

Article

Estimating Methane Emissions from a Dairy Farm Using a Computer Program

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Abstract: The aim of our study was to estimate methane (CH₄) emissions from a dairy cattle farm using a computer application. Emissions of CH₄ in the air were forecast for a representative dairy farm raising Holstein-Friesian cows. The cowshed was equipped with a mechanical forced ventilation system with a centrally located ventilation duct. The volume of emissions from the emitter was established, taking into account meteorological conditions. For one year of operation of the emitter, the average annual emission was 1.301 kg/h. The maximum emission of CH₄ was estimated at 3.51 kg/h. These data can be helpful in estimating the environmental burden of a dairy farm and in determining the role of ruminants in global warming.

Keywords: methane emission; greenhouse gas; ruminant; computer modelling; global warming

1. Introduction

According to the Food and Agricultural Organization, the livestock sector generates more greenhouse gases (GHG), measured in CO_2 equivalent, than the transport sector. Livestock farms, especially cattle farms, are among the main sources of emission of these gases. Emissions of methane (CH_4) and nitrous oxide (N_2O) associated with animal production around the world account for about 9% of total GHG emissions. As a GHG, CH₄ has been recognized as an important factor in climate change. It is produced in the digestive tract of ruminants and during anaerobic digestion of waste as a by-product of the decomposition of organic matter [1,2]. The amount of CH₄ produced in cow intestines is influenced by multiple factors, including the composition and balance of the diet, physiological differences between individuals, production level, and microclimatic conditions. Limiting the amount of CH₄ released from metabolic transformations and adaptation of suitable measurement techniques continue to pose problems for researchers [1,3-7]. In a study by Eckert et al. [8], the CH₄ emission rate estimated at milking stations was similar to that observed in cows in respiratory chambers. It was determined that owing to further validation of the method, monitoring of CH₄ emissions on the farm during milking can provide an inexpensive and reliable method for estimating daily CH₄ production by individual dairy cows. Respiration chambers are used for inventory purposes because they are widespread and easier than more detailed statistical methods. Hristov et al. [9] recommend simplified prediction models of enteric CH₄ based on dry matter intake (DMI) for analysis of data for dairy cattle.



In combination with data on the animals' diet, they can predict average CH₄ emissions with a similar accuracy to complex empirical models. These simplified models can be used for emission inventory purposes [9]. Efforts are being made to develop a method to predict enteric CH_4 emissions in dairy cows using Fourier-transform infrared spectroscopy or measurements based on gas chromatography of fatty acids from milk. Both techniques have potential, but cannot yet predict CH₄ emissions in dairy cows in practice. Additional CH₄ measurements are needed to improve the accuracy and reliability of specific spectra for predictive CH_4 emissions [10]. According to Niu et al. [11], intestinal CH_4 measurement on a large scale is costly and impractical, and therefore modelling is commonly used to predict CH₄ production. The authors cited found the intercontinental model to work best. Prediction models of CH₄ production, yield and intensity developed on an intercontinental basis were found to have similar performance in different regions. Conversion factors for CH₄ must be modified for individual regions in order to improve emission estimates in individual countries. Information on DMI is required for a reliable forecast, and other factors, such as the neutral detergent fibre (NDF) concentration, provide more detail in these calculations for better CH₄ release results. Some information on the production of enteric CH₄ in dairy cows can be obtained by analyzing metabolite content in milk. These data have modest potential for predicting emissions of this gas [12]. Modelling of emissions of gaseous pollutants into the air is often the basis for administrative decisions for many farms. For this reason, suitable measurement methods and indicators are needed to calculate the actual emissions of this gas. The aim of this research was to estimate the level of CH_4 emissions from a dairy cattle farm using a computer application.

2. Materials and Methods

Forecasting of CH_4 emissions was carried out for a representative dairy cattle farm with a stocking density of 100 livestock unit (LSU). During the data collection, Holstein-Friesian dairy cows were kept on the farm. The average milk yield for the herd during the research period was about 8000 L of milk per lactation per cow. The animals were kept on slatted floors without litter in a free-stall system. The cattle are fed a total mixed ration (TMR) balanced for the production of 28 kg of milk per cow per day with uninterrupted access to drinking water. The remaining energy demand is met by individual feeding with concentrate feed in the robot during milking (Table 1). The average milk yield during the study period was 35–36 L per cow per day for 209 days of lactation. The feed ration was balanced to provide the appropriate amount of energy, protein, minerals and vitamins. The cows were kept indoors year-round. The barn was equipped with a forced mechanical ventilation system with a centrally located ventilation duct.

Component	Dry Matter (%)	Milk Production (kg)	Share of Dry Matter in TMR (kg)
Maize silage	36	24	6.8
Alfalfa silage	47	6.0	2.8
Grass mixture (Lolium multiflorum, Trifolium incarnatum L, Vicia villosa)	37	4.0	1.5
Brewer's grain	22	10	2.2
Sugar beet pulp	24	7	1.7
Water	0.0	4.0	0.0
Wheat meal	86	2.8	2.4
Rapeseed meal	88	2.5	2.2
Additive preventing heating of TMR	95	0.5	0.47

Table 1. Total mixed ration composition.

The software used for the forecast was Operat FB, which is in compliance with the methodology given in the Regulation of the Minister of the Environment on the reference values of certain substances in the air [13]. The operating parameters of the emitter were determined according to the following formula:

$$dr = \sqrt{\frac{4pq}{\Pi}} \tag{1}$$

where p and q are the dimensions of the rectangular emitter, and dr is the equivalent diameter.

For the purpose of data analysis, the following parameters were adopted as input data in the program: emitter height: 12 m; diameter: 0.4 m; gas temperature: 283 K; and specific heat of gases: $1.30 \text{ kJ/m}^3/\text{K}$. The effective height of the emitter (*H*) was determined according to the following formula:

$$H = h + \Delta h \tag{2}$$

where the gas plume rise (Δh) depends on the exit velocity of the gases (v), heat emission (Q) and wind speed at the height of the outlet of the emitter. The gas plume rise is determined based on the Holland formula ($0 \le Q \le 16,000 \text{ kJ/s}$), the CONCAWE formula ($Q \ge 24,000 \text{ kJ/s}$) and a combination of these formulas (16,000 < Q < 24,000 kJ/s).

In accordance with the regulation on emissions [13], sub-periods were taken into account in calculating levels of substances in the air.

Modelling was carried out for two temperature periods—autumn/winter and spring/summer, with average annual temperatures of 275.1 and 278.1, respectively. The annual average temperature in the area for the entire year was 281.1 K. The CH₄ emission factor was 114 kg/cow/year/LSU, which takes into account both enteric fermentation and feces. Sub-periods were established taking into account variability in emissions, with the specific parameters of the emitters, their simultaneous operation, and meteorological data. Wind rose data for the calculation of concentrations within the sensor network were obtained from a nearby meteorological station. They took into account the state of equilibrium of the atmosphere (*c*) and the range of wind speed (wind rose). The aerodynamic roughness coefficient of the terrain (z_0) was determined within 50 h_{max} (*F*) by the following formula:

$$z_0 = \frac{1}{F} \sum_c F_c \cdot z_{oc} \tag{3}$$

The roughness of the terrain (topography), taking into account nearby buildings, tree stands and terrain relief, was set at 0.5 m, which corresponds to low buildings [13].

The maximum concentration of the gaseous substance (E_g) averaged for one hour (S_m) in specific meteorological conditions (*u*, wind speed) was calculated according to the following formula:

$$S_m = C_1 \frac{E_g}{\mu AB} \left(\frac{B}{H}\right)^g \cdot 1000 \left[\mu g/m^3\right]$$
(4)

where C_1 and g are dependent on the state of equilibrium of the atmosphere, A is the horizontal diffusion coefficient and B is the vertical diffusion coefficient. The following formulas were used to calculate the coefficients:

$$A = 0.088 \cdot \left(6m^{-0.3} + 1 - \ln\frac{H}{Z_0}\right) \tag{5}$$

$$B = 0.38m^{1.3} \cdot \left(8.7 - \ln \frac{H}{H_0} \right) \tag{6}$$

When calculating the levels of substances in the air, it was assumed that if the same substances are emitted from all the emitters on the farm, then the calculations are carried out for the complex of emitters.

There are no health resort areas at a distance of less than 30 x_{mm} from any of the emitters on the farm.

The average concentration of the gaseous substance (*S*) on the surface of the area (*x*, distance from the emitter to the point) was calculated according to the formula included in the regulation, where $\overline{E_g}$

is the average emission of the substance, \overline{u} is the average wind speed and σ_z is the vertical diffusion coefficient [13]:

$$\overline{S} = \frac{r}{\Pi \sqrt{2\Pi}} \cdot \frac{\overline{E}_g}{\overline{u}\sigma_z x} \exp\left(\frac{H^2}{2\sigma_z^2}\right) \cdot 1000$$
(7)

The frequency of exceedance of the reference value or the permissible level of the substance in the air for all meteorological conditions was determined using the formula with the software:

$$P(D_1) = \sum_{j} Pi \tag{8}$$

When calculating the average annual concentration, in accordance with the regulation [13], the concentration values calculated for all meteorological conditions are added, taking into account their frequency at a given wind rose. The maximum concentration S_{mm} is defined as the highest value from the set of all concentrations in various meteorological conditions. If the concentration caused by the emission of the substance from the emitters exceeds the permissible level of the substance in the air, the frequency of such exceedance is calculated. The frequency of exceedance of the reference value or permissible level of the substance in the air (D_1) was calculated if the concentration values for buildings near the emitters exceeded D_1 or if the condition $S_{mm} \leq D_1$ was not met. These values are considered to be met for the pollutant if the frequency with which the average concentration exceeds D_1 for one hour is not more than 0.2% of the year. The FB Proeko OPERAT software package, which operates on these assumptions, was used to estimate the emission volume.

3. Results

The CH₄ emissions from the analyzed site are presented in Table 2. For one year (8760 h) of operation of the emitter, the average annual emission was 1.301 kg/h, or 11.4 Mg/year. The maximum emission of CH₄ was estimated at 3.51 kg/h. Figures 1 and 2 show the distribution of maximum concentrations and average annual concentrations for CH₄ around the site.

Table 2. Methane (CH₄) emissions to the atmosphere during the modelling period.

Symbol	Velocity of Gases	Temperature of Gases	Max Emissions	Average Annual Emissions	Annual Emissions
E1 ¹	0.4 m/s	283 K	3.51 kg/h 975 mg/s	1.301 kg/h 361 mg/s	11.4 mg/year
¹ first emitter.					

Depending on the roughness of the terrain and local microclimatic conditions, particularly wind movement, the range of concentrations of substances in the air is highly variable. Figure 3 shows the CH_4 concentrations in the air around the emitter depending on wind velocity.

The highest maximum concentration was 1.089 mg/m³, which exceeds the permissible concentration (D_1) of CH₄ in the air averaged for one hour for the specified meteorological situation. Therefore, the distance of the maximum concentrations (x_{mm}) was calculated and found to amount to 43.5 m. To analyses the possibility of highly elevated concentration values, the area within a 1305 m radius of the emitter should be considered (Table 3).

Table 3. Methane (CH₄) emissions to the atmosphere during the modelling period.

Max Concentration S _{mm}	Acceptable Concentration $D_1 [\mu g/m^3]$	Distance of Max	Critical State	Critical Wind	Evaluation of Concentrations
[mg/m ³]		Concentration X _{mm} [m]	of Equilibrium	Velocity [m/s]	at Ground Level
1.089	3000	43.5	4	1	$0.1 \times D_1 < S_{mm} < D_1$



Figure 1. Maximum concentrations for methane (CH₄) emissions at a height of 10 m. Note: X axis—component of the distance from the emitter to the point for which the calculations were made, parallel to the wind direction; Y axis—component of the distance from the emitter to the point for which the calculations were made, perpendicular to the wind direction.



Figure 2. Average annual concentrations for methane (CH_4) emissions at a height of 10 m. Note: X axis—component of the distance from the emitter to the point for which the calculations were made, parallel to the wind direction; Y axis—component of the distance from the emitter to the point for which the calculations were made, perpendicular to the wind direction.



Figure 3. Variation in concentrations at various distances from the emitter depending on wind strength at ground level.

The concentrations calculated for the network of sensors at the height of 10 m exceeded the maximum allowable concentration of 3000 μ g/m³ (Table 4). The analysis showed that the reference value was exceeded at 8 of 81 analyzed sensor points. To illustrate the distribution of pollutants, the frequency of exceedances is presented in Figure 4.



Figure 4. Frequency of exceedances in the network of sensors at a height of 10 m.

x	Y	Max Concentration (mg/m ³)	Average Concentration (mg/m ³)	Critical State of Equilibrium	Critical Wind Velocity	Critical Wind Direction	Frequency of Exceedances (%) mg/m ³
80	80	5.5	0.063	6	1	NNE	0.30
100	80	8.2	0.103	6	1	Ν	0.82
120	80	5.5	0.070	6	1	NNW	0.28
80	100	8.2	0.104	6	1	E	1.03
120	100	8.2	0.129	6	1	W	1.15
80	120	5.5	0.063	6	1	SSE	0.34
100	120	8.2	0.132	6	1	S	1.08
120	120	5.5	0.096	6	1	SSW	0.41

Table 4. Calculated concentrations of aliphatic hydrocarbons in the network of sensors at a height of 10 m.

4. Discussion

Determination of the actual levels of GHG emissions is an essential element of the continuous improvement of European legal regulations: Integrated Pollution Prevention and Control (IPPC) and National Emission Ceilings (NEC) directives, and calculation of the acceptable CO2 equivalent limit for individual Member States [14,15]. Many models of GHG emissions from dairy production systems have been developed. These include fixed emission factors, variable emissions associated with herd management, and empirical or statistical models. Each of them can be very effective when used properly. Detailed simulation models of emission processes provide essential research tools, while simpler models are usually most useful as support for the issuing of environmental decisions. The Gaussian model used in our research is similar to the model of an integrated agricultural system based on gas emission factors [16]. Many authors perform regression analysis as a model in determining emissions, because it is used to estimate the relationship between a dependent variable and one or more descriptive variables. Regression analysis can be used to model the relationship between selected variables, as well as to predict values based on a specific model [17]. In our study, we used the Gaussian model (plume or cloud), which is a two-step deterministic model. Modelling of meteorological fields is carried out first, followed by modelling of the dispersion of pollution. The emission factor used makes it possible to obtain the distribution of the concentration of CH₄ isolines in the area. This model, while providing information on the total amount of CH₄ emitted from the farm, cannot be used to determine the factors affecting this value. Among the available strategies for mitigating the environmental impact of dairy farms, increasing attention is being paid to the genetic factor. CH₄ emissions have been found to differ significantly between dairy cows kept on the same farm. This variation should be taken into account when conducting inventory or testing mitigation strategies, but it may offer genetic selection options, while CH₄ emission rates can be obtained using CH₄ analyzers installed in automatic (robotic) milking stations [18]. However, based on the concentration of pollutants and atmospheric conditions, dispersion models can be created to simulate their dispersion and estimate their concentrations at any distance from the source. The majority of legal regulations regarding emissions of pollutants, including odors, are currently created on this basis. However, the minimum distances specified in them between the source of emissions and the residential area give rise to serious discussions among both producers and residents. Such models provide important tools for quantifying emissions, determining the possibility of reducing them, and selecting strategies to mitigate the impact of the farm on the environment [19,20]. The amount of gases emitted by dairy cows is closely correlated with the protein value of their diet, as well as the animal's physiological state during milk production. The CH₄ content in the gases excreted by cows is about 25%. This amounts to about 1000–1300 L of CH₄ per cow per day. According to the literature data, one cow emits 112 kg of CH₄ and 40 kg of ammonia a year [21], which is consistent with our own modelling results obtained using a computer application. Several systems have been developed for estimating CH_4 emissions from dairy farms. In vitro testing of production of this gas most often involves incubation of rumen inoculum under anaerobic conditions in special jars. The quantities of gas generated during this time are subjected to chromatographic analysis and calculated using calibration curves [22]. Individual CH₄ and CO₂ production was registered during milking in an automatic milking system (AMS) to estimate individual differences in CH₄ production

between cows. Measurements based on Fourier-transform infrared (FTIR) detection showed that gas emissions were positively correlated with consumption of concentrate feed but were not dependent on the cow's milk yield. The repeatability of the results for the CH_4 and CO_2 ratio was 0.39 for the Holstein breed and 0.34 for Jerseys. The results suggest that the ratio of CH_4 and CO_2 measured by this non-invasive method is an individual feature of cows and can be useful both in herd management and in genetic assessments of predisposition to enteric CH_4 production [23].

Another method is to analyses the composition of the feed ration and the content of protein substances that can be converted to CH₄ as a result of digestive processes. The feed analysis method uses the composition of the animal diet and calculated nutrient digestibility. According to Tomkins et al. [24], the results of these calculations may vary by up to 35%. This is due to the variable composition of feed and its intake by animals. Feed experiments require many repetitions to capture changes in individual parameters, as well as seasonal influences and the availability and quality of feed. Using this method, the most accurate data can be obtained with a respiration chamber, but the data pertain to individual animals. Although they can provide accurate data on the chemical composition of the air inside the chamber, there is a risk of changes in feed intake by the animal due to stress as well as losses of gas due to improper sealing of the chamber [15,24,25]. The high costs associated with the construction and maintenance of respiration chambers significantly limit the use of this method. For scientific purposes, estimation of individual emissions is still applied, especially in the search for gas reduction methods [15]. Recent research in dairy cattle has revealed hereditary variation in CH_4 production that enables the use of strategies based on selective breeding. The results indicate that CH₄ production is a trait highly correlated with the genotype of individual cattle. Studies show that the numbers of some bacteria and archaea in the cow's stomach are hereditary and associated with CH₄ production, but most changes in the relative numbers of bacteria and archaea in the rumen are due to non-genetic factors. The degree of variation in CH₄ production is therefore linked to the genetics of the host as well as the number of rumen bacteria and archaea. In this way, host genetics were determined to account for 21% of CH₄ production, and rumen microbes for 13% [26,27]. Research by Van Engelen et al. [28] indicates that reduction can be achieved through selective breeding. The authors conducted research on genetic variability and CH₄ emissions by Dutch Holstein-Friesian cows using infrared sensors installed in automatic milking systems. A 33% reduction in CH₄ emissions was found after 50 weeks of lactation. The authors recommend including the lactation stage in the CH₄ emission analysis model. Pszczola et al. [29] indicate that CH₄ emission is a hereditary trait and that the level of heritability changes during lactation. The changes observed and the low genetic correlations between days of lactation suggest that this may be an important element in determining emissions.

Calculation of the total emission of gases from livestock production, with reference to the NEC directive, requires a mathematical computation model using emission factors. These are helpful tools for estimating emissions of gaseous pollutants from farms. However, they do not take into account processes affecting the spread of gases and accompanying factors, e.g., diet modification. Computer simulations can provide a cost-effective and efficient method for estimating CH₄ emissions on dairy farms. The program used was based on the classic Gaussian Model using Pasquill's equation, which is most commonly used in practice. The basic assumption resulting in Gaussian equations is that the distribution of pollutant concentrations in the plume is consistent with the Gaussian distribution, and the concentration fields are obtained for a specific time. In estimating the uncertainty of the modelling of emissions of pollutants, a fundamental limitation is the accuracy of the model of their dispersion in the environment. It includes accurate and verifiable input data, taking into account the physical and chemical characteristics of the pollutant and the terrain relief of the area. The result of the modelling, presented as a percentile of exceedances of the distribution, is burdened with the greatest uncertainty of measurement at the peak values of the Gaussian distribution, and the uncertainty decreases with the percentile values. It is typically accepted that when good input data are used, dispersion Gaussian modelling can be used to predict concentrations within a factor of two [30,31]. They are very useful for developing management systems that can minimize emissions. Herd management scenarios using computer models similar to that used in our own research have been developed by the Agricultural Research Service (ARS) of the US Department of Agriculture. An analysis carried out using the Integrated Farm System Model (IFSM) for a representative cattle farm in Pennsylvania with 100 cows forecast a total annual average emission level of 20 Mg CH₄. This represented an average annual emission of 135 kg CH₄ per Holstein cow and an average emission of 5.4 kg CH₄/m³ of stored slurry manure [14,32]. The results were very similar to those presented in our own research on CH₄ emissions from dairy farms, confirming that computer models are effective in this type of analysis.

The introduction of good management practices on a farm can reduce emissions of this gas and improve profitability. The use of feed additives, as in the case of other animal species, may reduce the burden on the environment [4,28,33–37]. Not all GHG emissions are included in the Emission Trading Scheme (ETS). Non-ETS emissions include emissions from agriculture and households. According to the European Union Emission Trading System (EU ETS), the volume of emissions classified as non-ETS accounts for 55% of total emissions. Individual countries are granted limits on non-ETS in individual sectors. The problem of CH_4 emissions is an important issue in milk production and is continually taken up in research [38,39].

The presented data indicate that CH_4 released from cattle farms poses a real threat to the natural environment. At the same time, gaseous pollutants spread along with it may be a source of odor nuisance, leading to complaints among local residents. The use of a computer application before beginning an investment, or even modernizing one, can be helpful in assessing its impact on the environment. The proposed model can also be effectively used in a CH_4 emission reduction strategy, e.g., through the use of natural feed additives, or utilization of CH_4 for energy purposes. Calculation of the CH_4 concentration in the environment and knowledge of its energy value enable catalytic oxidation, which will provide a source of energy for farmers while at the same time reducing CH_4 emissions. The data presented above indicate the need to monitor CH_4 levels and find safe technologies to reduce the impact of this sector on global climate change.

5. Conclusions

The method described above for forecasting CH_4 emissions from a farm is an easy way to determine its environmental burden. Owing to the low cost and simplicity of the program, we can quickly obtain information regarding the volume of CH_4 emissions from a farm, taking into account the number of animals and the conditions prevailing around the site. These data can be helpful in estimating the environmental burden of the farm, finding means to neutralize pollutants, and determining the contribution of ruminants to global warming.

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