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STUDY OF BIOGAS DURING FERMENTATION OF CATTLE MANURE USING A STIMULATING ADDITIVE IN FORM OF VEGETABLE OIL SEDIMENT

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ABSTRACT

This article presents the design and implementation of an experimental biogas plant, which consists of a digester with a useful volume of 30 l and a wet gas tank. The main contribution of this work is the provision of a new tool in the field of biogas production by controlling the loading of the substrate into the digester. The substrate is prepared by mixing a measured amount of cattle manure with water and a vegetableoilsediment. As a result of the experimental study, it was established that the rational cycle of the fermentation of cattle manure is 13-14 days, a mixture of cattle manure and orhanat - 9-10 days. Biogas output increases with increasing fermentation temperature. For 14 days of fermentation, the average accumulated output of biogas during the fermentation of cattle manure at a fermentation temperature of 55 °C is 336 l/kg of dry organic matter (*DOM*), at a fermentation temperature of 50 °C is 283 l/kg *DOM*, 45 °C is 257 l/kg *DOM*, 40 °C is 184 l/kg *DOM*. Cattle manure after feeding livestock with silage and concentrated feed generates a slightly higher output of biogas compared to cattle manure after feeding livestock with straw based feed. The total volume of biogas obtained during the fermentation of the mixture of cattle manure and orhanat is higher than when the pure cattle manure is fermented. At the same time, a unit of *DOM* of pure cattle manure gives a greater output of biogas compared with a unit of DOM of a mixture of cattle manure and orhanat. When fermenting a mixture of cattle manure and orhanat at a temperature of 45 °C, it turns out 195.7 l/kg *DOM* of biogas, 45 °C - 175.7 l/kg *DOM* of biogas. The average calorific value of biogas obtained during the fermentation of cattle manure is in the range of 12-17 MJ/m^3. The biogas obtained during the fermentation of a mixture of cattle manure and orhanat does not burn at all at the initial stage of fermentation (2-5 days). In the next few days, the burning of biogas is very weak. At the same time in atmosphere of the laboratory room, there is a persistent smell of hydrogen sulfide. Subsequently, combustion is normalized and the calorific value of biogas approaches standard values.

Keywords: biogas, substrate, cattle manure, dry matter, digester, biogas plant, methane fermentation.

1. INTRODUCTION

Cattle manure often used for the receipt of biogas. It is accessible substrate that already contains in the composition of methane-producing bacteria that improves the process of methanogenesis. Substrates from cattle manure have ideal indexes (pH, correlation of nitrogen and carbon of and other) for the vital functions of association of methane-producing bacteria. At the same time, because of presence in manure of plenty of raw cellulose, the biogas yield at his fermentation is relatively subzero. For the increase of biogas yield is practiced joint fermentation of cattle manure with agricultural raw material: by green mass and silo of grass, corn, by her mixture with the sunflower of and other.

At the same time, this raw material can be used as a feed for agricultural animals and foodstuffs for a man. Therefore, for the improvement of biogas yield from manure it is desirable to use more cheap raw material as wastes of productions, at the same time costs of their utilization decrease. Suchrawmaterials include crudegly cerinandvegetableoilsediment, which are obtained in the production of biodiesel, as describedinscientificarticles (Pasae Y. *et al*, 2016; Pasae Y., 2017; Pasae Y. *et al*, 2019 and Pasae Y. *Et al*, 2020).

2. LITERATURE REVIEW

In work (Lijo L. *et al*, 2017) it is stated that biogas yield from animal manure is 450 m^3/kg *VS* (VS-volatile fatty acids), which is significantly less compared to biogas output during fermentation of corn silage (650 m^3/kg *VS*) or food waste (660 m^3/kg *VS*). Smaller biogas output during the fermentation of cattle manure compared with corn silage was also confirmed in (Bilandzija N. *et al*, 2013). At the same time, the yield of biogas during the fermentation of cattle manure (0.31 m^3/kg *VS*), as stated in (Samuna I. *et al*, 2013), is higher compared to the digestion of food waste (0.17 m^3/ kg *VS*), and in (Rahman K. M. *et al*, 2018) compared with bird droppings and straw (0.034, 0.030, and 0.142 m^3/kg, respectively). The content of methane in biogas is 60% and 62% and 74%, respectively. In (Guarino G. *et al*, 2014), the optimum pH for the fermentation of cattle manure was determined to be 7.0, the process temperature was 37 °C. Preliminary heat treatment of manure reduced the biogas yield; machining did not affect the biogas output systematically. In (Ren Z. *et al*, 2012; Xiong X. F. *et al*, 2015), the fermentation of bovine manure at a temperature of 35 °C was evaluated. It was found that biogas production exceeded 0.3 m^3/kg *DM*

ARPN Journal of Engineering and Applied Sciences

(*DM* - dry matter). The methane content in biogas was about 60% after 6 days of fermentation.

The best indicators of biogas production, as noted in (Sumardiono S. *et al*, 2018), were recorded at a fermentation temperature of 39.5 °C, and in (Hupfauf S. *et al*, 2018) 45 °C, with an average methane yield of 166 l/kg *VS*, which is 12.8% 9.6% higher than at 37 °C and 55 °C. The study (Yu D. *et al*, 2014) describes the study of the composition of the methanogenic community in the digester at the mesa- (35-37°C) and thermophilic (55-57 °C) modes. During the entire thermophilic mode, the number of bacterial cells was observed 6.25 times more than the number of archaeal cells, while the ratio of the number of cells in the mesophilic process ranged from 0.2 to 8.5. This suggests that the thermophilic process is more stable, but also that the relative abundance between bacteria and archaea can vary without seriously affecting the production of biogas. As noted in (Kerroum D. *et al*, 2014), a change in fermentation conditions from mesophilic (T = 35 °C) to thermophilic (T = 55 °C) leads to an increase in the biogas yield from 0.18-0.29 m^3/m^3·day to 0.39-0.96 m^3/m^3 day. In (Hu Y. *et al*, 2018), it was noted that with an increase in the organic load of up to 7.3 kg of *COC*/m^3·day (*COC* - chemical oxygen consumption) in the mesophilic mode (37 °C), the biogas yield decreased, which is not observed in the thermophilic mode (55 °C). The digestion of fat wastes was studied in (Orive M. *et al*, 2016), where a study was presented on the joint digestion of pig manure and vegetable oil sediment from olive oil production in the mesophilic mode (37 °C) with methane output, which ranged from 150.9 l/kg *VS*·day to 274.3 l/kg *VS* per day, in work (Grosser A. *et al*, 2013) of dry organic matter and vegetable oil waste at the same temperature with a biogas yield of 0.16 dm^3/kg *VS* to 0.32 dm^3/kg *VS*. In the work (Kurade M. B. *et al*, 2019) it is noted that the excessive addition of fats to the substrate at the initial stage reduced the methanogenic activity, however in the future the production of biogas increased by 21.7%. In the study (Awe O. W. *et al*, 2018) it is indicated that when loading a digester at 2.0 kg *VS*/l per day, the addition of 5% fat caused cessation of fermentation, whereas at 4.0 kg *VS* / l ·day the process remained stable for 10 days to accumulate volatile fatty acids (*VFA*), which caused a decrease in pH and, thus, reduced the production of biogas.

Adding NaOH to reactivate reactors only improved the pH value, but did not significantly affect biogas production and the concentration of *VFA*. An effective solution was achieved by recycling 50% of the digestate of the reactors, which led to an increase in biogas yield and stable operation of the reactors. The maximum allowable fat load from the grease trap during the fermentation of waste together with dry organic matter, as indicated in (Razaviarani V. *et al*, 2013), was 23%. At the same time, the output of biogas was 67% more than when fermenting only waste of dry organic matter. Mixing food waste and fat from a grease catcher with a lipid content of 55% and loading them at 1.61 kg/l per day, was proved expedient in (Wu L. J. *et al*, 2018), and the maximum methane yield increased by 68% compared to mono-digestion of food waste. The ratio of fats and food waste 50:50, with a content of 85% lipids and 15% protein, as indicated in (Ohemeng-Ntiamoah J. *et al*, 2018), gave a high methane yield of 1040 ml/h *VS* (versus 118 ml/h *VS* with food waste mono fermentation). In (Alqaralleh R. M. *et al*, 2016), it was found that, in a hyper thermophilic mode (70 °C), the addition of 60% of fats in a dry organic matter significantly increases the maximum methane production of 673.1 ± 14.0ml compared to 316.4 ± 14.3 ml of methane during the mono fermentation of dry organic matter. Since mono-fermentation of vegetable oil inhibits anaerobic degradation, the results of mixing it with pig manure were described in (Hidalgo D. *et al*, 2014). The methane yield was 0.3 m^3/kg *VS* with equal mixing of the components and 0.22 m^3/kg *VS* with a three-fold advantage in adding manure.

So, from the analysis of previous studies it follows that the output of biogas from cattle manure in different sources was estimated in different units, which complicates systematization: from 287 to 450 m^3/kg *VS*·day, 0.31 m^3/kg, 0.3 m^3/ kg *DOM* (*DOM* - dry organic matter), 58.6 m^3/t, methane yield coefficient from 0.13 to 0.20 l/h of *COC*, and with the addition of grease waste from 150.9 to 274.3 l/kg *VS*·day, from 0.16 dm^3/*VS* to 0.32 dm^3/kg *VS*, 0.22-0.3 m^3/kg *VS*, 1040 ml/kg *VS*. The average yield of methane during the fermentation of pure cattle manure is 55-60%. It is noted that the excessive addition of fats to the substrate at the initial stage inhibited the methanogenic activity, but in the future the production of biogas increased by 21.7%. Improving biogas yield contributes to the recycling of 50% of digestate reactors. Studies have shown an increase in biogas yield when adding up to 23% of fat to the substrate. Some studies indicate that the optimum substrate temperature during fermentation should be 39.5 °C or 45 °C, but most researchers express the opinion that the biogas yield in the thermophilic mode is higher than in the mesophilic mode. An analysis of the research shows that further research is needed on the intensification of biogas and electricity output based on the digestion of cattle waste with stimulating additives. At the same time, in the works considered above, the biogas yield was estimated only according to experimental data, which requires considerable time and cost, especially with periodic loading of substrates. Although in the present more modern biogas plants operate in the system with gradual loading. One of the approaches to eliminate these drawbacks is the use of mathematical models for predicting the yield of biogas during the transition from periodic to gradual loading of the digester.

The aim of the work is to increase the yield of biogas and electricity output from cattle manure by adding a stimulating additive in the form of vegetable oil sediment during the transition from periodic to gradual loading of the digester. To achieve this goal, it is necessary to solve the following tasks: to determine the output of biogas from cattle manure at different temperatures with periodic loading of the digester; to

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estimate the output of biogas during the fermentation of cattle manure with the addition of vegetable oil sediment, using the mathematical model in the MatLab-Simulink package, to predict the output of biogas and electricity for continuous loading of the digester.

3. MATERIALS AND METHODS

The studies were carried out on a laboratory biogas plant consisting of a methane tank with auseful volume of 30 liters and a wet gas tank (Figure-1). The digester I consists of an outer and an inner shell, between which a water shirt with an electric heater is placed. The water shirt serves to transfer heat to the substrate, which is housed in the inner casing. Fresh substrate is fed into the active area of the digester through a pipe that reaches almost to the bottom. Therefore, a fresh substrate is fed to the lower part of the digestion core, thereby displacing the waste digestate through a pipe that is located at the level of the substrate and biogas.

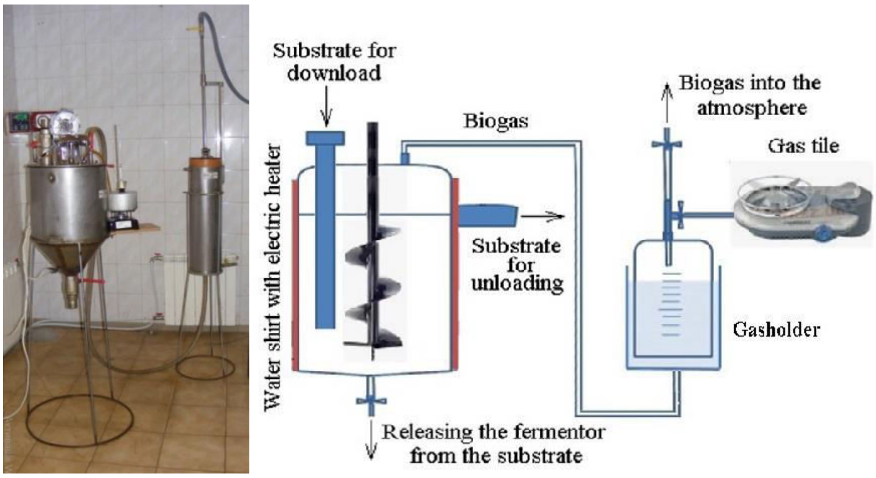


Figure-1. Laboratory biogas plant.

In order to preserve the microflora of the complex of methane-forming bacteria, it is necessary to keep at least 1/3 of the spent digestate in it when refueling the digester in order to preserve the culture of bacteria. To drain the entire digestate during maintenance of the digester, there is a pipe located in the lower cone of the fermenter. The output of biogas is fixed by raising the cylinder level gauge of a wet gasholder using a scale fixed on it, calibrated in centimeters.

Biogas is burned on a gas stove, while heating water in a calorific value meter. If necessary, it can be dumped into the atmosphere.

The mode of loading the substrate in the methane tank is periodic. The substrate is prepared by mixing a measured amount of cattle manure with water. In some experiments, vegetable oil sediment was added to the cattle manure. The digester is filled with 3/4 substrate. When laying a new experience changes not more than 1/3 of the volume of the substrate to save the community of methanogens. The output of biogas is fixed by raising the cylinder of a wet gasholder using a scale fixed on it, calibrated in centimeters.

In most literary sources, the yield of biogas from the substrate is estimated in l/kg DOM. Therefore, in order to be able to compare the obtained results with data from literary sources, we translate the obtained results into the dimension l/(h-kg *DOM*). To do this, determine the mass of dry matter of the substrate, which is loaded into the digester, according to the formula:

$$M_{DMs} = \frac{M_s \cdot DM}{100}, \tag{1}$$

where M_{DMs} – the dry matter mass of the substrate, kg; M_s – mass of the substrate, kg; DM – the dry matter content in the substrate, %.

$$M_{DOMs} = \frac{M_{DMs} \cdot DOM_{DM}}{100}, \tag{2}$$

where M_{DOMs} – the dry organic matter mass of the substrate, kg; DOM_{DM} –the content of dry organic matter in the dry matter of the substrate, %.

If the percentage of dry organic matter in the substrate is known, then the mass of the dry organic matter of the substrate that is loaded into the methane tank is determined by the formula:

$$M_{DOMs} = \frac{M_{DMs} \cdot DOM}{100}, \tag{3}$$

where M_{DOMs} – the dry organic matter mass of the substrate, kg; DOM– the content of dry organic matter in the substrate, %.

ARPN Journal of Engineering and Applied Sciences

Then the performance of the digester for biogas, related to the content in the substrate of dry organic matter, is determined by the formula:

$$Q_{b/DOM} = 10^{-3} \cdot \frac{Q_b}{M_{DOMs}}, \tag{4}$$

where $Q_{b/DOM}$ – biogas digestion capacity, related to the content in the substrate of dry organic matter, l/(h-kg *DOM*); Q_b - biogas digester performance, cm^3/h.

The relative humidity of the substrate consisting of several components with a known relative humidity of these components is determined by the formula:

$$W_s = \frac{m_1 \cdot W_1 + m_2 \cdot W_2 + ... + m_n \cdot W_n}{m_s}, \tag{5}$$

where W_s – the relative humidity of a multicomponent substrate, %; W_1, W_2, W_n – relative humidity of the 1st, 2nd, nth component of the substrate, %; m_s – the mass of multicomponent substrate, kg; m_1, m_2, m_n - the mass of the 1st, 2nd, nth component of the substrate, kg.

The heat of combustion of biogas is determined by its elemental composition according to the formula of Mendeleev:

$$Q_l = 128CO + 108H_2 + 234H_2S + 339CH_4 + 589C_nH_m, \tag{6}$$

where Q_l – the lowest heat of combustion of biogas, kJ/m^3; CO, H_2, CH_4, C_nH_m – the composition of the gaseous fuel, the percentage by volume under normal conditions (0 °C, pressure 760 mm Hg).

The elemental composition of biogas is determined by the GEM-500 gas analyzer.

In some cases, the heat of combustion was determined by the express method with the energy expended on heating a standard volume of water.

4. RESULTS AND DISCUSSIONS

4.1 Investigation of Biogas Output during Fermentation of Cattle Manure

In the digester loaded portion of the substrate weighing 8.5 kg, which consisted of 3.5 kg of cattle manure and 5.0 kg of water. The solid fraction of cattle manure contains 16.4% *DM*, of which about 80% is *DOM*.

Then the mass of the *DM* substrate according to the formula (1) is:

$$M_{DMs} = \frac{3.5 \cdot 16.5}{100} = 0.587 \text{ kg} \tag{7}$$

and the mass of the substrate *DOM* according to the formula (3):

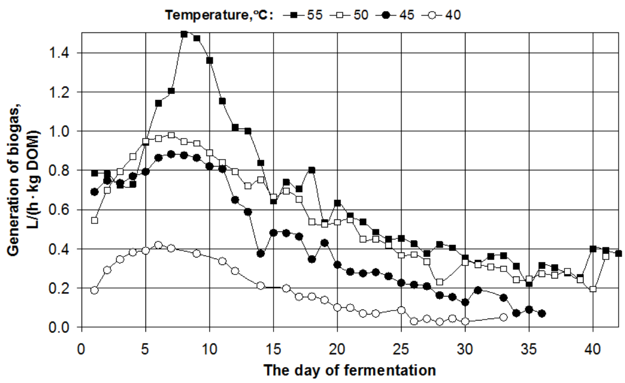
$$M_{DOMs} = \frac{0.587 \cdot 80}{100} = 0.462 \text{ kg}. \tag{8}$$

The relative humidity of the solid fraction of cattle manure is 84%, the relative humidity of water is 100%. The relative humidity of such a two-component substrate according to the formula (5) is:

$$W_s = \frac{3.5 \cdot 84 + 5.0 \cdot 100}{8.5} = 93.4\%. \tag{9}$$

The temperature mode of the digester in the study was set at 40 °C, 45 °C, 50 °C and 55 °C, that is, the studies were carried out in mesophilic and thermophilic modes. Studies were conducted in three repetitions. The research results are presented in Figure-2.

It has been established that in all temperature modes there is observed a fermentation process that is typical for periodic loading of the digester, which includes the lag phase (habituation phase), the logarithmic phase, the stationary phase, and the withering phase of bacteria. However, at a higher fermentation temperature, the time of the logarithmic phase and the initial stage of the withering phase decreases, which provides for the intensification of fermentation. The stationary phase is very short; it is even difficult to select it. When the fermentation temperature decreases, the areas corresponding to the logarithmic phase and the initial stage of the withering phase become gentler, and the stationary phase is easier to select. The final stage of the withering phase for all studies continued for a long period of time and was not completed with the end of the experiments. The lag phase was observed only at the fermentation temperature of 55 °C in the first repetition.



a)

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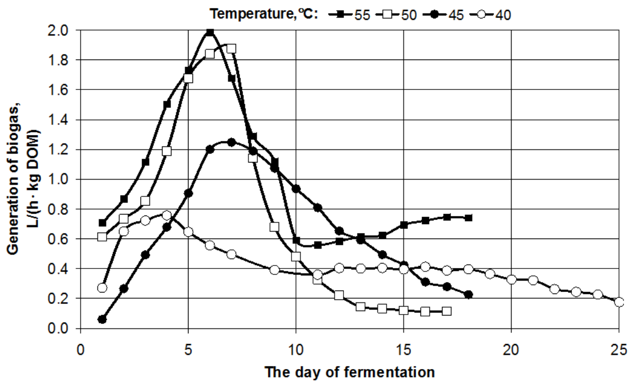

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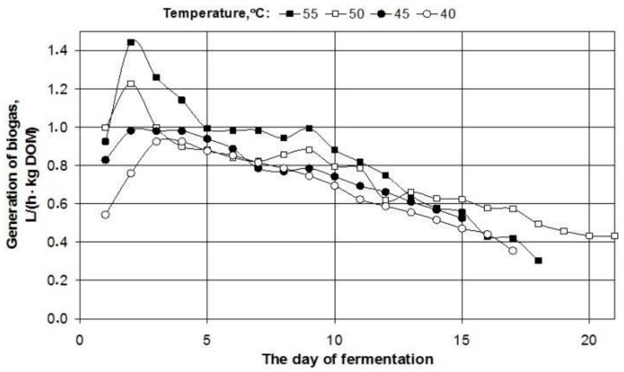

c)

Figure-2. Dynamics of biogas output during the fermentation of cattle manure for various temperature regimes of the digester: a- first repetition; b- second repeat; c- third repeat.

At the same time, biogas generation was uneven: it grew in the logarithmic phase, was uniform in the short stationary phase and decreased in the withering phase. This type of biogas generation is characteristic of any temperature mode of the digester with a periodic method of its loading. Since the withering phase lasts a very long time and is characterized by a low biogas yield, it is advisable to stop the fermentation cycle for 5-6 days after the withering phase begins. That is, the whole fermentation cycle (rational fermentation cycle) will last 13-14 days.

The maximum output of biogas during the fermentation of cattle manure is induced in the Table-1.

The dependence of the average maximum biogas yield on the fermentation temperature is shown in Figure-3. Coefficient of conversion from the dimension of biogas output l/(h·kg *DOM*) to the dimension l/(h·kg) - 18,398 kg/kg *DOM*.

In practice, on operating biogas plants, the periodic loading of the digester is rarely used; more often a gradual loading mode is used, when the substrate is loaded into the digester in small portions after a certain period of time (usually about 1 hour). At the same time, the output of biogas reaches the maximum value that can be achieved with a periodic loading system and is kept at such level throughout the entire operating time of the biogas plant (Figure-3). Therefore, on the basis of experiments with a periodic loading system of the digester, it is possible to simulate the output of biogas with a gradual loading system, which will be close to the maximum biogas yield with a periodic loading system.

Table-1. Maximum output of biogas during the fermentation of cattle manure.

Fermentation temperature, °C	Maximum output of biogas, l/(h.kg *DOM*)			
	Repeat 1	Repeat 2	Repeat 3	The average
40	0.419	0.788	0.925	0.701
45	0.882	1.248	0.982	1.037
50	0.979	1.876	1.226	1.360
55	1.493	1.982	1.443	1.639

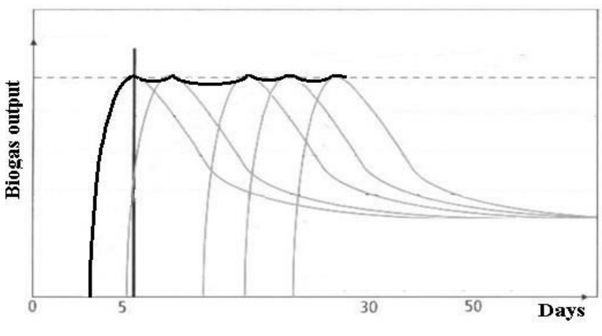

Figure-3. Scheme of biogas yield modeling with gradual (continuous) loading of the digester based on biogas yield data with periodic loading of the digester, the modified image from (Schulz H., 1996, Figure-2).

A mathematical model describing in time the processes of development of methanogenic bacteria (C), the concentration of nutrients in the substrate (S) and the generation of biogas (V) will look like:

$$\begin{cases} \dfrac{dC}{dt} = \left(\dfrac{\mu_m \cdot S}{a+S} - \dfrac{\mu_d \cdot b}{b+S} - p \right) \cdot C, \\ \dfrac{dS}{dt} = p \cdot (S_0 - S) - \left(\alpha \cdot \mu_m \cdot C + \dfrac{\beta \cdot S \cdot \mu_m}{a+S} \cdot C + \dfrac{k}{\rho_6} \cdot \dfrac{dV}{dt} \right), \\ \dfrac{dV}{dt} = \gamma \cdot S, \end{cases} \tag{10}$$

where C - the bacteria concentration, kg/m^3; S - the nutrient concentration in the substrate, kg/m^3; V - biogas yield, m^3/kg; μ_m and μ_d - the maximum possible relative rates of growth and death of bacteria, day^{-1}; α, β - the dimensionless substrate absorption rates; p - the relative rate of substrate entry, day^{-1}; γ -the coefficient of conversion of substrate nutrients into biogas, m^3/(day·kg/m^3); a - a constant that is numerically equal to a concentration of a substance at which the growth rate reaches half the limit, kg/m^3; b - empirical coefficient, kg/m^3; dV/dt -biogas yield change over time, m^3/(kg·h.).

The initial conditions for solving a system of differential equations are:

- the initial biomass concentration of methane-forming bacteria C_0 in the digester - 1 kg/m^3;
- the initial concentration of nutrients in the substrate S_0 was determined from the results of experimental studies: 8.5 kg of the substrate was loaded into the methane tank with a working volume of 30 l incl. 3.5 kg of cattle puts and 5 kg of water; consequently $S_0 = 3.5/(30 \cdot 1000) = 115$ kg/m^3;
- initial biogas yield V_0 - 0 m^3/kg·day.

In the Simulink package integrated into the MatLab program, a simulation was carried out of the biogas generation process, which is described by the system of differential equations (10). The density of biogas in the system of differential equations (10) is determined by the formula:

$$\rho_b = \frac{\sum \rho_k \cdot A_k}{\sum A_k}. \tag{11}$$

If biogas consists of 60% methane and 40% carbon dioxide, then its density according to the formula (11) will be:

$$\rho_b = \frac{0.7 \cdot 60 + 1.98 \cdot 40}{60 + 40} = 1.212 \text{ kg/m}^3.$$

Taking into account the fact that 0.27 g of methane is formed with 1 g of acetic acid, the nutrient conversion factor of the substrate into biogas is taken as k = 0.27.

In the case of periodic loading of the digester, the relative rate of arrival of the substrate $p = 0$ day^{-1}.

The simulation model (10) assumes the output of biogas in dimensions of m^3/kg, whereas as a result of experimental studies, we obtained dependences of the output of biogas with dimensions l/ (h.kg *DOM*). To bring the results of experimental studies to the dimension of the simulation model, we used the formula:

$$V_b\left(m^3 / kg\right) = \frac{V_b\left(m^3 / (h. \cdot kg\ DOM)\right)}{K \cdot 100}, \tag{12}$$

where K - the coefficient of biogas output conversion from dimension l/(h·kg *DOM*) to dimension l/(h.·kg).

For mono-fermentation of cattle manure K =18.398 kg/kg *DOM*, for co-fermentation of cattle manure with 1.3% vegetable oil sediment - 15.828kg/kg *DOM*.

By selecting parameters μ_m, μ_d, a, b, α, γ the simulated model was achieved to be closest to the dependence of the biogas yield in time obtained experimentally.

In the simulation of all substrates, it was assumed that the dimensionless coefficients of substrate assimilation took the values α =10^{-9}, β =25, b =20 kg/m^3. Coefficients μ_m, μ_d and γ were determined by selecting and comparing simulation data with experimental data to obtain the lowest possible coefficient of determination R^2.

The coefficients of the simulation model of biogas output during the mono fermentation of cattle manure for different fermentation temperatures are given in Table-2.

Table-2. Coefficients of a simulation model of biogas output during mono-digestion of cattle manure for various fermentation temperatures.

Fermentation temperature, °C	μ_m, day^{-1}	μ_d, day^{-1}	γ, m^3/(day·kg/m^3)	R^2
40	0.4	0.1	0.000008	0.9743
45	0.37	0.09	0.0000116	0.9640
50	0.33	0.076	0.0000147	0.9274
55	0.25	0.06	0.000018	0.9352

The coefficients μ_m, μ_d and γ in the Table-2 are described by second-order Newton polynomials:

$$\mu_m = -0.0001 \cdot t^2 + 0.0021 \cdot t + 0.4765 \text{ when } R^2 = 0.9993; \tag{13}$$

$$\mu_d = -0.00006 \cdot t^2 + 0.003 \cdot t + 0.075 \text{ when } R^2 = 0.9930; \tag{14}$$

$$\gamma = -3 \cdot 10^{-9} \cdot t^2 + 9.47 \cdot 10^{-7} \cdot t + 2.5 \cdot 10^{-5} \text{ when } R^2 = 0.9994. \tag{15}$$

The coefficients of a simulation model of biogas output during the fermentation of cattle manure with the addition of vegetable oil sediment at a fermentation temperature of 40 °C are given in Table-3.

Table-3. The coefficients of the simulation model of the output of biogas during the Fermentation of cattle manure with the addition of vegetable oil sediment at a fermentation temperature of 40 °C.

Content, %	μ_m, day^{-1}	μ_d, day^{-1}	γ, m^3/(day·kg/m^3)	R^2
Vegetableoilsediment				
1.3	0.114	0.034	0.000023	0.9869

Since the coefficients of determination of the simulation model of biogas output during mono fermentation of cattle manure and fermentation of cattle manure with the addition of vegetable oil sediment approach to 1, they accurately reflect the experimental data. When checking by the Fisher criterion, the significance of the coefficient of determination is established.

The simulated biogas output during the fermentation of cattle manure for a gradual system of loading the digester is shown in Figure-4.

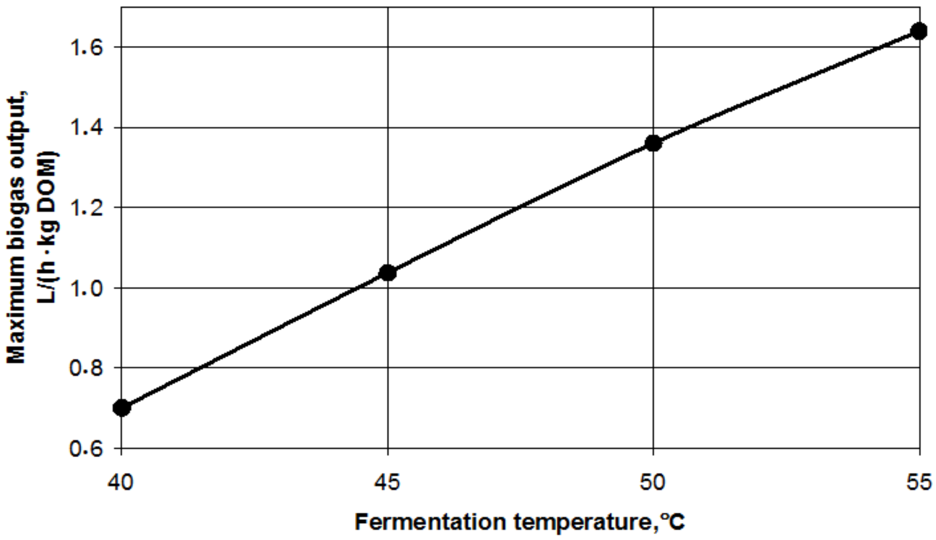

Figure-4. Simulated biogas output during the fermentation of cattle manure for a quasicontinuous digester loading system.

A simulated biogas output during the fermentation of cattle manure for a quasi-continuous system of loading the digester is approximated by a linear function:

$$Q_{b\,\mathrm{mod}} = 0.0628 \cdot T - 1.8 \quad \text{at} \quad R^2 = 0.9982, \tag{16}$$

where $Q_{b\,\mathrm{mod}}$ – the simulated biogas output for a step-by-step digester loading system., l/kg *DOM*; T – fermentation temperature,°C.

The coefficient of determination of the approximated linear function (16), describing the simulated biogas output during the fermentation of cattle manure for a gradual system of loading the digester, approaches to 1, which suggests that the obtained regression equation accurately reflects the experimental data. Another characteristic of methane fermentation of raw materials in the digester is the cumulative yield of biogas. The average value of the cumulative biogas yield during the fermentation of cattle manure within the same temperature mode is shown in Figure-5.

From Figure-5 it is possible to compare the average accumulated biogas yield for different temperature regimes of the digester. Thus, for 14 days of fermentation, the average accumulated output of biogas at a fermentation temperature of 55 °C is 336 l/kg *DOM*, at a fermentation temperature of 50°C– 283 l/kg *DOM*, 45°C- 257 l/kg *DOM*, 40°C- 184 l/kg *DOM*.

ARPN Journal of Engineering and Applied Sciences

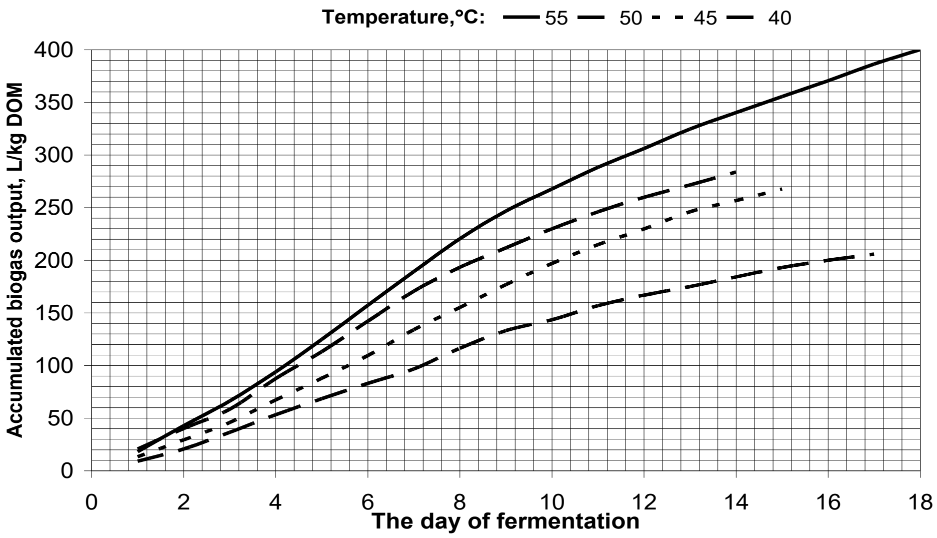

Figure-5. The average accumulated yield of biogas during the fermentation of cattle manure.

The results of experimental studies are close to the values indicated in the literature, specifying them depending on the temperature mode.

The average accumulated yield of biogas during the fermentation of cattle manure is approximated by a polynomial:

$$Q_{b\,cum} = b_n \cdot t^n + b_{n-1} \cdot t^{n-1} + b_1 \cdot t + b_0 \,, \tag{17}$$

where $Q_{b\,cum}$ - accumulated biogas yield, l/kg *DOM*; t - fermentation time, days; n - degree of polynomial.

The coefficients of the polynomial describing the average accumulated output of biogas during the fermentation of cattle manure are given in Table-4.

Table-4. The coefficients of the polynomial describing the average accumulated output of biogas during the fermentation of cattle manure.

№	Fermentation temperature, °C	Polynomial coefficients				R^2
		b_3	b_2	b_1	b_0	
1	55	-	-0.6696	35.843	-28.8	0.998
2	50	-	-0.6823	31.554	-20.9	0.9978
3	45	-0.074	1.4677	12.453	1.3	0.9999
4	40	-0.0258	0.3325	14.27	-7.7	0.9998

The coefficients of determination of the approximated curves with the coefficients given in Table-4, approaching to 1, which means that the obtained regression equations accurately reflect the experimental data. When checking by the Fisher criterion, the significance of the coefficient of determination is established. Student's test showed that all coefficients of polynomials (13) are significant.

The methane content in biogas was 50.4%, carbon dioxide 49.6%. The lower heat of combustion of biogas, defined by the formula (11), was $Q_н = 1339 \cdot 50.4 = 17.1$ MJ/m^3.

4.2 Research of Biogas Output while Adding Vegetable Oil Sediment to Cattle Manure

An oil vegetable oil sediment is a tank vegetable oil sediment released from oil during storage and consists of phospholipids, oil, moisture, and protein impurities.

In an experimental study of the output of biogas during the fermentation of cattle manure, 50 ml of vegetable oil sediment was added to the substrate, which consisted of 1.5 kg of cattle manure and 2.25 kg of water. The load factor of the digester was 0.5. When adding a new portion of the substrate, the fermented substrate was changed by half (emptying factor - 0.5). The temperature of the digester in the research was 40°C.

The mass of the *DOM* substrate based on cattle manure with the addition of vegetable oil sediment is 0.24 kg; the relative humidity is 92.6%. The content of vegetable oil sediment in the substrate is 1.3%.

The research results are presented in Figure-6.

From Figure-6, it is evident that diauxia is characteristic for the digestion of cattle manure with the addition of vegetable oil sediment. The first peak of biogas output is relatively small; the second peak of biogas output is twice the first one and stretches for much longer time. However, the appearance of the second peak of biogas output is observed only on the 20th day of fermentation.

The maximum yield of biogas (constant with the gradual loading of the digester) is 2,073 l/(h·kg *DOM*), which, however, occurs only on the 20th day of fermentation.

Conversion factor from the biogas output dimension l/(h·kg *DOM*) to dimension l/(h·kg) - 15828 kg/kg *DOM*.

The accumulated output of biogas during the fermentation of cattle manure with the addition of vegetable oil sediment is shown in Figure-7. In the same figure, for comparison, the accumulated output of biogas is shown during the fermentation of cattle manure. Figure-7 shows that on the 11th day of fermentation, the accumulated output of biogas during the fermentation of cattle manure with the addition of vegetable oil sediment is 273.6 l/kg *DOM* and almost three times more when fermenting cattle manure without the addition of co-substrate (99.2 l/kg *DOM*). On the 33rd day of fermentation, the accumulated yield of biogas during the fermentation of cattle manure with the addition of vegetable oil sediment is 7.5 times higher compared with the accumulated yield of biogas during the fermentation of cattle manure without the addition of co-substrate (1140.5 l/kg *DOM* versus 150.2 l/kg *DOM*). On the 48th day of fermentation, the accumulated yield of biogas during the fermentation of cattle manure with the addition of vegetable oil sediment comes to 1504.1 l/kg *DOM*.

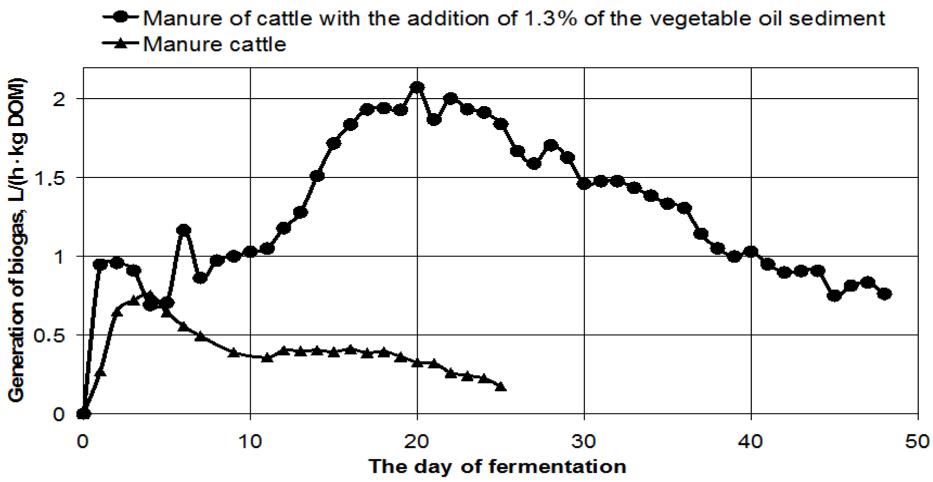

Figure-6. Dynamics of biogas output during the fermentation of cattle manure with the addition of vegetable oil sediment at a fermentation temperature of 40°C.

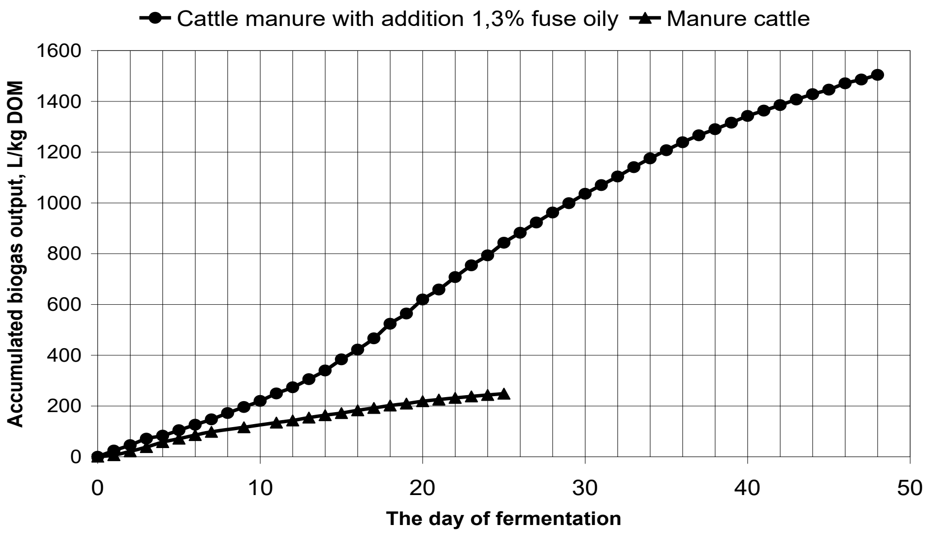

Figure-7. Comparison of the accumulated output of biogas during the fermentation of cattle manure with the addition of vegetable oil sediment and without using co-substrate at a fermentation temperature of 40°C.

VOL. 15, NO. 22, NOVEMBER 2020 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

The novelty of the work lies in the fact that, according to experimental researching of biogas output with periodic loading mode, prediction of biogas output is provided for the gradual loading of the digester. The accumulated output of biogas during the fermentation of cattle manure with the addition of 1.3% vegetable oil sediment to the contents of the substrate at a fermentation temperature of 40 °C is approximated by a polynomial (17) with the coefficients given in Table-5.

Table-5. Polynomial coefficients describing the average accumulated output of biogas during the fermentation of a mixture of cattle manure with the addition of 1.3% vegetable oil sediment to the contents of the substrate at a fermentation temperature of 40°C.

Polynomial coefficients					R^2
b_4	b_3	b_2	b_1	b_0	
0.00029	-0.0488	2.3136	-0.044	33.8	0.9994

The coefficient of determination of the approximated curve (17) with the coefficients of the polynomial, are given in Table-5, approaching to 1, which means that the obtained regression equation reflects the experimental data quite accurately.

When checking by the Fisher criterion, the significance of the coefficient of determination is established. Student's test showed that all coefficients b_0-b_3 of polynomial (17), Table-5, significant, and the coefficient b_4 unreliable.

However, the removal of the coefficient b_4 will lead to a change in the direction of the approximated curve in a finite period of fermentation, which may give incorrect results with further prediction.

When fermenting manure from a farm to 1000 head of cattle (of which 500 milk cows), the daily output of biogas will be 10600 m^3.

At the same time, the payback period of a biogas plant comprising two methane tanks of 2500 m^3 each (one of which acts as a fermenter, where up to 20% of biogas is produced), at a price of electricity generated from biogas at a "green" tariff of 0.145 \$/kW·h, is 10.1 years.

When added to the substrate based on cattle manure a vegetable oil sediment from a nearby oil seed factory, processing plant increases daily biogas output to 31200 m^3, and the payback period of a 6.7 MW biogas plant using the "green" tariff will be reduced to 5.1 years (Figure-8).

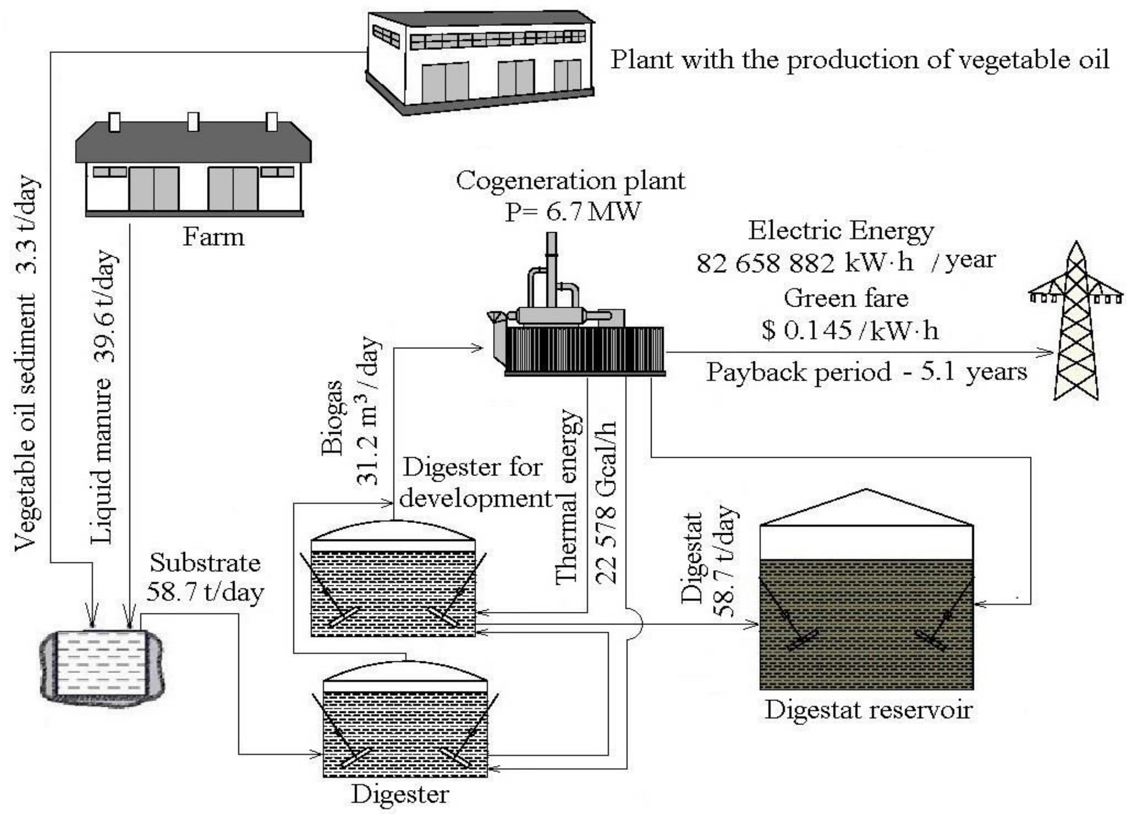

Figure-8. Comparison of the accumulated output of biogas during the fermentation of cattle manure with the addition of vegetable oil sediment and without using co-substrate at a fermentation temperature of 40°C.

CONCLUSIONS

The biogas yield during the fermentation of the substrate based on cattle manure depends on the fermentation temperature. As the fermentation temperature increases, the biogas output increases. So, for 14 days of fermentation, the average accumulated biogas yield at the fermentation temperature of 55°C is 336 l/kg *DOM*, at the fermentation temperature of 50°C- 283 l/kg *DOM*, 45°C- 257 l/kg *DOM*, 40°C- 184 l/kg *DOM*.

When fermenting a substrate based on cattle manure with the addition of vegetable oil sediment as a co-substrate for 11 days of fermentation, the accumulated biogas yield is 273.6 l/kg *DOM* which is almost three times more than when fermenting cattle manure without adding co-substrate (99.2 l/kg *DOM*). At the 48th day of fermentation, the accumulated yield of biogas during the fermentation of cattle manure with the addition of vegetable oil sediment reaches 1504.1 l/kg *DOM*. The maximum output of biogas with a periodic mode of loading of the digester comes on the 20th day of fermentation, while with mono-fermentation of cattle manure - for 3-8 days.

The predicted biogas yield with a gradual loading of the digester according to the results of experimental studies of the biogas yield with a periodic loading mode when adding 1.3% of cattle manure can increase to 2.073 l/(h·kg *DOM*). The using of vegetable oil sediment as a co-substratum will allow almost three-fold increase in the output of biogas end electricity.

When implementing a new methodological approach to forecasting biogas yield, the calculation results show that during the digestion of cattle manure and vegetable oil sediment, the daily biogas output from the farm per 1000 head of cattle increases to 31200 m^3, and the payback period of the biogas plant will be reduced to 5.1 years.

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