Determination of the Rate of Organic Biomass Decomposition in Biogas Reactors With Periodic Loading

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Abstract- The main indicator of biogas plant work is the output of gas per unit of biomass volume per day or other specified period of time. This indicator is used for energy and economic assessment of biogas plants. However, models for adequate determination of this indicator for biogas plants with periodic loading are almost absent. This is due to the fact that there is no indicator of the rate of biomass decomposition, especially for reactors with periodic loading, that is, when the reactor contains portions with different levels of organic biomass decomposition. They were obtained dependences for analytical determination of integral rate and decomposition level of organic biomass depending on fermentation time, reactor loading periodicity and fermentation temperature during anaerobic digestion. An algorithm for calculating the specific yield of biogas and biomethane during anaerobic fermentation and biogas reactor operation in the periodic loading mode was developed to determine the integral rate and level of organic biomass decomposition. The application of the algorithm for calculating the specific yield of biogas and biomethane during anaerobic fermentation of manure showed that the density of biogas under normal conditions 1.2 kg_{BG}/m^3_{BG} the output of biogas and biomethane in the biogas plant will be respectively 1.3 m^3_{BG}/m^3_{BM} per day and 0.91 m^3CH_4/m^3_{BM} per day, that corresponds to the performance of existing plants.

Keywords Biogas, biogas plant, decomposition rate, organic biomass, fermentation.

1. Introduction

An important direction in renewable energy is the production of biogas [1, 2]. Biogas production is widespread, both from plant biomass [3, 4] and from animal waste [5, 6]. In modern practice of biogas technologies the most widespread are reactors of periodic loading [7, 8]. The design of reactors for the production of continuous biogas is characterized by the fact that portions of biomass are fed into the reactor and removed from it after a certain period of time. These studies [7, 8] indicate that the frequency of biomass loading is one of the important parameters. However, the authors do not investigate the effect of loading frequency on biogas yield However, during the operation of biogas plants, a number of technical and technological problems arise related to compliance with the temperature regime, mixing modes and biomass loading, which is shown in the studies [9, 10]. The authors point to a change in temperature and mixing conditions when loading biomass, but also do not investigate the effect of loading period on biogas output. In particular, in [11] they were studied the temperature regimes of biomass fermentation and was proved that at the termophilic mode of operation of the biogas plants it was received a greater amount (output) of biogas, and at the mesophilic mode – higher calorific value of biogas. Besides, the study [12] proves the effectiveness of mixing the substrate for biogas production. In particular, without mixing, the yield of biogas from decomposed organic mass based on cattle manure under normal conditions amounted to 1.02 liters per liter of biogas plant volume per day, which is 10 times higher than without mixing. These studies prove the effectiveness of the influence of temperature regime and mixing regime on the efficiency of biogas plants. However, energy and economic assessment of biogas production process are necessary to confirm the effectiveness of the conducted research. Energy and economic assessment is based on the work of existing biogas plants [13, 14, 15]. The main indicator of energy and economic assessment is the specific yield of biogas or biomethane in terms of normal conditions per day and per one cubic meter of biomass in a biogas reactor [16]. This indicator depends on the density and humidity of biomass, the content of organic mass in biomass, as well as the density of biogas under normal conditions [17, 18]. However, the determining indicators of the intensity of the anaerobic digestion process is the intensity of decomposition of organic biomass per day and the yield of biogas or biomethane per unit of decomposed organic mass [19, 20]. However, the intensity of decomposition of organic biomass is also investigated without taking into account the frequency of biomass reactor loading. The mass yield of biogas per unit of decomposed organic mass is about 1 kg/kg, and biomethane – from 0.27 to 0.51 kg/kg depending on the type of biomass. In the first stage during biomass decomposition, the hydrolysis of the substrate with the formation of organic acids, alcohols, and simple carbohydrates are occursed. In the second stage, acetic acid, hydrogen and carbon dioxide are formed. Subsequently, the carbon dioxide is reduced to methane and the organic acids and alcohols are decomposed into methane and carbon dioxide [21]. It should be noted that easily soluble hydrocarbon compounds produce the minimum amount of biomethane during decomposition, and biomass containing fat compounds – the maximum.

Approximation of actual research data (fig. 1), which concerned the fermentation of manure [22] or household waste [23] showed that the intensity (1) of organic biomass decomposition during anaerobic digestion with a significant level of adequacy is described by exponential dependencies:

$$\alpha = \frac{M_0 - M^*}{M_0}\left[1-\exp\left(-k\tau\right)\right] = \alpha_0\left[1-\exp\left(-k\tau\right)\right] \qquad (1)$$

where: α – the level of organic matter decomposition at the current time, relative unit; M_0 – total organic matter content of biomass at the beginning of anaerobic digestion, kg; M^* – biomass organic matter content that does not decompose during anaerobic digestion, kg; k – the speed ratio of the biogas fermentation process, days^{-1}; τ – biogas fermentation time, days; $\alpha_0 = \frac{M_0 - M^*}{M_0}$ the maximum level of organic matter decomposition in the process of anaerobic digestion, relative unit

The maximum level of organic matter decomposition in the process of anaerobic digestion is different for different substrates and depends on the temperature, type of substrate and other factors.

On the basis of experimental data [24] it was also obtained the dependence of the rate coefficient of the biogas fermentation process on the temperature of anaerobic digestion (fig. 2) and found the value of the maximum level of organic matter decomposition, which is α_0 = 0.53 rel. un.

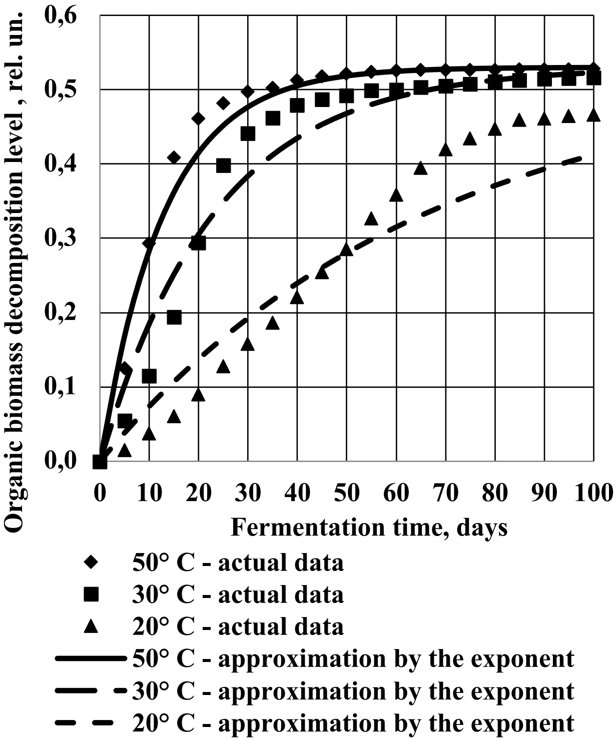


Fig. 1. Comparison of the actual data of studies that concerned anaerobic digestion of manure and their approximation with the help of experimental dependences.

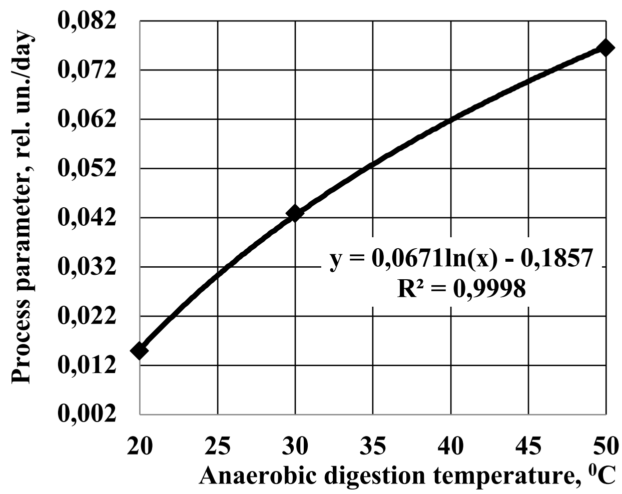


Fig. 2. The relationship of the biogas fermentation process parameter, which characterizes its rate depending on the anaerobic digestion temperature

Similar exponential correlations approximate the actual data of studies that concerned the fermentation of green grass mass [25, 26] and silage [25, 27, 28]. It was found the value of the rate of green grass mass biogas fermentation, which was 0.095 rel. un. and 0.119 rel. un. for the process of silage biogas fermentation. The value of the maximum level of organic matter decomposition for green grass mass was 0.45 rel. un., and for silage – 0.59 rel. un.

Thus, in many cases of anaerobic digestion of different organic biomass, the level of organic biomass decomposition over time can be approximated by experimental dependences. These dependences include the value of the rate coefficient of the biogas fermentation process and the value of the maximum level of organic matter decomposition, which are determined experimentally. However, there are no mathematical models to adequately determine the rate of decomposition of biomass for reactors with periodic loading, when portions with different levels of decomposition of organic biomass are in the reactor. Therefore, the aim of the presented studies is to analytically determine the integral level of organic biomass decomposition and integral rate of decomposition of organic biomass, depending on the fermentation time, the reactor loading period, and the fermentation temperature during anaerobic fermentation.

2. Materials and Methods

It is obvious that the number (2) of loaded portions of biomass in the biogas reactor will be:

$$n = \frac{\tau_F}{\tau_L}, \tag{2}$$

where: n – the number of downloaded portions of the biomass in the biogas reactor, un.; τ_F – fermentation time (total residence time of biomass in the reactor), days; τ_L – frequency of biogas reactor loading, days.

Obviously, the fermentation time (3) can be determined by the following ratio:

$$\tau_F = \frac{V_R}{V_{DL}}, \tag{3}$$

where: V_R – the working volume of the biogas reactor, m^3; V_{DL} – the volume of daily load in the biogas reactor, m^3/days.

In the case of an ideal situation where each portion of the loaded substrate is not mixed with the previous portions (reactor in the form of connected containers containing one downloaded portion of the substrate), as shown in Fig. 3, the residence time (4) of each loaded portion in the reactor at the time before unloading the first loaded portion from the filled reactor will be:

$$\tau_i = \tau_F - \tau_L i, \tag{4}$$

where: $i = 0 \ldots n = 0 \ldots \frac{\tau_F}{\tau_L}$ – numbering of the loaded biomass portion into the biogas reactor.

Knowing the residence time of each portion of the substrate in the biogas reactor, it is possible to determine the level (5) of decomposition of each individual portion of organic biomass during anaerobic digestion, using exponential dependences (1):

$$\alpha_i = \alpha_0 \left[1 - \exp\left(-k\left(\tau_F - \tau_L i\right)\right)\right]. \tag{5}$$

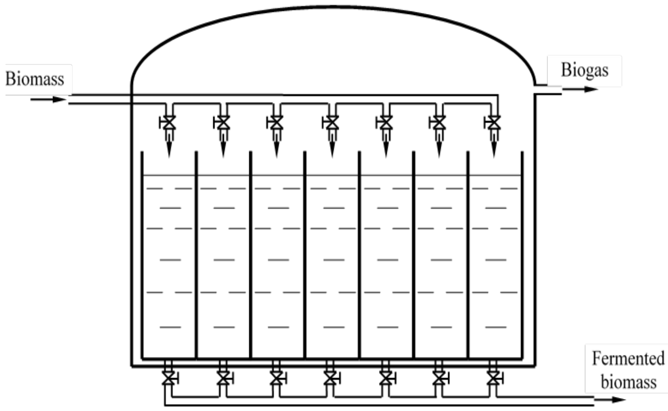


Fig. 3. Idealized scheme of biogas reactor in the form of combined tanks containing one loaded portion of substrate

Then the integral average level (6) of decomposition of organic biomass during anaerobic digestion will be:

$$\begin{aligned}
\alpha &= \frac{1}{n+1}\sum_{i=1}^{n}\alpha_i = \frac{1}{n+1}\sum_{i=1}^{n}\alpha_0\left[1-\exp\left(-k\left(\tau_F-\tau_L i\right)\right)\right] = \\
&= \frac{1}{n+1}\sum_{i=1}^{n}\alpha_0\left[1-\exp\left(-k\tau_F\right)\exp\left(k\tau_L i\right)\right] = \\
&= \alpha_0\left[1-\exp\left(-k\tau_F\right)\frac{1}{n+1}\sum_{i=0}^{n}\exp\left(k\tau_L i\right)\right] = \\
&= \alpha_0\left[1-\exp\left(-k\tau_F\right)\frac{\tau_L}{\tau_F+\tau_L}\sum_{i=0}^{n}\exp\left(k\tau_L i\right)\right].
\end{aligned} \tag{6}$$

The integral average rate (7) of organic biomass decomposition during anaerobic digestion will be:

$$\begin{aligned}
\frac{d\alpha}{d\tau} &= \frac{1}{n+1}\sum_{i=1}^{n}\alpha_0 k\exp\left(-k\left(\tau_F-\tau_L i\right)\right) = \\
&= \frac{1}{n+1}\sum_{i=1}^{n}\alpha_0 k\exp\left(-k\tau_F\right)\exp\left(k\tau_L i\right) = \\
&= \alpha_0 k\exp\left(-k\tau_F\right)\frac{1}{n+1}\sum_{i=0}^{n}\exp\left(k\tau_L i\right) = \\
&= \alpha_0 k\exp\left(-k\tau_F\right)\frac{\tau_L}{\tau_F+\tau_L}\sum_{i=0}^{n}\exp\left(k\tau_L i\right).
\end{aligned} \tag{7}$$

Thus, expressions are obtained to estimate the integral values of the level and rate of organic biomass decomposition during anaerobic digestion and biogas reactor operation in the periodic loading mode.

3. Results and Discussions

The use of integral values of the level and rate of organic biomass decomposition during anaerobic digestion for the data on anaerobic digestion of silage [25, 28] allowed obtaining integral values of the level and rate of decomposition of organic biomass of silage while anaerobic digestion during τ_F = 60 days and with the frequency of loading of τ_L = 5 days (Fig. 4 and Fig. 5).

As shown by calculations, despite the fact that the maximum level of decomposition of the organic mass of silage during anaerobic digestion is 0.59 rel. un., the integral decomposition level of organic biomass under anaerobic digestion at 12 loaded portions of silage biomass into the reactor will be 0.49 rel. un.

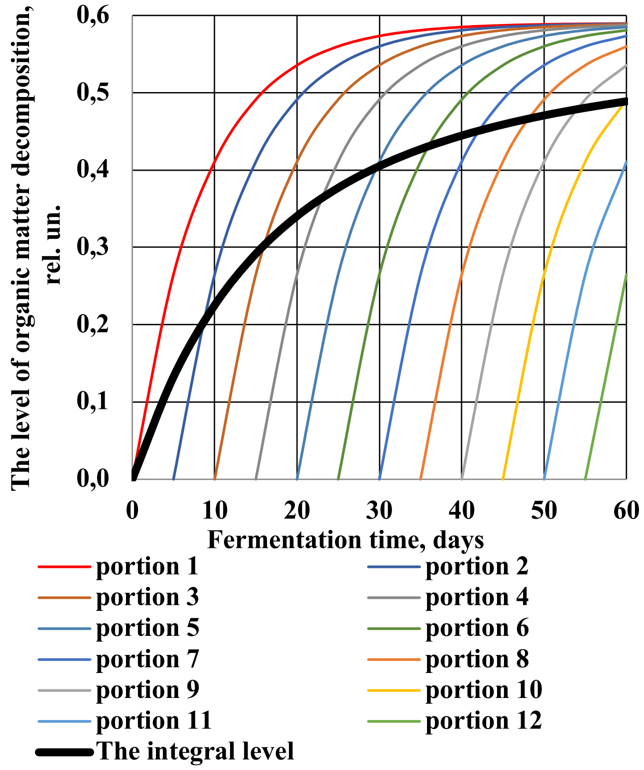


Fig. 4. The integral level of decomposition of the organic biomass of the silage while the anaerobic digestion

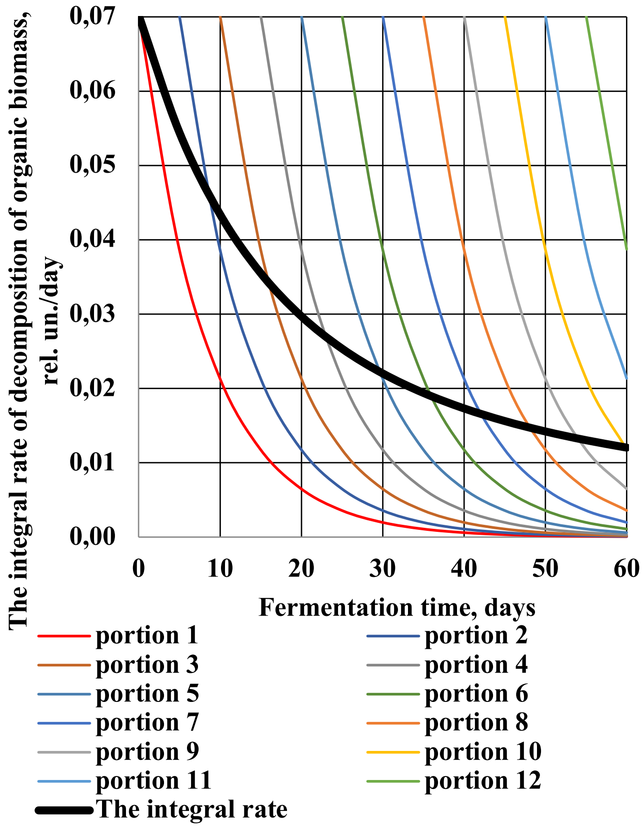


Fig. 5. Integral decomposition rate of organic silage biomass during anaerobic digestion

The maximum integral decomposition rate of organic biomass during anaerobic digestion of 12 loaded portions of silage biomass into the reactor will be 0.012 rel. un. or 1.2%.

The use of integral values of the level and rate of organic biomass decomposition during anaerobic digestion for data on anaerobic digestion of manure on the basis of experimental data [21] allowed obtaining integral values of the level and rate of decomposition of organic biomass silage while anaerobic digestion during τ_F = 21 days and with the frequency of loading of τ_L = 1 day (Fig. 6 and Fig. 7).

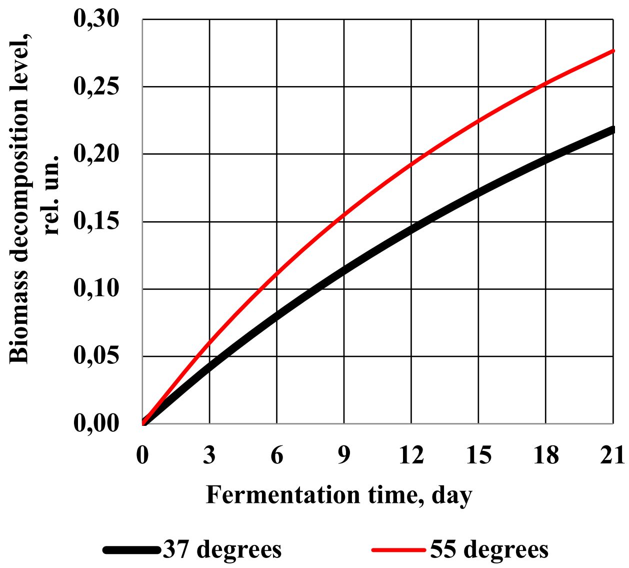


Fig. 6. Integral level of decomposition of organic biomass of manure during anaerobic digestion

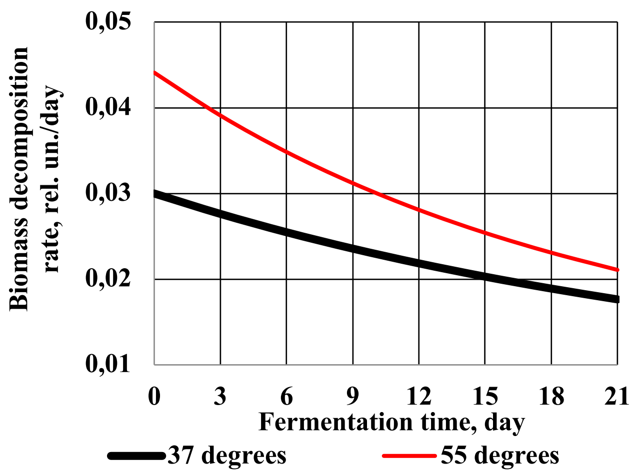


Fig. 7. Integral rate of decomposition of manure organic biomass during anaerobic digestion

It was found that the integral value of the level and rate of organic biomass decomposition during anaerobic digestion of manure depends on the temperature of anaerobic digestion. Thus, at the anaerobic digestion temperature of 37 ^{O}C the integral value of the decomposition level of organic biomass of manure was 0.22 rel. un., and the integral value of the decomposition rate of organic biomass was 0.017 rel. un. or 1.7%. At the same time, at the anaerobic digestion temperature of 55 ^{O}C the integral value of the decomposition level of organic biomass of manure was 0.28 rel. un., and the integral value of the decomposition rate of organic biomass was 0.021 rel. un. or 2.1%, which is almost by a quarter higher than at 37 ^{O}C.

It was also established that the integral value of the level and rate of organic biomass decomposition during anaerobic digestion of manure practically does not depend on the frequency of loading (Fig. 8).

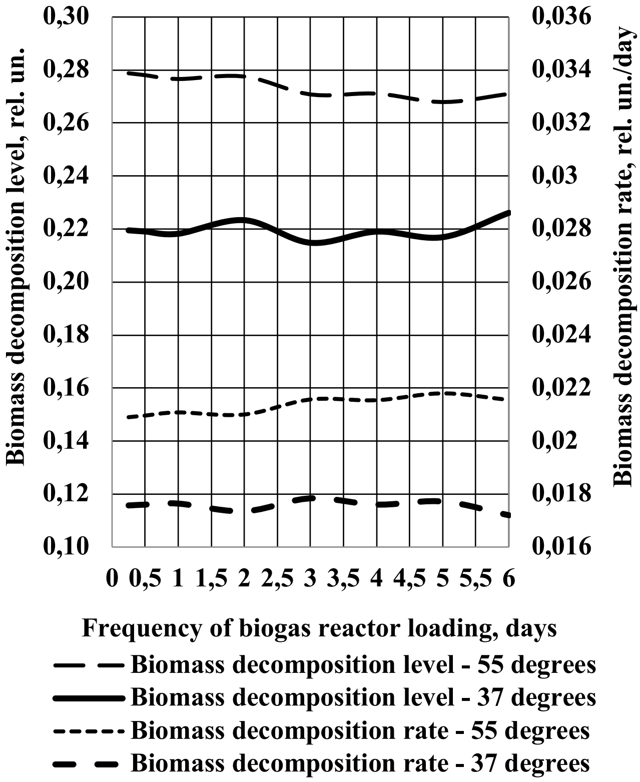


Fig. 8. Influence of loading periodicity on the integral decomposition level and decomposition rate of manure organic biomass during anaerobic digestion

Thus, at the anaerobic digestion temperature of 37 ^{O}C the integral value of the decomposition level of manure organic biomass was from 0.21 to 0.23 rel. un., and the integral value of the decomposition rate of organic biomass was from 0.017 to 0.018 rel. un. At the anaerobic digestion temperature of 55 ^{O}C the integral value of the decomposition level of manure organic biomass was from 0.27 to 0.28 rel. un., and the integral value of the decomposition rate of organic biomass was 0.021 to 0.022 rel. un.

Thus, the obtained dependences make it possible to analytically determine the integral rate of organic biomass decomposition depending on the fermentation time, the frequency of reactor loading and the fermentation temperature during anaerobic digestion.

Taking into account the above review of studies of the anaerobic digestion process and theoretical studies, the calculation of the specific yield of biogas during operation of the biogas reactor in the mode of periodic loading and in terms of normal conditions is advisable to carry out in the following sequence.

1. Determination of properties of biomass coming to anaerobic digestion:

1.1. Determination of biomass density, ρ_{BM}.

1.2. Determination of biomass moisture content, W_{BM}.

1.3. Determination of organic mass content in biomass dry matter, k_{OM}.

2. Determination of kinetics of biomass anaerobic digestion:

2.1. Determination of the experimental dependence of the level of decomposition of the biomass organic component on the time of anaerobic digestion.

2.2. Determination of the maximum level of decomposition of the biomass organic component depending on the time of anaerobic digestion, α_0.

2.3. Determination of biomass organic component decomposition rate, k.

2.4. Determination of dependence for approximation of experimental data of change in the level of decomposition of biomass organic component on the time of anaerobic digestion in the form of $\alpha = \alpha_0\left[1-\exp(-k\tau)\right]$.

2.5. Determination of biogas yield per unit of decomposed organic mass, m_{BG}.

2.6. Determination of volume content of biomethane in biogas, k_{CH4}.

3. Determination of the integral value of the level and rate of organic biomass decomposition during the biomass anaerobic digestion:

3.1. Determination of the fermentation time τ_F, as the ratio of the working volume of the biogas reactor to the volume of the daily load of the biogas reactor, the frequency of loading of the biogas reactor τ_L and the number of loaded portions of biomass in the biogas reactor n, as the ratio of the fermentation time (total residence time of biomass in the reactor) to the frequency of loading of the biogas reactor.

3.2. Determination of the integral value of the level of decomposition of the organic biomass depending on the time of digestion, frequency of substrate and temperature of fermentation during anaerobic digestion.

3.3. Determination of the integral value of the decomposition rate of organic biomass depending on the fermentation time, the frequency of reactor loading and the fermentation temperature during anaerobic fermentation.

4. Determination of specific indicators of anaerobic digestion of biomass:

4.1. Determination of specific biogas yield from the reactor during anaerobic digestion under normal conditions, V_{BG}.

4.2. Determination of specific yield of biomethane from the reactor during anaerobic digestion under normal conditions, V_{CH4}.

An algorithm for calculating the specific yield of biogas during operation of the biogas reactor in the mode of periodic loading and in terms of normal conditions is schematically shown in Fig. 9. An example of the calculation is given in table 1 at biogas density under normal conditions $\rho_{BG}^{N} = 1.2$ kg$_{BG}$/m$^3_{BG}$.

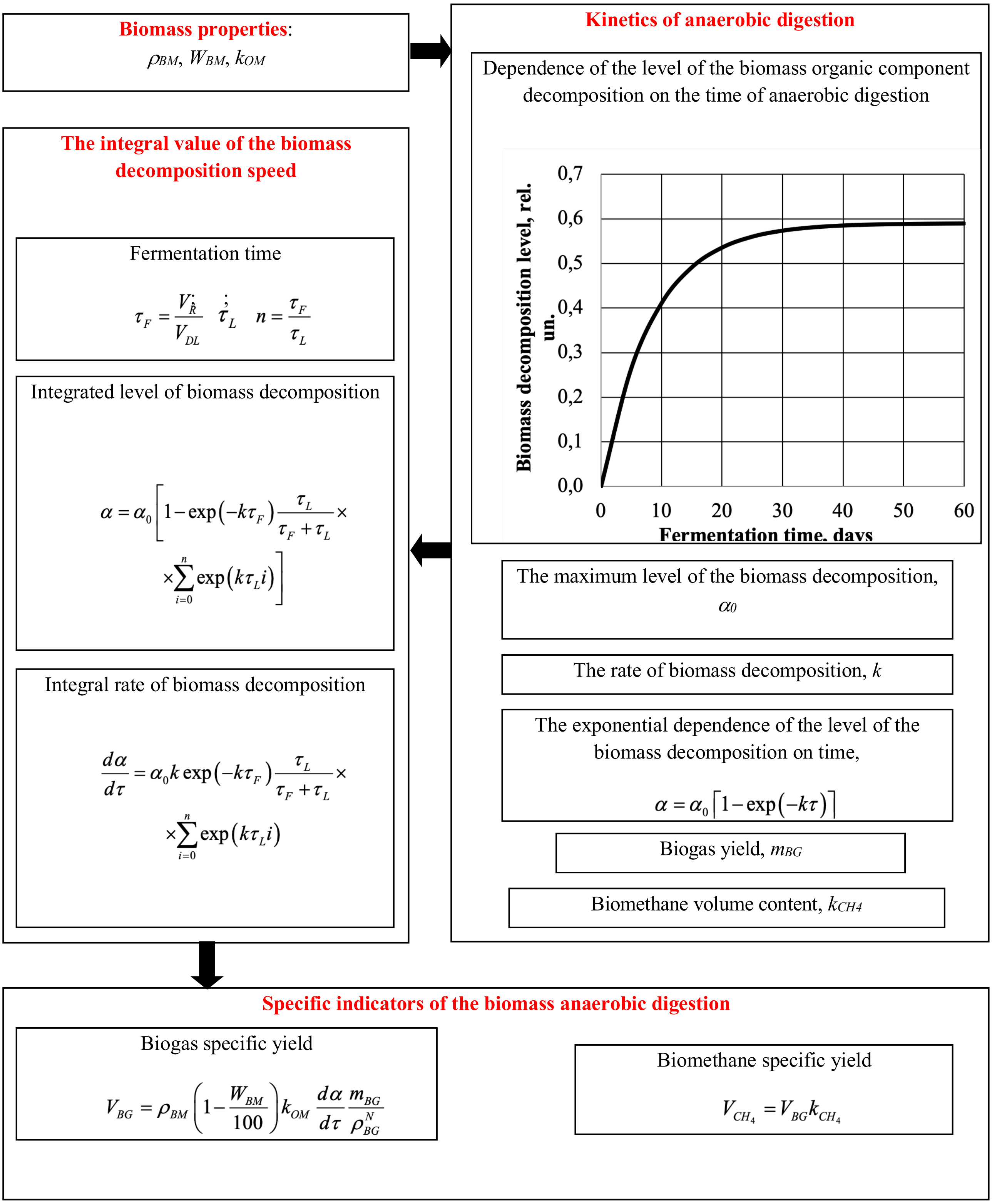
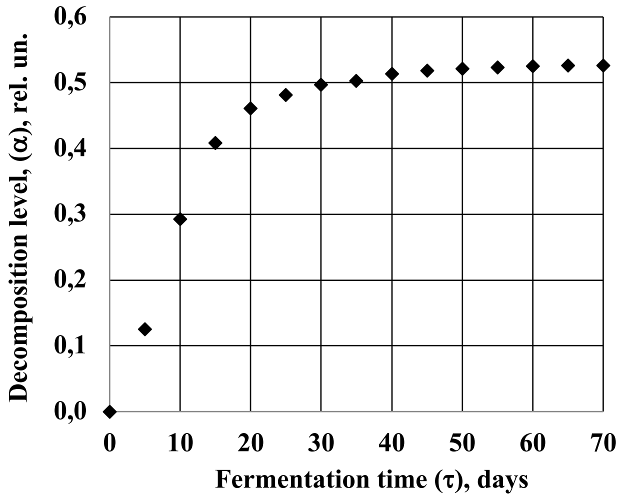


Fig. 9. Algorithm of calculation of specific output of biogas during the operation of biogas reactor in the mode of periodic loading

Table 1. Calculation of specific yield of biogas and biomethane

Properties of biomass supplied for anaerobic digestion			
Manure density	ρ_{BM}	kg_{BM}/m^3_{BM}	1050
Moisture	W_{BM}	%	92
Organic matter content	k_{OM}	%	80
Indices of the kinetics of biomass anaerobic digestion			
Experimental dependence of the level of decomposition of the biomass organic component on the time of anaerobic digestion of manure according to [19]			
The maximum level and rate of organic biomass decomposition	α_0	rel. un.	0.53
	k	days^{-1}	0.08319
Dependence for approximation of experimental data of change in level of biomass organic component decomposition on time of anaerobic digestion	$\alpha = \alpha_0\left[1-\exp(-k\tau)\right] = 0.53\left[1-\exp(-0.08319\ \tau)\right]$		
The yield of biogas from the decomposed dry organic matter (DOM) under normal conditions	m_{BG}	$кg_{BG}/кg_{DOM}$	1.1
The volume content of biomethane in biogas	k_{CH4}	%	70
Integral values of biomass decomposition level and rate under the following conditions of biogas plant operation: fermentation time τ_F = 21 days, frequency of biogas reactor loading τ_L = 1 day, the number of loaded portions of biomass into the biogas reactor n=21 un.			
Integral value of the level and rate of organic biomass decomposition	$\alpha = \alpha_0\left[1-\exp(-k\tau_F)\frac{\tau_L}{\tau_F+\tau_L}\sum_{i=0}^{n}\exp(k\tau_L i)\right] = 0.53\times \times\left[1-\exp(-0.08319\cdot 21)\frac{1}{21+1}\sum_{i=0}^{7}\exp(0.08319\cdot 1\cdot i)\right] = 0.2766$ rel. un.		
	$\frac{d\alpha}{dt} = \alpha_0 k\exp(-k\tau_F)\frac{\tau_L}{\tau_F+\tau_L}\sum_{i=0}^{n}\exp(k\tau_L i) = 0.53\cdot 0.068\times \times\exp(-0.068\cdot 21)\frac{1}{21+1}\sum_{i=0}^{7}\exp(0.068\cdot 1\cdot i) = 0.0211$ rel. un. per day		
Output of biogas and biomethane from the reactor under normal conditions	V_{BG}	m^3_{BG}/m^3_{BM} per day	1.3
	$V_{CH4;}$	m^3CH_4/m^3_{BM} per day	0.91

The calculated value of biogas output from the reactor under normal conditions in terms of manure weight is 1.24 m^3_{BG}/t of biomass per day. Actual biogas yield based on data analysis of biogas plant studies are shown in table 2.

Table 2. Actual value of biogas output

Actual biogas yield, m^3/t	Fermentation temperature, ºC	Biomass water content , %	Digestion time, days	Reference
2.50-2.60	54	93.6	5	[11, 30]
2.00	40	96.2	5	[5]
1.40-1.50	38-40	95.12	16	[7, 14, 29]
1.20	40	93.7	9	[7, 14]
1.10	40	99.5	10	[7, 14]
1.00-1.05	38	94.1	16	[7, 14]

Herewith, there are unknown such indicators as biomass density, organic mass content, the maximum level and rate of organic biomass decomposition, biogas yield from organic matter decomposed under normal conditions and volume content of biomethane in the biogas, as well as an integral value of the speed of organic biomass decomposition, which does not allow to assess more accurately the adequacy of the proposed calculation method the output of biogas and biomethane from the reactor under normal conditions. If we average the obtained data, we get biogas yield at the level of 1.575 m^3/t of biomass per day. This value differs from that obtained estimated biogas yield from the reactor under normal conditions by 27%, indicating that in terms of the presence of more accurate data on the parameters of biomass, availability of the dependence of the level of decomposition of the biomass organic component on the time of anaerobic digestion, and certain conditions of biomass fermentation, the proposed algorithm of calculation of specific biogas yield during operation of the biogas reactor in the mode of periodic loading can be successfully used in research and to assess the process of biogas production with the help of operating units.

4. Conclusion

1. In most cases of anaerobic digestion of manure and plant biomass, the level of decomposition of organic biomass over time can be approximated by an exponential relationship, which includes the value of the rate coefficient of the biogas fermentation process and the value of the maximum level of decomposition of organic matter, which are determined experimentally. As a result of the analysis of experimental results, it was found that the value of the maximum level of decomposition of organic biomass is in the range of 0.45 to 0.59 rel. un. and depends on the type of biomass.

2. Based on exponential dependences for determining the level of decomposition of organic biomass in time was obtained dependences for analytical determination of integral rate and organic biomass decomposition level depending on fermentation time, reactor loading periodicity and fermentation temperature during anaerobic fermentation and the specific yield of biogas or biomethane in terms of normal conditions per day and per cubic meter of biomass in a biogas reactor.

3. It was found that the integral value of the level and rate of decomposition of organic biomass during anaerobic fermentation of manure practically does not depend on the frequency of loading.

4. An algorithm for calculating the specific yield of biogas and biomethane during anaerobic fermentation and biogas reactor operation in the periodic loading mode was developed to determine the integral rate and level of organic biomass decomposition. The application of the algorithm for calculating the specific yield of biogas and biomethane during anaerobic fermentation of manure showed that the density of biogas under normal conditions 1.2 kg_{BG}/m^3_{BG} the output of biogas and biomethane in the biogas plant will be respectively 1.3 m^3_{BG}/m^3_{BM} per day and 0.91 m^3CH_4/m^3_{BM} per day, that corresponds to the performance of existing plants.

References

[1] A. Harrouz, M. Abbes, I. Colak, and K. Kayisli, “Smart grid and renewable energy in Algeria”, 2017 IEEE *6th International Conference on Renewable Energy Research and Applications* (ICRERA), San Diego, pp. 1166-1171, 5-8 November 2017.

[2] I. Carlucci, G. Mutani, and M. Martino, “Assessment of potential energy producible from agricultural biomass in the municipalities of the Novara plain”, 2015 IEEE *International Conference on Renewable Energy Research and Applications* (ICRERA), Palermo, pp. 1394-1398, 22- 25, November, 2015.

[3] M. R. A. Mamun, and S. Torii, “Anaerobic co-digestion of cafeteria, vegetable and fruit wastes for biogas production”, 2014 IEEE *International Conference on Renewable Energy Research and Application* (ICRERA), Milwakuee, pp. 369-374, 19-22 October 2014.

[4] Y. Ulusoy, A. H. Ulukardesler, R. Arslan, and Y. Tekin, “Biogas production potential of olive-mill wastes in Turkey”, 2017 IEEE *6th International Conference on Renewable Energy Research and Applications* (ICRERA), San Diego, pp. 664-668, 5-8 November 2017.

[5] A.K.P. Meyer, E.A. Ehimen, and J.B. Holm-Nielsen, “Future European biogas: Animal manure, straw and grass potentials for a sustainable European biogas

production", *Biomass and Bioenergy*, vol. 111, 2018, pp. 154-164, June 2017.

[6] M. A. Sanz-Bobi, F. de Cuadra, and C. Batlle, "A review of key points of an industrial biogas plant. A European perspective", 2012 IEEE *International Conference on Renewable Energy Research and Applications* (ICRERA), Nagasaki, 11-14 November 2012.

[7] K. Ahlberg-Eliasson, E.Nadeau, L. Levén, and A. Schnürer, "Production efficiency of Swedish farm-scale biogas plants", *Biomass and Bioenergy*, vol. 97, pp. 27-37, February 2017.

[8] H. M. Morgan, W. Xie, J. Liang, H. Mao, H. Lei, R. Ruan, and Q. Bu, "A techno-economic evaluation of anaerobic biogas producing systems in developing countries", *Bioresource Technology*, vol. 250, pp. 910-921, February 2018.

[9] G. Golub, K. Szalay, S. Kukharets, and O. Marus, "Energy efficiency of rotary digesters", *Progress in Agricultural Engineering Sciences*, vol. 13 (1), pp. 35-49, December 2017.

[10] G. Golub, O. Skydan, S. Kukharets, and O. Marus, "Substantiation of motion parameters of the substrate particles in the rotating digesters", *INMATEH – Agricultural Engineering*, vol. 57, no. 1, pp. 179-186, March 2019.

[11] N. Halder, "Thermophilic Biogas Digester for Efficient Biogas Production from Cooked Waste and Cow Dung and Some Field Study", *International Journal of Renewable Energy Research*, vol.7, No.3, pp. 1062-1073, September 2017.

[12] S. Kukharets, G. Golub, K. Szalay, and O. Marus, "Study of energy costs in process of biomass mixing in rotary digester", *Engineering for Rural Development* vol. 18, pp. 1331–1336, May 2019.

[13] K. P. Tsagarakis, and C. Papadogiannis, "Technical and economic evaluation of the biogas utilization for energy production at Iraklio Municipality, Greece", *Energy Conversion and Management*, vol. 47, no. 7-8, pp. 844-857, May 2006.

[14] F. Cucchiella, I. D'Adamo, and M. Gastaldi, "An economic analysis of biogas-biomethane chain from animal residues in Italy", *Journal of Cleaner Production*, vol. 230, pp. 888-897, September 2019.

[15] K. Kozłowski, M. Pietrzykowski, W. Czekała, J. Dach, A. Kowalczyk-Juśko, K. Jóźwiakowski, and M. Brzoski, "Energetic and economic analysis of biogas plant with using the dairy industry waste", *Energy*, vol. 183, pp. 1023-1031, September 2019.

[16] Y. Li, J. Lu, F. Xu, Y.Li, D. Li, G. Wang, and G. Li, "Reactor performance and economic evaluation of anaerobic co-digestion of dairy manure with corn stover and tomato residues under liquid, hemi-solid, and solid state conditions", *Bioresource Technology*., vol. 270, pp. 103-112, December 2018.

[17] N. K. Bulatov, D. K. Sarzhanov, S. Z. Elubaev, T. B. Suleymenov, K. S.Kasymzhanova, and O. T. Balabayev, "Model of effective system of processing of organic wastes in biogas and environmental fuel production plant", *Food and Bioproducts Processing*, vol. 115, pp. 194-207, May 2019.

[18] E.Surra, M. Bernardo, N. Lapa, I. A. A. C. Esteves, I. Fonseca, and J. P. B. Mota, "Biomethane production through anaerobic co-digestion with Maize Cob Waste based on a biorefinery concept: A review", *Journal of Environmental Management*, vol. 249, pp. 1-21, November 2019.

[19] N. H. Garcia, A. Mattioli, A. Gil, N. Frison, F. Battista, and D. Bolzonella, "Evaluation of the methane potential of different agricultural and food processing substrates for improved biogas production in rural areas", *Renewable and Sustainable Energy Reviews*, vol. 112, pp. 1-10, September 2019.

[20] S. Mirmohamadsadeghi, K. Karimi, M. Tabatabaei, and M. Aghbashlo, "Biogas production from food wastes: A review on recent developments and future perspectives", *Bioresource Technology Reports*, vol. 7, pp. 1-37, September 2019.

[21] V. Yilmaz, "A straightforward method: Biochemical methane potential assay", 2015 IEEE *International Conference on Renewable Energy Research and Applications* (ICRERA), Palermo, pp. 148-150, 22- 25, Novembe, 2015.

[22] O. J. Reátegui, H. L. Cárdenas, D. G. Peña, and et al., "Biogas production in batch in anaerobic conditions using cattle manure enriched with waste from slaughterhouse", 2017 IEEE *6th International Conference on Renewable Energy Research and Applications* (ICRERA), San Diego, pp. 819-822, 5-8 Novembe 2017.

[23] W. Baader, E. Dohne, and M .Brenndörfer, "Biogas in Theorie und Praxis" - Behandlung organischer Reststoffe aus der Landwirtschaft durch Methangärung, *Taschenbuch:KTBL,* 1987.

[24] G. Howell, C. Bennett, and D. Materić, "A comparison of methods for early prediction of anaerobic biogas potential on biologically treated municipal solid waste", *Journal of Environmental Management*, vol. 232, pp. 887-894, February 2019.

[25] Th. Amon, V. Kryvoruchko, B. Amon, W. Zollitsch, K. Mayer, S. Buga, and A. Amid, "Biogaserzeugung aus Mais – Einfluss der Inhaltsstoffe auf das spezifische Methanbildungsvermögen von früh- bis spätreifen Maissorten", *In: Bericht über die 54. Tagung 2003 der Vereinigung der Pflanzenzüchter und Saatgutkaufleute Österreichs,* Bundesanstalt für alpenländische Landwirtschaftam, pp 59-68, 25-27 November 2003.

[26] R. Bedoić, L. Čuček, B. Ćosić, D. Krajnc, G. Smoljanić, Z. Kravanja, and N. Duić, "Green biomass to biogas – A study on anaerobic digestion of residue grass", *Journal of Cleaner Production*, , vol. 213, pp.

700-709, March 2019.

[27] H. Himanshu, J. D. Murphy, J. Grant, and P. O'Kiely, "Antagonistic effects on biogas and methane output when co-digesting cattle and pig slurries with grass silage in in vitro batch anaerobic digestion", *Biomass and Bioenergy*, vol. 109, pp. 190-198, February 2018.

[28] M. Voelklein, D. Rusmanis, and J. Murphy, "Increased loading rates and specific methane yields facilitated by digesting grass silage at thermophilic rather than mesophilic temperatures", *Bioresource Technology*, vol. 216, pp. 486-493, September 2016.

[29] M. Torrellas, L. Burgos, L. Tey, J. Noguerol, V. Riau, J. Palatsi, and A. Bonmatí, "Different approaches to assess the environmental performance of a cow manure biogas plant", *Atmospheric Environment*, vol. 177, pp. 203-213, March 2018.

[30] S. Ishikawa, K. Iwabuchi, K. Takahashi, R. Hara, and H. Kita, "Performance evaluation based on long-term operation results of biogas plant for livestock manure management", *Engineering in Agriculture, Environment and Food*, vol. 12, is. 2, pp. 155-161, April 2019.