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Investigation of the Anaerobic Fermentation Process of Organic Waste

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Abstract. *Reactors used in the anaerobic fermentation of carbon-containing waste (agricultural, sewage sludge, livestock, etc.) for biogas production have been studied. Various designs of equipment intended for the production of biogas and bio-organic fertilizers through the anaerobic fermentation of waste have been proposed. The advantage of anaerobic fermentation in such reactors lies in the fact that, unlike classical aerobic biological treatment methods, all bacteria function under the same conditions in properly organized anaerobic systems. Bacteria operate under diverse physical and chemical conditions. This allows for the optimization, control, and ultimately improvement of the quality of waste treatment. Equations have been derived to determine biogas productivity based on the proposed biogas systems. From this perspective, the calculation of the biogas plant and the yield of biogas depend empirically on the design and technical parameters of the system. The paper studies the design and technological features of biogas production units for anaerobic fermentation of organic waste. A classification of biogas production technologies and biomass mixing methods is proposed. The types of mixing devices in the chemical industry are considered and the distribution of medium flows during their operation is described. It is established that a promising direction for improving mixing systems in biogas plants is the combination of mechanical and bubbling types of mixing.*

Keywords: *bioreactor, fermentation, biogas, methanotank, organic waste*

Introduction

It is well known that the main element of any technological scheme is the device in which the process takes place – namely, the reactor (Aghayev, 2019). The anaerobic fermentation process of organic waste is carried out in bioreactors, and the output parameters of the process depend primarily on the design that ensures the required technological modes (Huang, 2007). The construction of the bioreactor must prevent the formation of scum, provide complete mixing of the reaction mass, a rational heating system, and continuous operation. Furthermore, the design should not complicate its manufacturing or maintenance. Numerous patents related to bioreactors for anaerobic fermentation processes are available in the literature. Many bioreactors are equipped with mechanical stirrers and heating systems (Gaifullin, 2024; Obono, 2022). It should be noted that these types of reactors have some significant drawbacks. The presence of shaft seals can compromise the hermeticity of the bioreactor, while sludge sticking to the surface of heaters reduces their heat transfer efficiency (Mehraliyev, 2014; Patent AZ I 2007).

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The formation of scum on the surface of the substrate reduces biogas production, and large scum fragments can clog the outlet pipes. Sediment accumulation at the bottom of the bioreactor, where there is no movement, is also among these deficiencies. In general, these bioreactors have complex designs and thus require complex technological and maintenance mechanisms (Bilge, 2012; Obono Mba, 2022). Bioreactors with a dome-shaped lid and a cylindrical body with a conical bottom also exist. These are equipped with inlet/outlet pipes for substrate loading, product and gas discharge, and a circulation line. In such bioreactors, the gas holder and methanotank are integrated into a single body, which contributes to certain functional drawbacks. In the methanotank, fresh organic matter is added to the fermenting mass and mixed (Muradov, 2024).

Thus, the decomposition of organic waste mainly involves the following reactions: hydrolysis process (sugar, amino acids, fatty acids), oxidation phase (C_x – C_6 carbon/fatty acids, C_5 valeric CH_3-CH_2CH_2-CH_2-COOH, C_4 fatty CH_3-CH_2-CH_2-COOH, C_3 propionic CH_3-CH_2-COOH), acid formation (C_2 acetic acid CH_3 – COOH, C_1 formic acid HCOOH) and methane (methane CH_4, carbon dioxide CO_2, H_2O, H_2S, N_2). Based on these, gas is ultimately formed by the following reactions:
1) $C + CO_2 = 2CO$;
2) $C + H_2O$ (g) = $CO + H_2$;
3) $C + 2H_2O$ (g) = CO_2+2H_2;
4) $C + 2H_2 = CH_4$;
5) $CO + H_2O$ (g) = $CO_2 + H_2$;
6) $CO + 3H_2 = CH_4 + H_2O$ (g).
In this regard, bioreactors should ensure the implementation of the indicated processes. This weakens the action of hydrolytic microorganisms in the first phase of anaerobic fermentation and worsens the operating conditions for methane-producing bacteria in the second phase. Moreover, the presence of a circular water compartment around the methanotank body – used for the hydraulic seal of the rising bell-type gas holder – complicates the manufacturing and maintenance of the bioreactor. Thus, based on the aforementioned, it can be concluded that the efficiency of anaerobic fermentation processes largely depends on the design of the reactor, i.e., the bioreactor. For this reason, this study focuses on the development of new bioreactor constructions that eliminate the above-mentioned deficiencies and improve performance. In this type of biogas plant, the production of methane occurs under anaerobic conditions. These reactions can be represented as follows:
1. *Methane formation reaction:*
$CH_3COOH \rightarrow CH_4+CO_2$
2. *Hydrogen reduction:*
$CO_2+4H_2 \rightarrow CH_4+2H_2O$
Two new bioreactor constructions for the anaerobic fermentation process have been developed (Gaisina, 2022; Osmonov, 2011). One of the most important areas of development of the national economy of the Azerbaijan Republic is the technological modernization of systems and equipment of chemical and related industries. In this case, further development of theoretical description of processes and devices of various industries plays an important role. Recently, much attention has been paid to the study of biotechnological processes and the development of equipment for their implementation. One of these processes is the process of obtaining biogas as a result of anaerobic fermentation of organic waste (Patent, 2007).

Materials and Methods

Bioreactor with an External Circulation Collector
The bioreactor consists of a cylindrical body with a conical bottom and a lid, pipes for substrate feeding, gas removal, and discharge of the target product (Pristupa, 2007). It also includes a circulation system. According to the research, a circular collector is placed in the upper part of the reactor, connected to the body through pipes mounted at different angles relative to the reference line touching the seating point. Additionally, a Z-shaped collector is installed in the conical bottom

section, directed toward the base of the reactor (Kuznetsova, 2013). The design of these collectors and the placement of inlet systems are engineered such that the flow during circulation breaks up the top layer of the substrate, effectively preventing scum formation. Periodic circulation ensures uniform temperature distribution throughout the bioreactor's volume and accelerates the fermentation process through effective mixing. The downward-directed flows from the lower collector periodically flush out the sediment that accumulates at the bottom of the reactor. The schematic diagram of the bioreactor, as well as diagrams of its individual components, are presented in Figures 1–4. The general view of the bioreactor with relevant connections is shown in Figure 1. It consists of the main body (1), the collector (2), and the circulation system. Pipes (3) and (4) are designated for substrate loading and discharge, respectively.

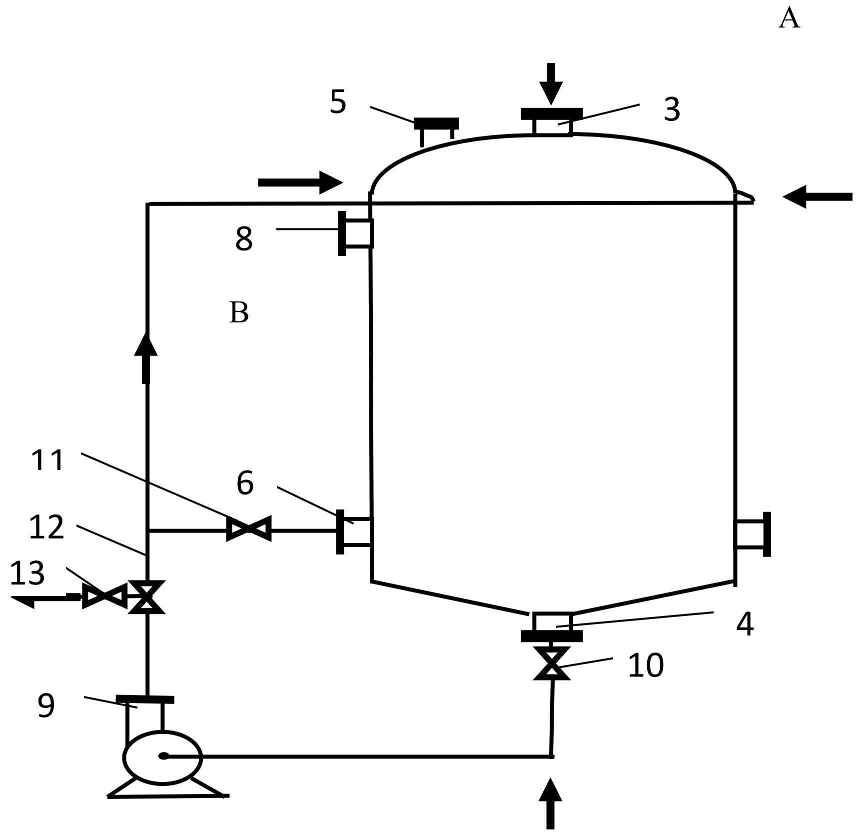

Figure 1. General External View of the Bioreactor

1 – Body; 2 – Collector; 3, 4, 5, and 6 – Branch Pipes; 7, 8 – Tubes; 9 – Circulation Pump; 10, 11, 12, 13 – Valves

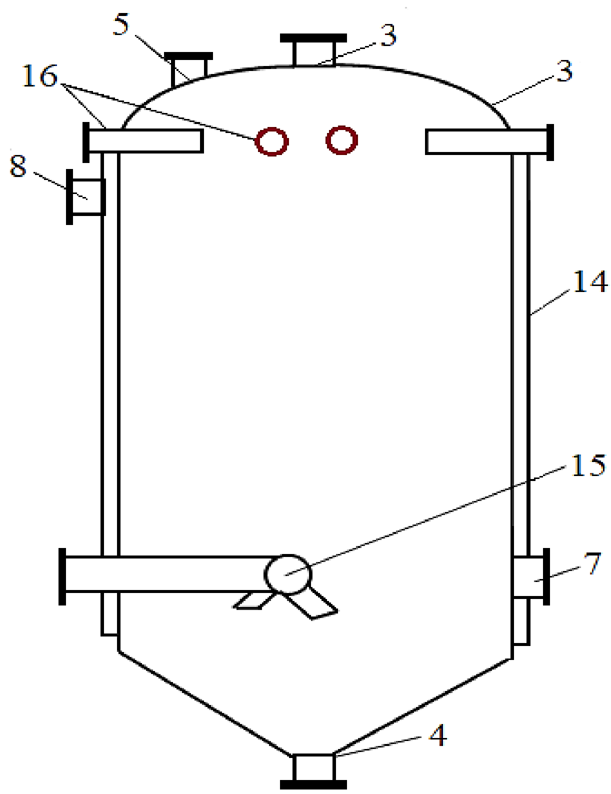

Figure 2. General Sectional View of the Bioreactor

1 – Body; 2 – Collector; 3, 4, 5, and 6 – Branch Pipes; 7, 8 – Tubes; 9 – Circulation Pump; 10, 11, 12, 13 – Valves; 14 – Thermal Jacket; 15 – Z-shaped Collector; 16 – Tubes

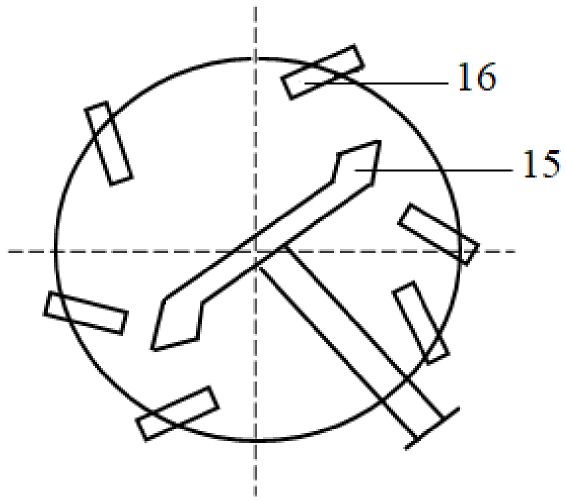

Figure 3. Top Sectional View of the Bioreactor

15 – Z-shaped Collector; 16 – Tubes

The biogas plant works as follows. Organic waste (manure, litter, straw, etc.) is fed through a pipe into a methane tank, where it is fermented to produce biogas and high-quality biofertilizer. A bimetallic temperature sensor signals a change in temperature. Fermentation can occur in psychophilic (5-25°C), mesophilic (27-40 °C) and thermophilic (44-60 °C) temperature modes. The substrate is heated by passing the biogas through vortex tubes. The pressure in the methane tank is controlled by an electric contact pressure gauge. The biogas obtained in the methane tank is sent through a pipeline via a condensate drain to the biogas purification filter, where harmful impurities are removed, and then sent through a pipeline to the compressor. To ensure a uniform temperature in the methane tank and prevent the formation of a crust under the dome, which prevents the release of biogas, the compressor is turned on for two minutes every four hours. To do this, the valve is opened, and the biogas in the compressor is fed into the vortex tube under pressure. This causes a large difference in the temperatures of the gas passing through the vortex tube, since the cold biogas from the cavity enters the gas holder, which has a lower ambient temperature, and is then sent to the consumer.

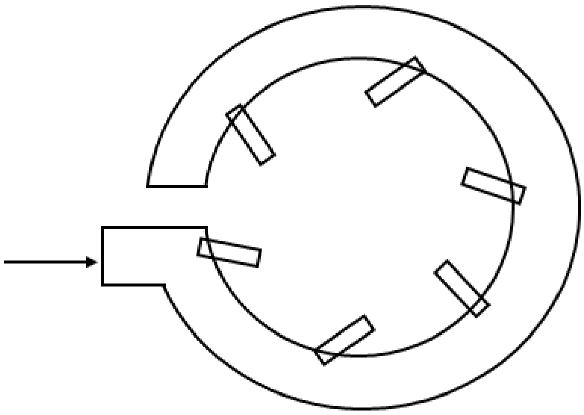

Figure 4. General View of the External Distribution Collector

Pipes 5 and 6 are intended for biogas extraction and for directing the flow into the lower internal collector. The circulation of the reaction mass and the discharge of the fermented mixture are carried out via pump 9. Valves 10, 11, 12, and 13 are designated for flow direction during circulation and discharge operations. The sectional views A-A and B-B of the bioreactor are shown in Figures 2 and 3. Six tubes are positioned at various angles along the perimeter of the bioreactor body and are connected to the external circular collector. The angles at which the tubes are mounted on the body are determined relative to the tangents drawn at those points. The bioreactor is equipped with thermal jacket 14 and a special Z-shaped collector 15. The upper circular collector 2, as shown in the top view (Figure 4), is designed to distribute the flow into tubes 16 during circulation. The view of the lower collector is presented in Figure 5. It has a Z-shaped configuration, with its ends directed downward toward the bottom of the bioreactor. This collector is designed to agitate and remove the sediment accumulated at the bottom section. The operation of the described bioreactor is carried out as follows (Sadigov, 2025). Flow technology was previously used to feed most biogas plants. It involves feeding a certain amount of fresh substrate into the reactor, while simultaneously moving the already fermented residue into a specially designed storage facility. It can be moved into the storage facility by displacement or by selection from the reactor in one of the ways. With this loading technology, the reactor always remains filled and is emptied only for inspection and regular repair work (Hardi, 2025; Yu, 2013).

Results and Discussion

As a result of anaerobic digestion, the main part of biodegradable organic matter is decomposed (oxidized) into CO_2, H_2O and NH_3 (Ziganshin, 2013; Yu, 2023). The remaining organic matter loses its tendency to be processed. Four groups of bacteria participate in anaerobic digestion, mainly *Bacillus, Micrococcus, Pseudomonas* and *Clostridium*, which carry out the stages of enzymatic hydrolysis and acid formation. Microorganisms secrete enzymes, breaking down complex compounds into simple ones (Hasanova, 2021; Nasirova, 2022). Bacteria grow in the presence of a nutrient medium containing carbon and oxygen. The results of many scientists' studies show that a stable fermentation temperature is important for the successful methane production process, and temperature changes affect not only the speed of the process, but also the quantitative composition of the resulting products. The thermophilic mode (50-55 °C) is most applicable in practice. In Azerbaijan, due to difficult climatic conditions, the medium temperature mode (33-35 °C) is mainly used, which is not energy-consuming for biogas plants.

Operation and Structure of the Internal Circulation Collector Bioreactor

After the diluted (substrate) waste is loaded into the bioreactor through pipe 3 to the required volume, a heat carrier (steam or hot water) is supplied to the thermal jacket of the bioreactor. Once the desired temperature regime is established, the circulation pump (9) is activated. At this stage, valves 10 and 12 are opened, while valves 11 and 13 remain closed. In this mode, the flow drawn from the bottom of the reactor enters the upper collector, is distributed into the pipes, and induces a rotational motion in the upper substrate layer, ensuring thorough mixing. If valves 10 and 12 are closed while 11 and 13 are opened, the flow is directed from pipe 6 into the lower collector and removes sediment from the bottom of the reactor. When valves 10 and 11 are open and valves 12 and 13 are closed, the fermented biomass is discharged from the reactor. The biogas generated during fermentation is directed to the gas holder via pipe 5.

Bioreactor with Internal Circulation Collector

The bioreactor consists of a cylindrical body with a dome-shaped cover and a conical bottom. It is equipped with inlet/outlet pipes for substrate loading, product and biogas removal, a gas collector, and a circulation line. At the upper internal part of the reactor, a distributor-mixer collector is installed, containing several pipes positioned at specific angles and distances from each other relative to the substrate surface. At the lower internal part, above the conical bottom, a segment-shaped heat exchanger is mounted, consisting of separate elements connected by pipes.

The structure of the distributor-mixer collector enables the circulation flow to moisten and disintegrate the surface of the substrate, activating both horizontal and vertical motion of the reaction mass and ensuring efficient mixing. This prevents scaling within the bioreactor and ensures uniform temperature distribution throughout the entire reaction volume. The heat exchanger at the bottom not only creates and maintains the temperature regime but also acts as a barrier, preventing large substrate particles and scale from entering the outlet pipelines.

The schematic diagram of the bioreactor and its individual components are shown in Figures 5 to 9. Figure 5 presents the general cross-sectional schematic of the bioreactor, which includes: the main body (1), heat exchanger (2), distributor-mixer collector (3), inlet and outlet pipes for substrate, biomass, and biogas (4, 5, 6), heat carrier inlet pipes (7, 8), circulation pump (9), and control valves (10, 11, 12). The substrate loading level is regulated by the overflow line (13). For maintenance purposes, an inspection hatch (14) is provided inside the bioreactor. To prevent heat loss, thermal insulation (15) is used. The heat exchanger layout is shown in figure 6, where two segmental distributors are connected by pipes 16 and 17. The distributor-mixer collector shown in figures 7 and 8 consists of the body (18) and multiple outlet pipes (19).

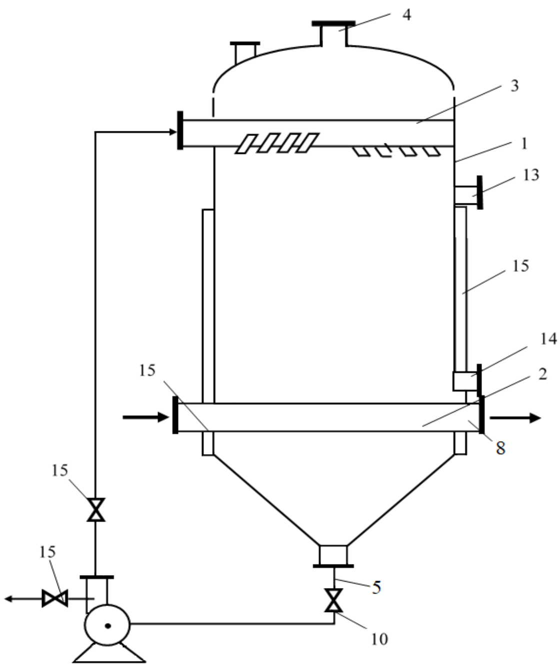

Figure 5. General Sectional View of the Bioreactor

1 – Body; 2 – Heat Exchanger; 3 – Distributor and Mixer Collector; 4, 5, 6, 7, 8, 13, 14 – Branch Pipes; 15 – Thermal Jacket; 10, 11, 12 – Valves; 9 – Circulation Pump

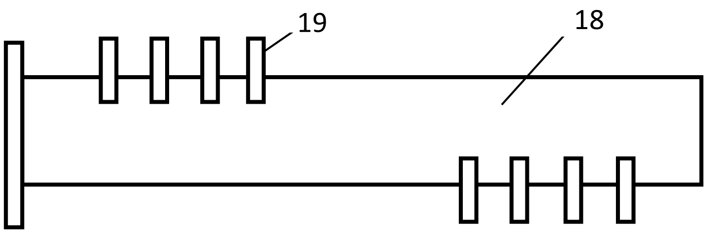

Figure 6. General View of the Distributor and Mixer Collector

18 – Body; 19 – Tubes

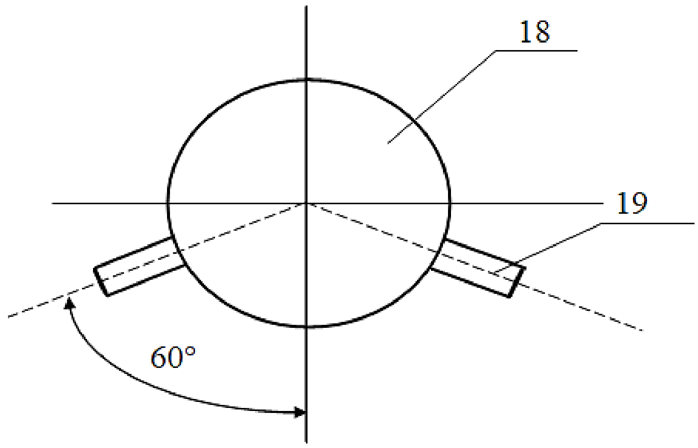

Figure 7. Scheme of the Connection of Tubes to the Body

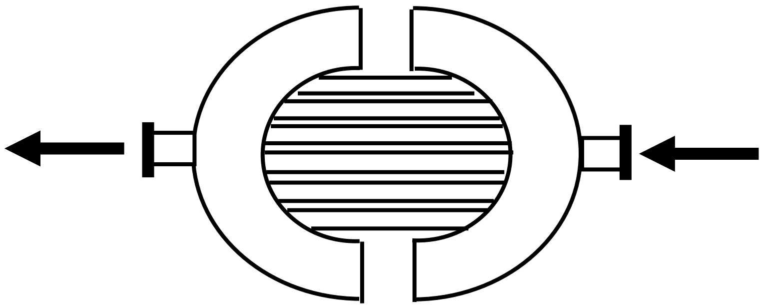

Figure 8. Top View of the Special Heat Exchanger

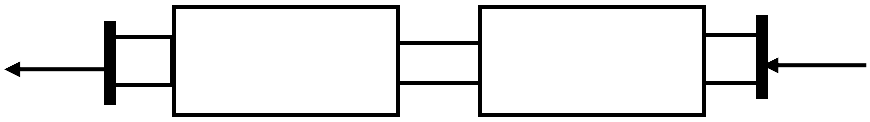

Figure 9. Side View of the Special Heat Exchanger

The tubes are connected to the body at specific angles and are directed in various directions relative to the radius of the bioreactor. The bioreactor operates as follows: The pre-prepared solution is loaded into the bioreactor through branch pipe number 4. After the bioreactor is filled to the required volume, steam or hot water is supplied to heat exchanger number 2, and circulation pump number 9 is activated. Circulation is carried out in a periodic mode. The circulation line is connected to the distributor and mixer collector number 3. During circulation, the solution taken from the lower heated zone of the bioreactor is directed into collector 3, and jets exiting the tubes under pressure strike the surface of the substrate, breaking it up and mixing it in both radial and vertical directions. Thus, complete mixing within the bioreactor volume and uniform temperature distribution are ensured.

The gas flow rate starts after filling, reaches maximum productivity in a few days, and then begins to decrease slowly. Finally, after the specified fermentation time has elapsed, the fermentation chamber is emptied in one go. In this case, part of the fermentation sludge is returned back to seed the next batch of substrate fed to the reactor. Constant flow rate for one reactor is not possible; it is possible to equalize the fluctuations in gas output by fermenting in several reactors with loading shifted in time.

The advantage of anaerobic methods is that, unlike classical aerobic methods of biological treatment, when all bacteria work under the same conditions, in properly organized anaerobic processes, bacteria are separated – they work under different physical and chemical conditions. This allows you to optimize the anaerobic digestion process in terms of productivity, manage it and, ultimately, improve the quality of waste processing.

Conclusion

As a result of a set of theoretical and experimental studies, the nature of the influence of biomass temperature on the efficiency of the anaerobic fermentation process in the mesophilic mode was established. A dependence of the growth rate of microorganisms on temperature was proposed and the values of the coefficients included in it were determined. The obtained dependencies allow one to determine the speed and specific yield of biogas and can be used in the design of industrial biogas complexes.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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