https://doi.org/10.15407/scin16.04.023

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INCREASING THE BIOGAS RELEASE DURING THE CATTLE MANURE FERMENTATION BY MEANS OF RATIONAL ADDITION OF SUBSTANDARD FLOUR AS A COSUBSTRATE

Introduction. *The processing of livestock waste and agricultural production enables not only improving environmental safety, but also obtaining energy resources.*

Problem Statement. *Cow manure is used to produce biogas, but its yield is relatively low. One way to increase biogas yield is the joint fermentation of cow manure with substandard flour, which cannot be used as human food and as feed for farm animals. However, the flour content in the substrate, at which the biogas yield is maximum and there is no inhibition of the methane fermentation process, is not a solved issue.*

Purpose. *Increase biogas yield by adding substandard flour to a cow manure-based substrate.*

Materials and Methods. *Research of biogas yield during methane fermentation of substrate based on cow manure with the addition of substandard flour was carried out on a biogas plant consisting of a methane tank with a working volume of 30 l and wet gasholder at periodic substrate loading and fermentation temperature 35 °C. The portion of the substrate included 1.7 kg of manure, 2.5 kg of water and 50, 100, 250 or 500 g of flour. The composition of flour in the substrate was 1.2%, 2.3%, 5.6% and 10.6%. The dichotomy method was used to determine the optimal flour content in the substrate, provided the maximum biogas yield.*

Results. *The maximum biomethane release is 14.3 l/kg dry organic matter (DOM), at 1.2% of the flour content in the substrate; 20.9 l/kg DOM, at 2.3%; 19.2 l/kg DOM, at 5.6%. At a content of 10.6% flour in the substrate, the biogas did not burn, fermentation quickly stopped. The optimum flour content in the substrate based on cow manure, in which the biogas yield increases 1.5 times, is 3.7%.*

Conclusions. *Based on the conducted experimental studies, a model of biogas yield with gradual loading of the substrate was built and the optimal flour content in the substrate was determined, at which the maximum biogas yield is provided.*

Keywords: biogas, methanetank, substandard flour, cattle manure, biogas plant, and methane fermentation.

Currently, one of the most important and urgent problems is processing of animal waste and agricultural production, not only for environmental safety, but also for obtaining energy resources. Based on the use of biogas technologies, cow manure is used, as a rule,

Citation: Polishchuk, V.M., Shvorov, S.A., Tarasenko, S.Ye., and Antypov, I.O. Increasing the Biogas Release During the Cattle Manure Fermentation by Means of Rational Addition of Substandard Flour as a Cosubstrate. *Sci. innov.* 2020. V. 16, no. 4. P. 23—33. https://doi.org/10.15407/scine16.04.023

for biogas and high-quality fertilizers. However, the biogas release during the fermentation of manure is relatively low due to a sufficiently large amount of crude fiber. One of the ways to increase the release of biogas is the joint fermentation of cow manure with substandard agricultural raw materials, which cannot be used as food for humans and animal feed. Therefore, to increase the release of biogas from manure, it is advisable to use cheaper raw materials such as waste from agricultural production and substandard products. Such wastes include wastes from biodiesel production [1; 2], molasses, vinasse, pulp, etc. By agricultural residues that increase yield of biogas can also include substandard flour. Analysis of recent research and publications on the grain waste disposal show that their anaerobic processing is the most effective for biogas production. According to the results of the study described in research [3], the release of biogas at a fermentation temperature of 38°C from substrates with the addition of rye bread is 0.459 l/g dry organic matter (DOM), in research [4], various types of grain release — from 0.634 l/g DOM (for rye bread) to 0.943 l/g DOM (for wheat bread with egg and milk additives). As it is stated in research [5], the common fermentation of biowaste with the waste of wheat and rye bread with an organic loading rate of 14 kg/m^3 per day, was stable to their organic loading rate kg/m^3 per day and enabled producing 3 times more biogas. The release of methane at the fermentation of grain with DOM in the proportion of 1:9, 3:7 and 5:5 is 233 ml/g volatile substance (VS), 298 ml/g VS and 344 ml/g VS [6]. In research [7] it is stated that the release of biogas when dry bread is added to the substrate is 650 l/kg VS with a content of methane 47%. As noted in research [8], as the result of co-digestion of grain waste with beer pellet and fish waste, there were obtained 671—763 ml/g VS biogas and 441—482 ml/g VS methane. The time of hydraulic maintenance and the time of technical splitting were 21.0—23.8 days and 40.5—52.8 days, respectively.

In research [9], the effect of feed (grains, seeds of oilseeds, husk) on methane release was investigated. It was found that the largest daily release of methane was obtained when feeding cattle with grain and products of its processing, namely: wheat flour (11.6 ml/g dry matter (DM)), wheat grain (11.4 ml/g DM), maize corn (10.3 ml/g DM), oat grains, and (6.9 ml/g DM). It was found in research [10] that the release of biogas during the fermentation of a substrate with the addition of boiled rice to a methane tank of 100 liters is 0.6 m^3/day, which is higher than with the addition of potato peels (0.44 m^3 day), orange peel (0.32 m^3/day) and a mixture of these three types of raw materials (0.21 m^3/day). The release of biogas from the substrate by the addition of flour was low, 0.01—0.04 m^3/ day. In research [11], there was compared the release of biogas with the addition of flour waste after cleaning the mill, ground chopped jetropha, crushed paper mass to the substrate on the basis of cow manure. The largest biogas release (3.2 l/day) and methane (66.3%) were obtained by adding flour to the substrate in the proportion C:N = 27:1. Comparison of the biogas release after adding to the substrate on the basis of cow manure of grain, fruits and vegetables at a temperature of 27°C to 36°C and a pH of 6.5 to 7.5 is described in research [12]. The largest release of methane was obtained from the substrate with the addition of grain inclusions (2546 ml), whereas with the addition of fruit waste, 2000 ml was obtained, vegetable waste — 1468 ml. In research [13, 5], the release of biogas from barley grains is estimated as 353—658 m^3/t VS, from wheat as 384—426 m^3/t VS, from triticale as 337—555 m^3/t VS, from oats as 250—295 m^3/t VS, from sorghum as 295—372 m^3/t VS, and from rye as 283—492 m^3/t VS. The release of methane from processed brewing grain, as stated in researches [14] and [15], is 0.284 l/g of HSC. According to [16], the total methane release of processed brewing grain without preliminary treatment is 409.8 m^3/t VS, whereas the release of pre-heated at a temperature of 100—200 °C is

467.6 m^3/t VS. The results of the studies described in research [17] showed that the potential of biogas from the processed brewing grain is 120 l/kg. In a single-stage system, the release of biogas from unprocessed grain (87.4 l/kg) is almost equal to the release of biogas from pre-processed grain (89.1 l/kg), while the release of methane was 51.9 l/kg and 55.3 l/kg respectively, and biodegradation was 62.0 and 62.2%. In the two-stage process, preliminary grain cultivation showed better results, with a 103.2 l/kg of biogas release and 73.6% biodegradation, whereas the biogas release from untreated grain was 89.1 l/kg with a biodegradation of 63.5%. In the two-stage process, methane releases from untreated and pre-processed raw materials were identical — 58.7 l/kg. The average specific production of biogas, as stated in [18], is 414 ± 32 l/kg of DM, with a biomethane release of 224 ± 34 l/kg of DM. The release of biogas from processed grains, obtained in the studies described in [19], is 0.596 m^3/kg VS with 65% of methane content.

On the other hand, as noted in [20], the lowest costs for processing cow manure are provided during anaerobic digestion, and when selling energy from exhaust gases to a farm, one can get from 6.8 to 13.6 m^3/day of warm water [21]. In [22], it was shown that biogas release from manure is 450 m^3/t VS, which is significantly less compared to biogas release during the fermentation of food waste (660 m^3/t VS). When fermenting cattle manure compared with corn silage, it produced less biogas release, which was also confirmed in [23]. According to [24], the release of biogas during the fermentation of cow manure (0.31 m^3/kg VS) is higher compared to the digestion of food waste (0.17 m^3/kg VS). The high release of methane (1040 ml/g VS versus 118 ml/g VS for mono-fermentation of food waste) gives the ratio of fats and food waste 50:50, with a content of 85% lipids and 15% protein, as noted in [25].

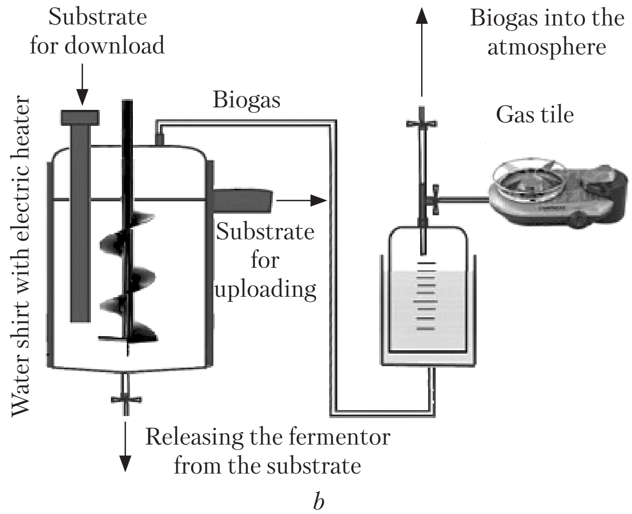
In the case of joint fermentation of processed brewing grain and phytomass of the artichoke under thermophilic conditions, the release of methane was 6—8 l/100 g of processed brewing grain with its loading of 50 g/l and 9—11 l/100 g of processed brewing grain when loaded 100 g/l [26]. According to [27], the highest biochemical methane potential of the processed brewing grain is 515 l/kg.

Thus, there is a need for further research to determine and justify the modes of fermentation of cereals and grain waste by means of fermentation of substandard flour with cow manure. The purpose of the article is to increase the release of biogas using the rational mode of the manure fermentation with the addition of substandard flour as a co-substrate. To achieve this goal it is necessary to solve the following tasks:

1. To determine the content of DM, DOM and substrate moisture based on cow manure with the addition of flour;
2. To carry out an experimental study of the biogas release during the fermentation of cow manure with the addition of flour;
3. To construct a model of the biogas release and to determine the optimal composition of the flour been gradually loaded for the fermentation of cow manure.
4. Justify recommendations regarding the content of flour in the substrate for the gradual loading of the methane tank.

Studies were conducted on a laboratory biogas plant, with a volume of 30 l (Fig. 1, *a, b*). Determination of biogas release was carried out with the help of a wet gasholder. In doing so, the heating of the digester is provided by a water jacket with an electric heater, which is placed between the outer and the inner hull. The substrate is pumped into the active zone of the inner shell through a pipe that almost reaches the bottom. At the same time, the processed digestate is fed through a pipe, which is located at the level of the substrate and biogas boundary. Refueling of the digester is carried with regard for not less than 1/3 of the processed digestate with uterine bacteria culture in it. The release of biogas is recorded on a scale, graduated in centimeters, of a raised cylinder gauge of a wet gasholder. The calorific value of biogas is determined by burning

a



b

Fig. 1. Laboratory biogas plant: *a* — appearance; *b* — plant layout

it on a gas stove, while heating the water in the calorific value measurer.

The substrate is prepared by mixing cow manure with water and flour added to it. The methane tank was filled with the substrate by ¾ with a periodic loading mode.

Experimental study of the biogas release during the fermentation of cow manure with the addition of flour was carried out at a fermentation temperature of 35° C (in mesophilic mode). A methane tank was loaded with a portion of the substrate, which consisted of 1.7 kg of cow manure, 2.5 kg of water and 50, 100, 250 or 500 g of flour. Meanwhile, the content of flour in the substrate was 1.2, 2.3, 5.6 and 10.6%.

Determination of the content of DM, DOM and substrate moisture on the basis of cow manure with the addition of flour. In the solid fraction of cow manure there is 16.4% of DM [28], of which about 80% is DOM [29].

Then the mass of dry matter of cow manure, which is part of the substrate, is:

$$M_{DMs} = \frac{1.7 \cdot 16.5}{100} = 0.2805 \text{ kg}, \qquad (1)$$

and the mass of dry organic matter of cow manure, which is part of the substrate, according to the formula (2):

$$M_{DOMs} = \frac{0.2805 \cdot 80}{100} = 0.2244 \text{ kg}. \qquad (1)$$

The highest grade wheat flour contains 85% of dry matter, of which 99.5% is organic matter [30].

Then the mass of dry matter of flour, which is part of the substrate, according to the formula (1) is:

at the weight of flour 50 g:

$$M_{DMs} = \frac{0.05 \cdot 85}{100} = 0.0425 \text{ kg};$$

at the weight of flour 100 g:

$$M_{DMs} = \frac{0.1 \cdot 85}{100} = 0.085 \text{ kg};$$

at the weight of flour 250 g:

$$M_{DMs} = \frac{0.25 \cdot 85}{100} = 0.2125 \text{ kg};$$

at the weight of flour 500 g:

$$M_{DMs} = \frac{0.5 \cdot 85}{100} = 0.425 \text{ kg};$$

The mass of dry matter of flour, which is part of the substrate, according to the formula (2) is:

at the weight of flour 50 g:

$$M_{DOMs} = \frac{0.0425 \cdot 99.5}{100} = 0.0423 \text{ kg};$$

at the weight of flour 100 g:

$$M_{DOMs} = \frac{0.085 \cdot 99.5}{100} = 0.0846 \text{ kg};$$

at the weight of flour 250 g:

$$M_{DOMs} = \frac{0.2125 \cdot 99.5}{100} = 0.2114 \text{ kg};$$

at the weight of flour 500 g:

$$M_{DOMs} = \frac{0.425 \cdot 99.5}{100} = 0.0429 \text{ kg}.$$

The total dry organic matter of the substrate is defined as the sum of dry organic matter of cow manure and flour:

at the weight of flour 50 g:

$$0.2244 + 0.0423 = 0.2667 \text{ kg},$$

or

$$\frac{0.2667 \cdot 100}{1.7 + 0.05 + 2.5} = 6.3\% \text{ of substrate mass};$$

at the weight of flour 100 g:

$$0.2244 + 0.0846 = 0.309 \text{ kg},$$

or

$$\frac{0.309 \cdot 100}{1.7 + 0.1 + 2.5} = 7.2\% \text{ of substrate mass};$$

at the weight of flour 250 g:

$$0.2244 + 0.2114 = 0.4358 \text{ kg},$$

or

$$\frac{0.4358 \cdot 100}{1.7 + 0.25 + 2.5} = 9.8\% \text{ of substrate mass};$$

at the weight of flour 500 g:

$$0.2244 + 0.4229 = 0.6473 \text{ kg},$$

or

$$\frac{0.6473 \cdot 100}{1.7 + 0.25 + 2.5} = 13.8\% \text{ of substrate mass}.$$

The content of DOM of flour in DOM of substrate is:

at the weight of flour 50 g:

$$\frac{0.0423 \cdot 100}{0.2667} = 15.9\%;$$

at the weight of flour 100 g:

$$\frac{0.0846 \cdot 100}{0.309} = 27.4\%;$$

at the weight of flour 250 g:

$$\frac{0.2114 \cdot 100}{0.4358} = 48.5\%;$$

at the weight of flour 500 g:

$$\frac{0.4229 \cdot 100}{0.6473} = 65.3\%.$$

Relative moisture of the solid fraction of cow manure is 84% [31], that of flour is 15% [30], that of water is 100%. Relative moisture of the three-component substrate of this type is:

at the weight of flour 50 g:

$$W_S = \frac{1.7 \cdot 84 + 0.05 \cdot 15 + 2.5 \cdot 100}{1.7 + 0.05 + 2.5} = 92.6\%;$$

at the weight of flour 100 g:

$$W_S = \frac{1.7 \cdot 84 + 0.1 \cdot 15 + 2.5 \cdot 100}{1.7 + 0.1 + 2.5} = 91.7\%;$$

at the weight of flour 250 g:

$$W_S = \frac{1.7 \cdot 84 + 0.25 \cdot 15 + 2.5 \cdot 100}{1.7 + 0.25 + 2.5} = 89.1\%;$$

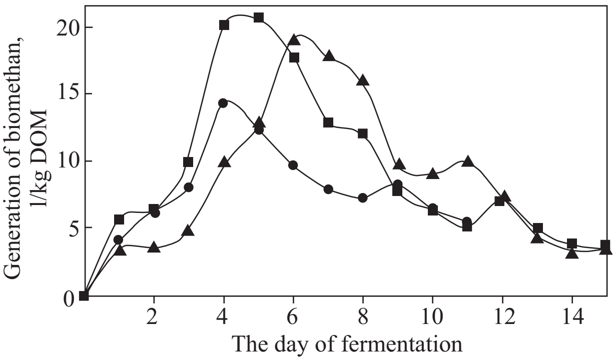
at the weight of flour 500 g:

$$W_S = \frac{1.7 \cdot 84 + 0.5 \cdot 15 + 2.5 \cdot 100}{1.7 + 0.5 + 2.5} = 85.2\%.$$

Experimental study of biogas release during the fermentation of cow manure with the addition of flour. The study of the substrate fermentation on the basis of cow manure with the addition of flour as a co-substrate was carried out to check the theses given in the papers [32, 69], [32, 88], [33, 81—82] that:

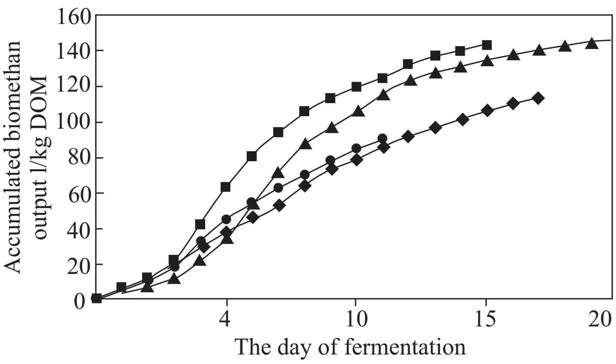
- when grains of cereals are fermented, a high release of biogas at the level of 620 m^3/t of substrate with a methane content of about 50% is provided;
- grain (or grain products) decomposes very quickly, resulting in rapid peroxidation; due to the high content of proteins in the grain, the risk of delay in the bacteria development because of the ammonia action also increases.

In addition to that, quantitative indicators of the addition of flour to methane tank are currently not sufficiently complete for obtaining maximum volumes of biogas, and thus require additional research.



The content of flour in the substrate, %: 1.2; 2.3; 5.6

Fig. 2. The biogas release during the process of cow manure fermentation with an addition of flour at a temperature of 35 °C



The content of flour in the substrate, %: 0; 1.2; 2.3; 5.6

Fig.3. Accumulated biogas release during the fermentation of the cow manure and flour mixture at a temperature of 35 °C

Experimental study of the biogas release during the fermentation of cow manure with the addition of flour was carried out at a fermentation temperature of 35 °C (in mesophilic mode). A methane tank was loaded with a portion of the substrate, which consisted of 1.7 kg of cow manure, 2.5 kg of water and 50, 100, 250 or 500 g of flour. In this case, the content of flour in the substrate was 1.2, 2.3, 5.6 and 10.6%, and the substrate moisture was 92.6, 91.7, 89.1 and 85.2% respectively

The research results are presented in Fig. 2.

As it can be seen in Fig. 2, with the fermentation of cow manure and flour mixture in all concentrations investigated, the first day of the fermentation fixes the maximum release of biogas, which subsequently gradually decreases. There is also diaxis. In some cases, it is clearly expressed, in others it is barely noticeable, for example, when the content of flour in the substrate is 1.2%.

The maximum biomethane release is 14.3 l/kg DOM, at 1.2% flour content in the substrate, 20.9 l/kg DOM, at 2.3% flour content, 19.2 l/kg DOM, at 5.6% flour content, and biogas did not burn, at 10.6% flour content.

The conversion coefficient of biomethane release from the dimension of l/kg DOM to the dimension l/kg is 15.936 kg/kg DOM, at 1.2% of the flour content in the substrate, 13.917 kg/kg COP, at 2.3% flour content, and 10.210 kg/kg DOM, at 5.6% flour content.

Accumulated biomethane release during the fermentation of the cow manure and flour mixture is shown in Fig. 3, from which it is evident that the total release of biomethane during the fermentation of the cow manure and flour mixture for 11 days of fermentation is: 89.9 l/kg DOM with a content of flour in the substrate 1.2%, 124.3 l/kg DOM at the content of flour in the substrate is 2.3%, 115.9 l/kg DOM with a content of flour in the substrate 5.6%.

Compared to pure cow manure, the release of biomethane during the fermentation of the mixture of cow manure and flour is 1.5—2 times higher in almost all investigated proportions (except for the content of flour in the substrate 10.6%). Accumulated release of biomethane during the fermentation of cow manure with the addition of flour at a fermentation temperature of 35 °C is approximated by a polynomial (3):

$$Q_{accumul} = b_n + t^n + b_{n-1} + t^{n-1} + b_1 + t + b_0, \quad (3)$$

where $Q_{accumul}$ is accumulated biomethane release, l/kg DOM; b is polynomial coefficients; t is time of fermentation, days; n is the degree of polynomial.

The coefficients of polynomial (3) are given in Table 1.

The determination coefficients of the approximated curves (3), with the coefficients of the polynomial, are given in the Table 1, defined by

[34], approaching a unit, indicating that the obtained regression equations accurately reflect the experimental data. When checking on Fisher's criterion [35] the significance of the determination coefficients is identified. Verification by Student's Criteria [35] showed that all coefficients of polynomials (3), Tabl. 1, are significant.

Biogas obtained during the fermentation of flour added to cow manure (with a content of flour in the substrate 1.2, 2.3 and 5.6%) in the first 2—3 days of fermentation (when the first peak of biogas release is observed) does not burn, on the next day it burns badly. The heat of combustion of biogas with the content of flour in the substrate 1.2% after the stabilization of the methane content is 13—14 MJ/m³, with the content of flour in the substrate 2.3% it reaches 17.5 MJ/m³, with the content of flour in the substrate 5.6% — up to 20 MJ/m³. At the contents of the flour in the substrate 10.6% biogas burning did not occur during the whole time of the experiment.

Thus at the release of biogas, the optimal amount of flour added to the substrate is 2.3%. When increasing the content of flour in the substrate over 5.6%, the burning stops.

Biomethane release model of the gradual loading during the fermentation of cow manure with the addition of flour. In. Fig. 2 it is seen that 1, the maximum release of biomethane at a fermentation temperature of 35°C is 14.3 l/kg DOM, at 2% flour content in the substrate, — 20.9 l/kg DOM, at 2.3% flour content, and 19.2 l/kg DOM, at 5,6% flour content; at 10.6%, biogas did not burn, in the absence of flour in the substrate, and the yield of biomethane was 9.3 l/kg DOM. Modelled release of biomethane during the fermentation of cattle manure with the addition of flour for the gradual load of methane during fermentation temperature of 35 °C, as obtained on the basis of the experimental results of biogas release during periodic load, is given in Fig. 4.

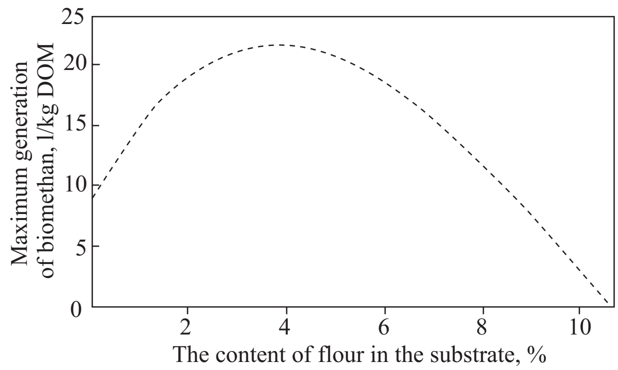


Fig. 4. Modelled release of biogas during the fermentation of cow manure with the addition of flour for the gradual loading of the methane tank

Modelled release of biomethane during the fermentation of cow manure with the addition of flour for the gradual loading of methane tank at a fermentation temperature of 35 °C is approximated by the mathematical equation:

$$Q_{mod} = 0.0381 \cdot x^3 - 1.1629 \cdot x^2 + 7.2235 \cdot x + 8.74, \quad R^2 = 0.9854, \qquad (4)$$

where Q_{mod} is modelled biomethane release for quasi-continuous methane tanks loading system, l/kg DOM; x is the content of flour in the substrate, %.

The approximation equation is valid with the content of flour in the substrate not more than 7%.

Table 1. **Coefficients of a Polynomial That Describes the Average Accumulated Release of Biomethane During the Fermentation of Cow Manure with the Addition of Flour**

No	Flour content in the substrate, %	The coefficients of a polynomial					R^2
		b_4	b_3	b_2	b_1	b_0	
1	0	—	–0.0183	0.3067	6.7662	–1.68	0.999
2	1.2	0.016	–0.4327	3.6303	–0.7284	0.42	0.9989
3	2.3	0.015	–0.503	4.9478	–2.0793	0.59	0.9981
4	5.6	0.0053	–0.2459	3.3486	–3.6649	1.06	0.9975

As can be seen in Fig. 4, when the flour is added to the substrate, the biomethane release increases and reaches the maximum value at the content 2.3% of flour in the substrate. When more flour is added to the substrate, the biomethane release begins to decrease, and when the flour content reaches 10.6% stops.

Determination coefficient of the approximated function (4), determined by [34] that describes the modelled release of biomethane during the fermentation of cow manure with the addition of flour for the gradual loading of the methane at a fermentation temperature of 35 °C, approaches a one, indicating that the obtained regression equation accurately reflects experimental data. When checking by Fisher's criterion [35] the significance of the determination coefficient was introduced. Verification by Student's Criteria [35] showed that the coefficients of the polynomial are significant.

To find the extremum (maximum) of function (4), we use the half-division method (dichotomy method) using the Internet calculator [36] in the following formulation of this problem:

Required in the interval $0 < x < 7$ (watch Fig. 4) to find the maximum of function $f(x) = -0.038x^3 - 1.16x^2 + 7.22x + 8.74$ when the accuracy of the solution is $\varepsilon_n < 0.1$ and the increment step $\delta = 0.01$. For this purpose, the objective function (4) can be represented as: $F(\max) = -F(\min)$, that is:

$$F_{(max)} = -0.0385 \cdot x^3 + 1.16 \cdot x^2 - 7.22 \cdot x - 8.74.$$

Solution of the mathematical problem using dichotomy method: choose the increment step $\delta = 0.01$.

Suppose $a_1 = a$, $b_1 = b$. Thus:

$$x_1 = (0 + 7 - 0.01) / 2 = 3.495,$$

$$x_1 = (0 + 7 + 0.01) / 2 = 3.505.$$

Calculate $f(x_1) = -21.40782655$, $f(x_1) = -21.41266031$,

$$\varepsilon_1 = \frac{b - a - \delta}{2^n} + \frac{\delta}{2} = \frac{7 - 0 - 0.01}{2^{1+1}} + \frac{0.01}{2} = 1.7525.$$

Iteration No 1. Since $f(x_{11}) > f(x_{12})$, то $a_2 = 3.505$, $b_2 = b_1$.

$$\varepsilon_2 = \frac{7 - 3.505 - 0.01}{2^{2+1}} + \frac{0.01}{2} = 0.440625,$$

$$x_{11} = (3.505 + 7 - 0.01) / 2 = 5.2475,$$

$$x_{12} = (3.505 + 7 - 0.01) / 2 = 5.2575,$$

$$f(x_{21}) = -20.1287, f(x_{22}) = -20.1103.$$

Iteration No 2. Since $f(x_{21}) > f(x_{22})$, то $b_3 = 5.2475$, $a_3 = a_2$.

$$\varepsilon_3 = \frac{5.2475 - 3.505 - 0.01}{2^{3+1}} + \frac{0.01}{2} = 0.11328125,$$

$$x_{21} = (3.505 + 5.2475 - 0.01) / 2 = 4.37125,$$

$$x_{22} = (3.505 + 5.2475 + 0.01) / 2 = 4.38125,$$

$$f(x_{31}) = -21.2775, f(x_{32}) = -21.2699.$$

Iteration No 3. Since $f(x_{31}) > f(x_{32})$, то $b_4 = 4.3713$, $a_4 = a_3$.

$$\varepsilon_3 = \frac{4.37125 - 3.505 - 0.01}{2^{4+1}} + \frac{0.01}{2} = 0.03175781,$$

$$x_{31} = (3.505 + 4.37125 - 0.01) / 2 = 3.933125,$$

$$x_{32} = (3.505 + 4.37125 + 0.01) / 2 = 3.943125,$$

$$f(x_{41}) = -21.4796, f(x_{42}) = -21.478.$$

Iteration No 4. Since $f(x_{41}) > f(x_{42})$, то $b_5 = 3.9331$, $a_5 = a_4$.

$$\varepsilon_3 = \frac{3.933125 - 3.505 - 0.01}{2^{5+1}} + \frac{0.01}{2} = 0.0115332,$$

Table 2. **Results of the Step-By-Step Solution of the Problem Using the Dichotomy Method**

n	a_n	b_n	b_n-a_n	x_{n1}	x_{n2}	$F(x_{n1})$	$F(x_{n2})$	ε_n
1	0	7	3.5	3.495	3.505	–21.4078	–21.4127	1.7525
2	3.505	7	3.495	5.2475	5.2575	–20.1287	–20.1103	0.4406
3	3.505	5.2475	1.7425	4.3713	4.3813	–21.2775	–21.2699	0.1133
4	3.505	4.3713	0.8663	3.9331	3.9431	–21.4796	–21.478	0.03176
54	3.505	3.9331	0.4281	3.7141	3.7241	–21.4792	–21.4807	0.01153

$x_{31} = (3.505 + 3.933125 - 0.01) / 2 = 3.7140625,$

$x_{32} = (3.505 + 3.933125 + 0.01) / 2 = 3.7240625,$

$f(x_{51}) = -21.4792, f(x_{52}) = -21.4807.$

The remaining calculations are summarized in Table 2.

Since at iteration No. 5 the condition is satisfied for a given accuracy of the result of the problem solving, i.e. $|-21.47881363 - (-21.47994443)| \leq \leq 0.1$, we find x as the middle of the interval $[a, b]$: $x = (3.933125 + 3.505) / 2 = 3.7190625$. Thus, provided

$$\varepsilon_n = \frac{b-a-\delta}{2^n} + \frac{\delta}{2} = \frac{3.933125 - 3.505 - 0.01}{2^{4+1}} + \frac{0.01}{2} = 0.440625,$$

$$x = 3.7190625, f(x) = 21.47994443.$$

According to experimental data, for the gradual loading of methane tank, the optimum content of flour in the substrate is 3.7%. According to the proposed model, it is possible to recommend rational content of flour in the substrate within the limits of 2.3—4.2%.

On the basis of the research conducted the following results were obtained:

- the maximum release of biomethane for the periodic loading of the substrate is determined, which is 14.3 l/Kg DOM at 1.2% of the flour content in the substrate; 20.9 l/kg DOM at 2.3%; 19.2 l/kg DOM at 5.6%; adding 10.6% of flour to the substrate causes the fermentation to stop;
- a new model of biomethane release was developed during the fermentation of cow manure with the addition of flour-based Newton polynomial of the second order and a new approach was developed for optimizing fermentation of cow manure with the addition of flour based on the use of the dichotomy method;
- an optimal content of flour in the substrate is determined for the gradual loading of the methane tank, that is 3.7%;
- the recommendations on the rational content of flour in the substrate within the limits of 2.3—4.2% were substantiated, within these limits the biomethane release during the fermentation of the mixture of cow manure and flour is increased by 1.5 times.

Prospects for further research in this direction are the preliminary rotor-pulsation (cavitational) treatment of non-standard grain and its mixing with cow manure and other agricultural waste to increase the release of biomethane. A promising direction is also the development of a method for intensifying anaerobic fermentation processes [37], based on the effect of a rotating magnetic field on aqueous substrates of biomass waste.

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Received 27.03.19
Revised 12.06.19
Accepted 16.09.19

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ПІДВИЩЕННЯ ВИХОДУ БІОГАЗУ ПРИ ЗБРОДЖУВАННІ ГНОЮ ВЕЛИКОЇ РОГАТОЇ ХУДОБИ НА ОСНОВІ РАЦІОНАЛЬНОГО ДОДАВАННЯ НЕКОНДИЦІЙНОГО БОРОШНА В ЯКОСТІ КОСУБСТРАТУ

Вступ. Важливим господарським питанням є переробка відходів тваринництва і сільськогосподарського виробництва не тільки для покращення екологічної безпеки, а й для отримання енергетичних ресурсів.

Проблематика. Коров'ячий гній застосовується для отримання біогазу, однак його вихід при цьому відносно низький. Одним із шляхів підвищення виходу є спільне зброджування коров'ячого гною з некондиційним борошном, яке не можна використовувати як продукт харчування для людини та як корм для сільськогосподарських тварин. Проте вміст його в субстраті, при якому вихід біогазу є максимальним і не відбувається інгібування процесу метанового бродіння, не визначено.

Мета. Підвищення виходу біогазу шляхом раціонального додавання некондиційного борошна до субстрату на основі коров'ячого гною.

Матеріали й методи. Дослідження виходу біогазу при метановому зброджуванні субстрату на основі коров'ячого гною з додаванням некондиційного борошна здійснювали на біогазовій установці у складі метантенка робочим об'ємом 30 л і мокрого газгольдера при періодичному режимі завантаження субстрату і температурі бродіння 35 °C. Порція субстрату: 1,7 кг гною, 2,5 кг води та 50, 100, 250 або 500 г борошна. При цьому склад борошна в субстраті становив 1,2 , 2,3%, 5,6% та 10,6 %. Для визначення оптимального вмісту борошна в субстраті, за умови максимального виходу біогазу, було застосовано метод дихотомії.

Результати. Максимальний вихід біометану при вмісті 1,2 % борошна в субстраті становить 14,3 л/кг сухої органічної речовини (СОР), при 2,3 % — 20,9 л/кг СОР, при 5,6 % — 19,2 л/кг СОР. При вмісті 10,6 % борошна в субстраті біогаз не горів, бродіння швидко припинялося. Оптимальний вміст борошна в субстраті на основі коров'ячого гною, при якому вихід біогазу збільшується в 1,5 рази, становить 3,7 %.

Висновки. На основі проведених експериментальних досліджень побудовано модель виходу біогазу при поступовому завантаженні субстрату та визначено оптимальний вміст борошна в субстраті, при якому забезпечується максимальний вихід біогазу.

Ключові слова: біогаз, метантенк, некондиційне борошно, гній великої рогатої худоби, біогазова установка, метанове бродіння.