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Results of experimental studies of a small-volume biogas plant

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Abstract. Utilisation of organic waste from agriculture is one of the most acute environmental problems that require immediate solution. This problem is relevant for the majority of farms and agricultural complexes, regardless of the number of animals. Violation of waste disposal rules can lead to contamination of soil and water bodies, as well as to negative consequences for human and animal health. This paper considers the method of anaerobic digestion of agricultural organic waste as an effective solution to this problem. Anaerobic digestion is a process in which organic matter decomposes without access to oxygen, resulting in the formation of biogas and high quality organic fertilisers. The processing of organic waste in a biogas plant contributes to sustainable agriculture. The aim of the research is to increase the energy efficiency of the organic waste utilisation process by developing the design and substantiating the main parameters of a low-volume biogas plant. Experimental studies were carried out according to the known methods on the newly developed biogas plant. The digestion temperature was maintained within the range of 50-55 °C. Experimental studies allowed to determine the rational design and technological parameters of the low-volume biogas plant.

1 Introduction

In today's agricultural business, organic animal waste is a serious problem. The treatment of manure effluent from pig and poultry farms is an important challenge that is solved by various chemical methods such as liquid chlorine, anhydrous ammonia (NH_3) and nitrogen. Many dairy and meat plants are faced with excess manure and litter. These wastes, while having a high potential as fertilisers, often go unused. However, their direct application to soil is limited due to toxicity. Today, organic wastes are processed using various technologies (composting, drying, vermicomposting, etc.), but still the issues of environmental pollution are not completely solved [1, 2].

Nevertheless, one of the most effective ways of manure utilisation is the thermal method using biogas plants. This approach not only efficiently utilises agricultural waste, but also creates valuable fuel and biofertilisers that contribute to the improvement of soil conditions. Anaerobic digestion of organic waste is a highly efficient method with many advantages over aerobic processes. Anaerobic processes produce methane, which is an environmentally friendly biofuel. It is estimated that the costs of aerobic processes far exceed the requirements of anaerobic processes, making the latter economically more favourable. Anaerobic fermentation promotes the sequential decomposition of complex organic matter into simpler compounds, which converts a significant portion of carbon into biogas and carbon dioxide. Anaerobic methane-producing bacteria, which are highly sensitive to environmental conditions, play a key role in this process. The product of the methanogenic stage is methane (CH_4). The destruction of organic acids results in an increase in the pH of the medium, leading to an alkaline reaction. Therefore, the methanogenic stage is often referred to as 'alkaline fermentation' [3, 4].

According to literature sources [5, 6], more than 45% of livestock complexes, the manure generated by the activity is not exported to their fields as organic fertiliser. Eventually, organic wastes of animals and birds are accumulated in lagoons, often located next to natural water bodies.

Since ancient times, manure, especially horse manure, has been used as a fertiliser, but in recent years microbiological conversion of manure into biogas has become increasingly popular. The activities of agricultural enterprises of the agro-industrial complex lead to alarming changes in the soil ecosystem, where the humus content is noticeably decreasing and mineral nutrient reserves are being depleted. These processes can provoke a disturbance of the natural balance, opening the way to land degradation. The most important aspect of sustainable agriculture is the production of biogas and biofertilisers that fulfil strict requirements. Key conditions are the absence of nutrient losses of nitrogen, phosphorus and potassium, as well as the need to decontaminate and deodorise the fertiliser produced. Furthermore, biofertilisers must be free of weed seeds, viable eggs or helminth larvae. It is also important to comply with the norms of heavy metal concentrations and maximum pesticide residues in the products, which is regulated by the Russian Federal Service for Supervision of Consumer Rights Protection and Human Welfare. This guarantees not only safety for the

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ecosystem, but also ensures soil fertility necessary for further sustainable agricultural development [7, 8].

The process of manure conversion in biogas plants allows the production of high quality biofuel, and also helps to minimise nitrogen losses by converting it into mineral forms, as well as effectively destroying weed seeds and helminth eggs. As a result of recycling, macronutrients become available for plant uptake. During this process, pathogenic microorganisms, weed seeds and other undesirable components are completely destroyed, thus improving soil quality and increasing its agronomic value. Animal waste treatment is aimed at obtaining useful products and waste neutralisation, which allows reducing their hazard class to IV-V [9, 10].

2 Materials and Methods

The low-volume biogas plant developed at Kazan State University of Economics (Figure 1) consists of a reactor, stirrer, heating element, programmer, gas holder, gas meter, compressor, control devices, burner and other elements. To start up the biogas plant, the substrate to be processed is first prepared and then loaded into the reactor. The process of loading the prepared substrate into the reactor can be carried out in two main ways: manually, through the top of the reactor, or automatically, using pumping equipment connected to the outlet of the plant. For the preparatory part of the start-up, the reactor must be connected to an electrical network with 220 V voltage, which ensures its operation and control. During the operation of the biogas plant, it is important to maintain a stable temperature regime, as this critically affects the efficiency of methane formation, during which microorganisms decompose organic matter and produce methane. The temperature in the reactor must be within optimum values to ensure the activity of the methanogenic bacteria. Our biogas plant uses a heating element for heating to minimise heat loss. Once the reactor is started, biogas production begins. The biogas produced is accumulated directly in the reactor, after which it passes through a water gate and enters the small gas holder. The water gate prevents the biogas from flowing back into the reactor, which ensures the safety of the plant and prevents possible emergencies. In addition, the presence of gas bubbles in the water seal serves as a visual indicator of the active gassing process, which allows operators to monitor the efficiency of the biogas plant. The volume of biogas produced is recorded by a gas meter, which provides accurate data on the capacity of the plant. The biogas is then forcibly pumped to the gasholder through a filter cleaner to remove various impurities and ensure the quality of the biogas. A low speed compressor is used for pumping, which ensures safe pumping of biogas.

To increase the safety of the plant, a safety valve is provided to prevent over-pressurisation of the gasholder. The vent valve automatically operates when the set pressure is exceeded, which protects the equipment and prevents emergencies.

The continuous burning of biogas, which is observed during the flammability test, is an important quality indicator. Several factors should be considered during the flammability test, including flame colour, flame stability and burn time. If the biogas burns with an even, bright flame with no sudden fluctuations, this indicates a high content of methane, which is the main component of biogas. Stable and continuous combustion indicates that there are no impurities that could degrade the quality of the biogas. The use of biogas as an alternative energy source not only contributes to the reduction of greenhouse gas emissions but also allows efficient waste utilisation, making it a promising solution for sustainable development. The results of the flammability test of biogas not only confirm its high quality, but also emphasise its potential as an energy source for various needs, including heating and electricity generation. The process from substrate loading to biogas production and utilisation is a complex and multi-stage system that requires careful monitoring and control to maximise efficiency and safety.

The resulting biofertiliser is removed by gravity through an outlet or forced by a pump.

Figure 1. Small-volume biogas plant: 1 - reactor; 2 - small gas holder; 3 - burner; 4 - electro-contact manometer; 5 - gas holder; 6 - bimetallic thermometer; 7 - temperature regulator; 8 - programmer OVEN PR 110; 9 - safety valve.

3 Results and discussion

In order to achieve an efficient biogas production process, it is necessary to ensure good substrate mixing, which affects the efficiency of methanogenesis. The torque generated on the agitator frame is due to the differences in velocity between the frame and the substrate being processed. This torque can be quantified based on the forces acting on the frame. In the simplest case, when the agitator rotates with a blade, which is a frame of height (h_f) and the axis of rotation of the frame coincides with the axis of the cylinder, a force is applied to an elementary section of the frame length, which creates a torque [11].

$$d\mathrm{M}_{\mathrm{rot}} = \varsigma_f \frac{\rho u^2(r)}{2} h_{\mathrm{f}} r dr, \tag{1}$$

where ς_f – hydraulic resistance coefficient of the frame sides (according to the reference book); ρ - substrate density, kg/m; *u(r)* - velocity of the frame edge flow at distance r, m/s; h_f - frame height, m; *r* - half of the frame width, m

The moment of forces resulting from the hydraulic resistance of the cylindrical part of the biogas plant reactor wall is determined considering the influence of various factors such as flow velocity, viscosity of the working substrate and geometrical parameters of the reactor.

$$M_{Wall} = S_{cyl}\frac{D}{2}\cdot\tau. \tag{2}$$

$$S_{cyl} = LH, \tag{3}$$

Where S_{cyl} wetted wall area of the cylindrical part of the reactor, m^2; *H* - reactor height, m; *τ* - tangential stresses, Pa; *L* - wetted perimeter of the cylindrical part of the reactor, m $(L = \pi D)$.

The reactor bottom resistance moment M_{bot} can be determined by integrating the expression describing the distribution of forces acting on the bottom. This requires integration between 0 and $\frac{D}{2}$, which represents the radius.

$$dM_{bot} = \pi\rho\varsigma_f V^2(r) r^2 dr, \tag{4}$$

where $V = kr$. *k* is the correction factor, s^2; *r* is the radius, m.

$$M_{bot} = \pi\rho\varsigma_f V^2 \frac{2}{D}\int_0^{D/2} V^2(r) r^2 dr. \tag{5}$$

Integrating expression (5) within the range from 0 to $\frac{D}{2}$, we obtain

$$M_{bot} = \frac{1}{90}\pi\rho\varsigma_f \kappa^2 D^4, \tag{6}$$

where *k* – correction factor, s^2.

To determine the total moment of resistance of the reactor vessel, the geometric parameters of the structure, substrate properties, and operating conditions must be taken into account:

$$M_{ves} = M_{CT} + M_{bot} =$$
$$= \frac{1}{8}LHD^2\varsigma_f\rho\kappa + \frac{1}{90}\pi\rho\varsigma_f\kappa^2 D^4 = \tag{7}$$
$$= \pi D^3\varsigma_f\rho\kappa\left(\frac{H}{8} + \frac{D\kappa}{90}\right).$$

It follows from expressions (6) and (7) that in order to reduce the momentum of hydraulic resistance forces of the reactor wall, as well as to reduce the energy consumption of the process, it is necessary to strive to minimise the wetted area of the cylindrical part of the reactor [11]. Achieving this at a given reactor volume (V) is possible solely by optimising the D/H ratio.

With a fixed reactor volume, the surface area of the reactor can be determined using the following expression:

$$S_{\mathrm{surf}} = \left(\frac{D^2}{4} + \frac{DH}{2}\right), \tag{8}$$

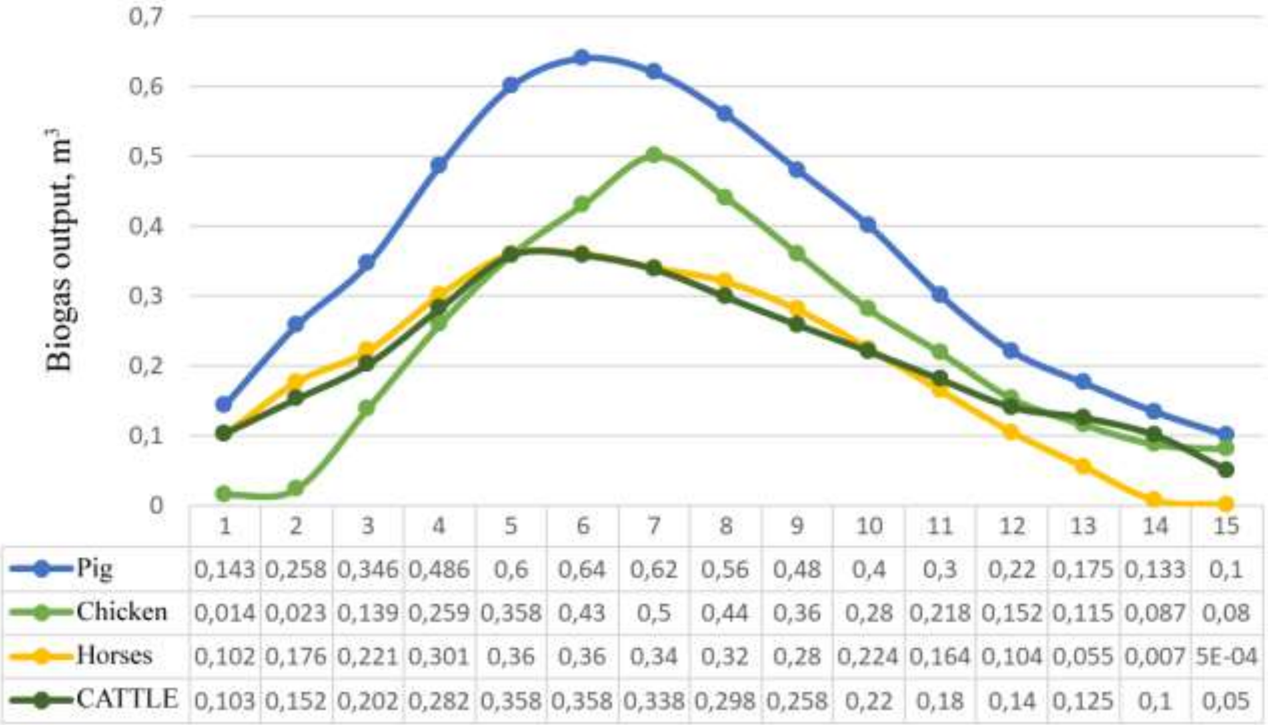
differentiating expression (8) by $\frac{dS}{dD}$ we obtain,

$$\frac{dS}{dD} = \frac{\pi}{4}\left(2D - \frac{8V}{\pi D^2}\right) = 0,$$
$$2D - \frac{8V}{\pi D^2} = 0,$$
$$2D = \frac{8V}{\pi D^2},$$
$$D^3 = \frac{4V}{\pi},$$
$$D = H.$$

Based on the presented mathematical calculations [11, 12] the height of the reactor filling should be equal to its diameter. Such ratio of the reactor favours uniform distribution of microbial mass and nutrients, which, in turn, provides maximum biogas yield.

To evaluate the biogas production from various organic wastes under thermophilic digestion conditions, field experiments were conducted and the results are presented graphically in Figure 2. Prior to each experiment, a recyclable substrate including cattle (cattle) manure, pig, horse and poultry manure was prepared. These diverse components served as the basis for an in-depth study of the biogas potential, revealing the diversity of processes occurring in the thermophilic environment. A unique portion of substrate was incorporated into each substrate batch to track the dynamics of outgassing and identify optimal conditions for biochemical decomposition.

The prepared substrate was then loaded into a reactor where digestion took place. During the experiments, the temperature was gradually increased and kept constant after reaching 55 °C, which is the optimum regime for thermophilic digestion. Periodic stirring of the substrate was carried out to break the crust formed, which contributed to a more uniform distribution of microorganisms and improved the biogas formation process. The biogas output was recorded using a gas meter to accurately measure the volume of biogas produced during the experiment. The biogas produced was then pumped to a gas holder for further analysis and utilisation.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Pig	0,143	0,258	0,346	0,486	0,6	0,64	0,62	0,56	0,48	0,4	0,3	0,22	0,175	0,133	0,1
Chicken	0,014	0,023	0,139	0,259	0,358	0,43	0,5	0,44	0,36	0,28	0,218	0,152	0,115	0,087	0,08
Horses	0,102	0,176	0,221	0,301	0,36	0,36	0,34	0,32	0,28	0,224	0,164	0,104	0,055	0,007	5E-04
CATTLE	0,103	0,152	0,202	0,282	0,358	0,358	0,338	0,298	0,258	0,22	0,18	0,14	0,125	0,1	0,05

Figure 2. Experimental results when thermophilic digestion is used

Experimental dependences of the volume of biogas release at the low-volume biogas plant were established in the process of thermophilic digestion of various types of organic waste, which are presented in Fig. 2. The results of the research allow us to draw conclusions about the potential of utilisation of these wastes for renewable energy sources.

4 Conclusion

To analyse the presented figure showing the results of the thermophilic digestion regime, attention should be paid to the coordinate axes: the X axis denotes the consecutive cyclic digestion days (from 1 to 15) and the Y axis demonstrates the volume of biogas released in cubic metres. Most notable is the peak of biogas yield observed on day 6, when the pig manure substrate reaches a maximum value of 0.64 m^3, while chicken and horse waste show results of about 0.5 m^3 and 0.37 m^3, respectively. Pig manure consistently leads in terms of biogas released throughout the experiment, while cattle manure substrate shows lower biogas yield. The graph shows that the biogas yield starts from the first day, reaches a maximum on day 6-7, and then gradually decreases, approaching zero by day 15. Thus, the thermophilic regime is most effective for pig manure, while it is less productive for cattle waste. It is recommended to optimise the digestion process, paying attention to timing and substrate type, in order to achieve maximum biogas yield.

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