volume. The assumption is that the silage only consists of maize or grass. Hence, the sum of their fractions is set as one. A linear relationship could be built through a loop analysis between the methane emission and one of the two fractions. The start and end points represent the pure maize or grass conditions. An anticipatory effect is around 15%. To process the verification, we define some matrices and variables that are data-correlated to methanogenesis in the code below. Next, we calculated methane production based on the C / N ratio and adjusted for the type of fed silage. Lastly, we show the calculated data in the geographical form as shown below [8].

Code:

```
import numpy as np
import matplotlib.pyplot as plt
# Clearing variables
A = np.array([24.6, 25, 24.5, 22])
AA = np.array([6.77, 6.74, 6.73, 6.72])
B = np.array([399, 414, 411, 387])
mean_value = np.mean(B)
S = np.std(B)
n = np.size(A)
N = len(A)
SS = np.sqrt(S**2 * (n-1) * 8 / (n * 8 - 1))
SE = SS / np.sqrt(n * 8)
miu = 400
t = (mean_value - miu) * np.sqrt(n) / S
df = n - 1
p = 1 # This line needs to be adjusted based on an equivalent Python function for the f distribution
c12 = 1
c18 = 0 # C/N ratio
if c12 == 1:
    cnr = np.array([0.189, 0.175, 0.247])
    CH4 = np.array([29.06, 7.09, 10.76])
else:
    cnr = np.array([0.184, 0.174, 0.235])
    CH4 = np.array([8.9, 2.62, 8.9])
```

```
c12 = 0.5
c18 = 1 - c12
cnr = c12 * np.array([0.189, 0.175, 0.247]) + c18 * np.array([0.184, 0.174, 0.235])
CH4 = c12 * np.array([29.06, 7.09, 10.76]) + c18 * np.array([8.9, 2.62, 8.9])

# Plot figure (fresh manure complete slurry)
c12 = 0
c18 = 1 - c12
CNR = []
CH = []
while c12 <= 1:
    cnr = c12 * 0.189 + c18 * 0.184
    CNR.append(cnr)
    CH4 = c12 * 29.06 + c18 * 8.9
    CH.append(CH4)
    c12 += 0.05
    c18 = 1 - c12

plt.plot(CNR, CH)
plt.xlabel('C/N Ratio')
plt.ylabel('CH4')
plt.title('Plot of CH4 vs C/N Ratio')
plt.show()

# Determine the silage type
grass = 0
maize = 1
if maize == 1:
    CH = np.array(CH) * (1 - 0.15)

plt.plot(CNR, CH)
plt.xlabel('C/N Ratio')
plt.ylabel('CH4')
plt.title('Plot of CH4 vs C/N Ratio (with Silage Type Adjustment)')
plt.show()
# Fat ingredient
fat = 0.03
delta = 0.03
fat += delta
FAT = []
while fat <= 0.07:
    FAT.append(fat)
fat += 0.001
```

3.2.2. Result analysis

Two linear graph are shown.

DOI: 10.54254/2753-8818/48/20240219

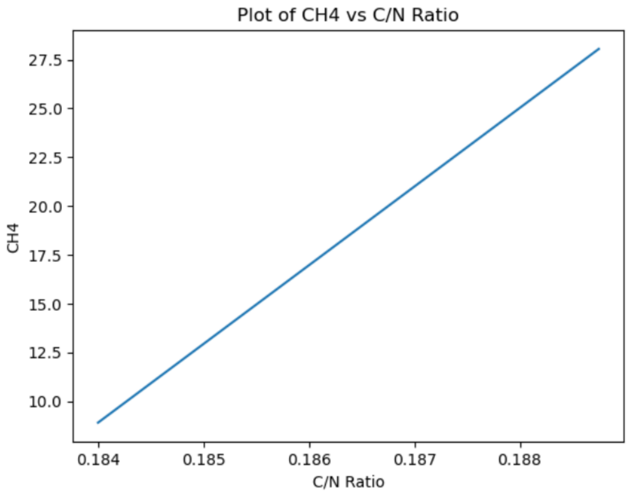

Figure 2. The relationship between C/N ratio and methane concentration before adjustment.

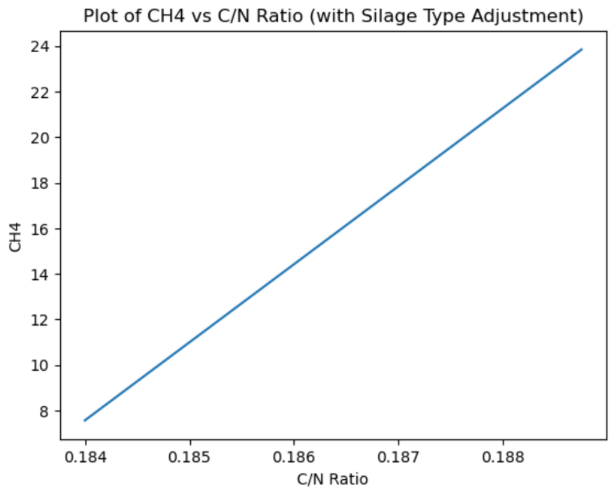

Figure 3. The relationship between the C/N ratio and methane concentration after adjustment.

There are two conclusions through two graphs. Firstly, the data supports that as the C/N ratio increases, the concentration of methane will increase. This finding supports the theory that increased carbon concentration will create a condition that favors methanogenesis and increases methane production. Secondly, the adjusted type of silage produces a lower concentration of methane. It supports that maize silage is beneficial to reduce methane emissions from cows.

3.3. *Fat supplementation*

Both fat and carbohydrates can provide energy for dairy cows, so fat can be used as a substitute for carbohydrates to lower methane production without affecting the energy intake of dairy cows [3]. This is because fat can reduce the fermentation of organic matter and the digestibility of cellulose. It can also inhibit some methanogens in the rumen with the help of hydrogenation of unsaturated fatty acids [7]. What's more, fats cannot be digested in the rumen. Methane will not be produced.

3.3.1. Verification of this theory

The high-fat contents might affect the cow's digestive process, which would have a negative effect. As usual, the silages contain a fat fraction of around 3%. The methane emissions will be increased once

DOI: 10.54254/2753-8818/48/20240219

the fat fraction exceeds 7% based on the study. Therefore, a fat range would be set first through a judgment algorithm. This method will be abandoned if the fat fraction is over the limit. On the contrary, later the fat supplement would be gradually added. The best effect is around a 3.5% proportional decrease in methane emission for each percentage of fat fraction. With the use of these information, we initialize the code by setting “fat=0.03” and “delta=0.03”. Then calculate the methane production and loop the calculation of methane to different fat levels. Finally, we plot the graph.

The whole code is shown:

```
# Fat ingredient
fat = 0.03
delta = 0.03
fat = fat + delta
j = 1
chm = np.mean(CH)
FAT = []
CHf = []
while fat <= 0.07:
    fat = fat + 0.001
    FAT.append(fat)
    CHf.append(chm * (1 - 0.0035 * j))
    j += 1
plt.figure()
plt.plot(FAT, CHf)
plt.title("Fat Ingredient")
plt.xlabel("Fat")
plt.ylabel("CH4")
plt.show()
```

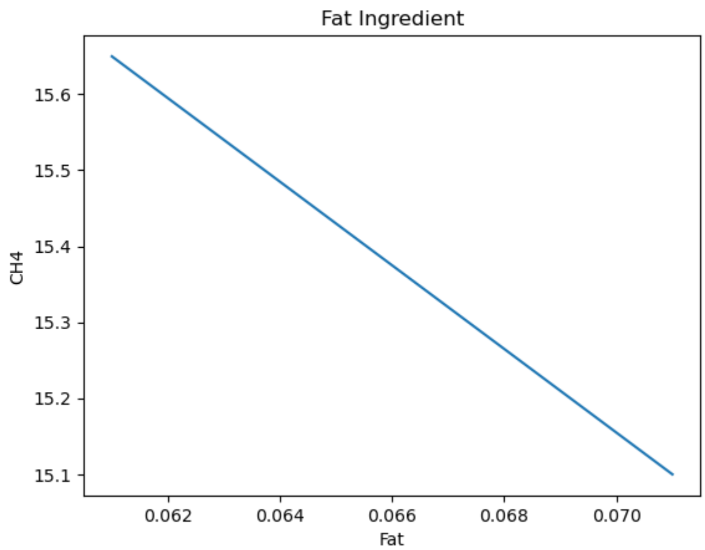

Figure 4. Result of the relationship between fat concentration and amount of methane emission.

3.3.2. Result analysis

The result of the code is shown. It is a downward-sloping linear curve. As the fat increases, the methane production will decrease. The result matches the fact that fat can reduce the digestibility of cellulose to lower methane production [7].

DOI: 10.54254/2753-8818/48/20240219

4. Conclusion

Based on the above biochemical theoretical research and mathematical model verification of changing the diet of dairy cows to reduce methane emissions, we conclude that replacing grass silage with corn silage and fat supplementation can effectively reduce methane emissions in dairy cows. However, our paper still has some shortcomings.

Firstly, if too much fat is fed to the dairy cows, problems include decreasing in the yield of milk production will arise. The fat content in dairy recipes should not exceed 7% of the dry products in the diet. Generally, dairy cows contain about 3% fat, so the supplement is generally 3% ~ 4%. That is to say, every cow needs to supplement 0.45 kg ~ 1.36 kg of fat every day. Adding more than 7% fat in the feed will reduce the activity of microorganisms in the first stomach, affect the digestion of crude fiber, reduce the appetite of dairy cows, and reduce the intake of dry feed and milk yield. Reduced digestive function may further enhance carbon emissions in dairy cows.

Second, the three emission reduction methods proposed in our article are analyzed independently. However, these three methods may have a mutual influence on each other. What's more, real methane emissions are more influenced by cow breeds and feed types. Farmers also need to consider the economic costs. For example, if corn silage is limited in an area, then the replacement of grass silage with corn silage is of high cost and will affect the economic benefits of farmers.

Therefore, it is hoped that future researchers can limit pastures to regional analysis, considering environmental and economic factors. And, the timeliness of each method, the amount of fat digestion are also necessary to consider the factors.

References

[1] Trupa, A., Aplocina, E., & Degola, L. (2015). Forage quality and feed intake effect on methane emissions from dairy farming. Engineering for Rural Development, 601-605.

[2] Sejian, Veerasamy & Shekhawat, Indu & Ujor, Victor & Ezeji, Thaddeus & Lakritz, Jeffrey & Lal, Rattan. (2013). Global Climate Change: Enteric Methane Reduction Strategies in Livestock. Environmental Stress and Amelioration in Livestock Production. 469-499. 10.1007/978-3-642-29205-7_16.

[3] Intergovernmental Panel on Climate Change. (2007). Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

[4] Alvarez-Hess, P. S., Williams, S. R. O., Jacobs, J. L., Hannah, M. C., Beauchemin, K. A., Eckard, R. J., ... & Moate, P. J. (2019). Effect of dietary fat supplementation on methane emissions from dairy cows fed wheat o

[5] Van Gastelen, S., Fernandes, E. A., Hettinga, K. A., Klop, G., Alferink, S. J. J., & Dijkstra, J. (2014). Replacing grass silage with maize silage affects rumen fermentation characteristics and enteric methane production in dairy cattle.

[6] Brask-Pedersen, D. N., Lamminen, M., Mogensen, L., Hellwing, A. L. F., Johansen, M., Lund, P., ... & Børsting, C. F. (2023). Effect of substituting grass-clover silage with maize silage for dairy cows on nutrient digestibility, rumen metabolism, enteric methane emission and total carbon footprint. Livestock Science, 274, 105273.

[7] Külling, D. R., Dohme, F., Menzi, H., Sutter, F., Lischer, P., & Kreuzer, M. (2002). Methane emissions of differently fed dairy cows and corresponding methane and nitrogen emissions from their manure during storage. Environmental Monitoring and Assessment, 79, 129-150.

[8] Alvarez-Hess, P. S., Williams, S. R. O., Jacobs, J. L., Hannah, M. C., Beauchemin, K. A., Eckard, R. J., ... & Moate, P. J. (2019). Effect of dietary fat supplementation on methane emissions from dairy cows fed wheat or corn. Journal of Dairy Science, 102(3), 2714-2723.