The synergistic effect of the thickened digestate treatment in the vortex layer apparatus prior to its recirculation into the reactor on the characteristics of anaerobic bioconversion of organic waste

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Abstract. For the first time, the effect of thickened digestate treatment in a vortex layer apparatus (VLA) prior to its recirculation into anaerobic reactor on the efficiency of anaerobic bioconversion of an organic substrate was investigated. At the hydraulic retention time of the recirculated digestate in VLA for 30 seconds, of the substrate in the anaerobic bioreactor for 8 days and the recirculation coefficient of 1.5, the average specific yield of biogas increased by 75.2%, and the average volumetric methane production – by 16.8%. There was no increase in methane concentration in biogas, while the average concentration of hydrogen sulfide in biogas decreased by 8 times.

1. Introduction

Currently, interest in deriving energy from renewable sources, such as plants and agricultural waste from plant growing and animal husbandry, the food and alcohol industries, otherwise called biomass, including from sewage, is still great. Basically, biomass contains cellulose, hemicellulose, fats, proteins, carbohydrates and other components and can be converted into solid (granules, briquettes), liquid (bioethanol) or gaseous (hydrogen, methane) energy carriers [1–4].

Using microbiological conversion of biomass under anaerobic conditions, valuable gaseous fuels like hydrogen and methane can be obtained. Calculations show that the efficiency of energy storage in hydrogen during fermentation does not exceed 20-30%, while more than 80% of the energy originally contained in the organic substances is converted to methane [5, 6]. Virtually any organic raw material, with the exception of untreated lignin and waxes, can be subjected to methane fermentation [7–9].

One of the ways to increase the efficiency of the process of anaerobic bioconversion of organic waste is to increase solid retention time in the reactor by means of digestate recirculation [10]. As a result of industrial tests, after the introduction of recirculation, it was possible to achieve the degree of volatile solids (VS) destruction to an average of 56.6%, while 42.2% VS destruction was achieved without recirculation. The increase in destruction degree led to a significant improvement of the
effluent sedimentation. The average increase in biogas yield was 3.0%. The negative effect of sludge recirculation on the technological work of the digester was not recorded [11].

An important stage in the technology of anaerobic processing of organic waste is the preliminary processing (preparation) of waste for fermentation. The main tasks of preparing waste for fermentation are:

1. separation of gross inclusions (stones, boards, large debris, etc.);
2. mixture homogenization;
3. heating the mixture to a process temperature.

To solve these tasks, various equipment is used, such as sieves, centrifuges, grinders, homogenizers, heat exchangers, etc. This equipment has a significant energy consumption, so the search and development of new technical solutions for preparing organic waste for anaerobic processing in a digester is an urgent scientific and engineering task.

One of the most promising and energy-efficient methods of preparing a substrate for fermentation is the processing in an apparatus of vortex layer of ferromagnetic particles (VLA), which is created by exposure to a rotating magnetic field [12]. The positive effect of processing of various organic substrates in VLA on the characteristics of methanogenic fermentation, and in particular, on the kinetics of methanogenesis, the degree of destruction of organic matter, the methane content in biogas, and the disinfection of waste, was previously shown [13–16].

The aim of this work was to investigate for the first time the efficiency of the implementation of VLA for processing of recirculated digestate during methane fermentation of organic waste.

2. Materials and methods

2.1. Experimental plant

The experimental biogas plant was designed to study the effect of digestate recirculation with simultaneous pre-treatment of a mixture of digestate with the initial substrate on the efficiency and stability of the process of anaerobic bioconversion of liquid organic waste. The main parameters determined during the experiment were the duration of pretreatment of the mixture of digestate with the initial substrate and the ratio of the volumes of recirculated digestate and the initial substrate, at which the process of anaerobic bioconversion proceeded stably, and the specific biogas yield was the highest together with improvement of the biogas quality (increase in methane, as well as decrease in carbon dioxide and hydrogen sulfide content).

The technological scheme of the experimental biogas plant is shown in Figure 1. Experimental plant worked as follows. The initial substrate was fed into the laboratory reactor for preparation (RP) of the substrate for anaerobic digestion – 7 through the loading device. Also, digestate was fed into RP – 7, by means of the digestate recirculation pump – 18 from a device for digestate thickening – 13. In the RP – 7, the mixture of the initial substrate and the digestate was heated to the process temperature (55 °C) and vigorously stirred by the mixing device – 10 before this mixture was loaded into the laboratory anaerobic bioreactor (LABR) – 3. Heating was carried out by the heater – 9. Through the pipe outlet of the RP – 7, the mixture of the initial substrate and the digestate was fed by the recirculation pump – 11 into the working chamber of VLA – 4, where pre-treatment took place for a predetermined time, and the pre-treated mixture was displaced into RP – 7 through the loading device. Next, pretreated and heated mixture flowed by gravity through the loading valve – 19 and the loading device – 12 into the LABR – 3.

In the LABR – 3, the pre-processed mixture of the substrate and digestate was digested in thermophilic mode, after which it was automatically discharged (overflow) through the device for unloading – 2 into the device for digestate thickening – 13 upon adding the next portion of the feed. After a predetermined separation time (24 hours), the supernatant from the device for digestate thickening – 13 was removed through the supernatant removal valve – 14. Biogas generated during the anaerobic bioconversion of the organic matter of the substrate was collected in the upper part of the LABR – 3 and discharged through gas meter and analyzer – 1.
Figure 1. Technological scheme of an experimental biogas plant 1 – Gas meter and analyzer; 2 – LABR discharge device; 3 – LABR; 4 – working chamber of the VLA; 5 – VLA; 6 – VLA coil; 7 – RP; 8 – RP mixer drive; 9 – RP heater; 10 – RP mixing device; 11 – circulation pump; 12 – RP loading device; 13 – device for digestate thickening; 14 – supernatant removal valve; 15 – LABR heater; 16 – LABR mixing device; 17 – LABR mixing device drive; 18 – digestate recirculation pump; 19 – loading valve of the prepared mixture.

2.2. Initial substrate
The initial substrate for anaerobic treatment was a mixture of a model of the organic fraction of municipal solid waste (feed-stuff K-65) [15] and tap water in a ratio of 50 g/l. The substrate was prepared as follows: K-65 was added to tap water and kept for 30 minutes at room temperature. Characteristics of the initial substrate were as follows: humidity – 95.7%; organic matter content – 40 g/l.

2.3. The thickened digestate
The thickened digestate was obtained in a device for digestate thickening by gravitational separation for 24 hours. After 24 hours of gravity separation, the supernatant was removed through the supernatant removal valve. Characteristics of the thickened digestate were as follows: average humidity – 94.4%; average organic matter – 45.6 g/l.

2.4. Experiment setup
The experimental plant worked in two modes:
– “C” – mode without pretreatment in VLA and recirculation of the thickened digestate (control);
– “VLAR” – mode with the recirculation of the thickened digestate and the processing of the mixture of the initial substrate and digestate in VLA.

In “C” mode (control), 6 l of initial substrate was loaded daily for 40 days, while the hydraulic retention time (HRT) of the laboratory anaerobic bioreactor was 8 days, and its organic loading rate (OLR) was 5 kg VS/(m³ day). The amount of biogas generated and the biogas content were measured daily.
In the «VLAR» mode (with recirculation of the thickened digestate and processing of the mixture of the initial substrate with digestate in VLA) 4 l of the initial substrate was added daily for 40 days, with the addition of 2 l of the thickened digestate. HRT in LABR was 8 days, and OLR was 3.33 kg VS/(m²·day). The processing time of the mixture in VLA was 6 min (HRT in the working chamber of VLA was 30 s, as the most optimal, according to [13]). The recirculation coefficient was 1.5. The amount of biogas generated and the biogas content were measured daily.

2.5. Analytical methods
The total solids content (TS) was determined after drying the sample to constant weight at 105 °C. The ash residue was determined by burning a dry sample in a muffle furnace to a constant weight at 650 °C. The content of volatile solids (VS) was calculated as the difference between TS and the ash residue.

The concentration of methane, carbon dioxide and hydrogen sulfide in the gas phase was determined using an MRU Biogas Optima 7 gas analyzer by taking gas samples from a sampler.

Sensors installed in the gas analyzer:
- methane concentration – NDIR sensor;
- carbon dioxide concentration – NDIR sensor;
- hydrogen sulfide concentration – electrochemical sensor;
- oxygen concentration – electrochemical sensor.

3. Results and discussion
The results of the experiment in two modes are shown in Figures 2–4, as well as in Table 1. Figure 2 shows the specific biogas yield during the experiment, based on VS of initial substrate. The specific biogas yield throughout the experiment was higher in the «VLAR» mode than in the “C” mode. On average, the increase in the specific biogas yield was 75.2% (Table 1). This can be explained by the fact that processing the substrate in VLA provides fine grinding of suspended particles in the substrate with simultaneous intensive mixing, as well as introducing iron particles into the substrate by several tenths of a percent, as shown in [16], which intensifies the process of anaerobic bioconversion due to the process of direct interspecies electron transfer [17]. Also, the magnetic properties of the ash were found when determining the ash content of the digestate. It should be noted that the organic matter (OM) contained in the thickened digestate acts not only as a nutrient medium along with the OM of the initial substrate for anaerobic microorganisms, but also as a source of the anaerobic microorganisms themselves. Moreover, from [14] it is known that substrate treatment in VLA does not affect the viability of anaerobic microorganisms.

Figure 3 shows the volumetric methane production during the experiment. In [11], recirculation of the digestate led to increase in the average biogas yield up to 3.0% during methane fermentation of sewage sludge. Figure 3 shows that the volumetric methane production in “VLAR” mode was higher than in “C” mode throughout the experiment, with the exception of the first 4 days. Average concentration of methane in biogas was the same in both modes (Table 1), however, the volumetric methane production in the “VLAR” mode was 16.8% higher than in the “C” mode. In [15], treatment of the similar substrate in VLA resulted in 18% higher specific biogas yield obtained in a batch mode under thermophilic conditions.

Figure 4 shows the dynamics of the hydrogen sulfide content in biogas during the experiment. Concentration of hydrogen sulfide in biogas in “VLAR” mode was significantly lower than the concentration of hydrogen sulfide in biogas in the “C” mode throughout the experiment. This can be explained by the fact that during processing in VLA, iron particles are introduced into the digestate, which contribute to the binding of hydrogen sulfide in the form of iron sulfides. The average concentration of hydrogen sulfide in “VLAR” mode was 8 times less than in “C” mode (Table 1). It should be noted that such a significant reduction in the content of hydrogen sulfide in biogas will reduce the cost of cleaning and upgrading biogas before its direct use, for example, as a gas engine fuel.
**Figure 2.** Specific biogas yield during the experiment

**Figure 3.** Volumetric methane production during the experiment.
Figure 4. The concentration of hydrogen sulfide in biogas during the experiment.

Table 1. Parameters of the anaerobic bioconversion process under different modes.

| Mode          | The average concentration in biogas | The average specific biogas yield, l/(day·kg VS) | Average volumetric methane production, m³/(m³·day) |
|---------------|------------------------------------|-----------------------------------------------|-----------------------------------------------|
|               | CH₄, % | CO₂, % | H₂S, ppm |                                    |                                                |
| “C”           | 58.11  | 40.43  | 112      | 330                                 | 0.96                                          |
| “VLAR”        | 58.11  | 40.54  | 14       | 578                                 | 1.12                                          |
| “VLAR” /“C” ratio | 1.003 | 0.125  |          | 1.75                                 | 1.17                                          |

4. Conclusion

The influence of recirculation of the thickened digestate together with the processing it in VLA on methane fermentation efficiency was studied. The processing in VLA provides grinding of substrate components with simultaneous intensive mixing, which improves the rheological properties of the substrate. The recirculation of the thickened fraction of the digestate increases the solid retention time of the substrate in the reactor, as well as the return of a significant part of the anaerobic microorganisms into the system, which ultimately helps to intensify anaerobic bioconversion of organic matter of both the initial substrate and the thickened fraction of the digestate. At the same time, the processing of the digestate in VLA does not violate the viability of anaerobic microorganisms. In addition, processing in VLA provides the introduction of iron particles into the mixture, which contribute to both the intensification of the process of anaerobic bioconversion in general and the improvement of the quality of biogas in particular.

Recirculation of the thickened digestate together with the processing it in VLA (with HRT in VLA for 30 seconds) during anaerobic bioconversion of organic waste with HRT in the main anaerobic bioreactor for 8 days and a recirculation coefficient of 1.5, led to a significant improvement in the parameters of anaerobic bioconversion of organic matter:

– the average specific biogas yield increased by 75.2%;
– the average volumetric methane production increased by 16.8%.
No increase in methane concentration in biogas was observed, while the average concentration of hydrogen sulfide in biogas decreased by 8 times. Thus, the recirculation of the thickened digestate together with the processing it in VLA is an effective way to both intensify the process of anaerobic bioconversion of organic waste and reduce costs of cleaning and upgrading biogas for using the latter as a motor fuel.

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