Technological Features of Biogas Production WhileAnaerobic Co-Digestion of Faecal Sludge, Sewage Sludge and Livestock

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Abstract. The article studies technical possibilities of co-digestion of various types of organic waste in order to increase biogas yield and to solve the problem of efficient disposal of faecal sludge. The objects of study were: faecal sludge from a septic tank, sewage sludge from wastewater treatment plant, cattle manure and poultry manure from a livestock farm. Technological features and determination of optimal operating parameters of organic waste anaerobic digestion were investigated. Priority composition of organic waste mixture for anaerobic digestion that provide the maximum biogas yield, as well as the ratio of nitrogen and phosphorus in the digestate was determined.

1. Introduction
In Russian Federation, as well as throughout the world, with the population growth, volumes of organic waste, sewage sludge and fecal sludge are constantly increasing. At the same time, quantity of liquid and solid waste on livestock farms are increasing, especially on pig farms, since the production growth and the usage of automated wet cleaning systems (e.g. self-flushing system of livestock waste and subsequent separation). Livestock waste, which is a mixture of solid and liquid animal excreta, belongs to the III hazard class in Federal Classificatory Catalogue of Wastes [1]. Poultry manure is a serious problem, especially in connection with the increase in the number of large and small poultry farms. Annually, in Moscow region, approximately 877,000 tons of organic waste from agriculture, forestry and fish farming are generated [2]. This waste can be recyclable material for generation a renewable energy source - biogas.

One of the utilization methods for organic waste is anaerobic digestion. Anaerobic digestion allows recycling organic waste with anaerobic microorganisms. A result of anaerobic digestion is formation of biogas and digestate that rich in nitrogen and phosphorus [3]. Co-digestion of liquid organic waste from a septic tank, municipal sewage sludge and livestock waste is a promising way to reduce the organic waste volume in places of temporary storage, which can significantly reduce the anthropogenic load on the environment, including the emission of greenhouse gases, and at the same time obtain energy (methane and hydrogen) and organic fertilizers [4,5].

2. Anaerobic digestion
Anaerobic digestion is a biochemical process while organic material is decomposed under anaerobic conditions to simple compounds, including methane (an environmentally friendly renewable energy
source) [6,7]. Velocity and efficiency of digestion depends on the formed microbiocenosis. These microorganisms are partly in syntrophic relationships and occupy different ecological niches [3,4].

Anaerobic processing is preferable for liquid waste since moisture content of effective digestion is more than 80-90%. Moreover, anaerobic digestion is most preferable for processing of fresh organic waste that has not yet undergone significant degradation [3,4,8]. Thus, while co-digestion there is no need for preliminary separation of organic waste into liquid and dry fractions.

3. Anaerobic digestion units

In many countries, local built-in biogas plants are widely used. These plants process faecal sludge from pit latrines and septic tanks mixed with cattle manure or sewage sludge. Anaerobic digestion unit is a sealed reactor that promotes digestion of different organic waste. Biogas is formed as a suspension and is collected in the upper part of reactor (Fig. 1) [9,10,11,12].

In anaerobic digestion units, faecal sludge from pit latrine or septic tank and livestock waste flow into biogas reactor by gravity. Commonly, the reactor is located directly under the floor of cattle pens and pig houses. Removing the accumulated solid sludge from anaerobic digesters is the greatest challenge resulting that many plants are no longer used. Net calorific value depends on the efficiency of anaerobic digestion units or other units used to process biogas [4,9].

In developing countries, three main types of digester have been introduced: fixed dome digester, floating drum digester and tubular digester. They are wet dehydrogenation systems (a system for processing organic waste into gas with a calorific value of approximately 17-30 MJ/m3). The moisture content of the waste is 80-90%. Such systems of anaerobic digestion are continuous, most often there is a mesophilic mode (from 25 to 40 °C). Digesters are usually made from local materials. Due to their simple design, digesters rarely break down and are easy to operate [3,4,8,9,14].

Biogas is a mixture of gases generated while digestion process of organic products. Biogas generation process is continuous. Biogas is generated both during the day and at night and its output relies heavily on the temperature mode of fermentation. Biogas can be stored in hermetically sealed gas-storage receiver without loss of energy value, which is an advantage in comparison with other renewable energy sources. Depending on pressure, biogas can occupy a different volume [3,6,11,15].

| Components             | Dry matter |
|------------------------|------------|
| Methane (CH₄)          | 50 – 70%   |
| Carbon dioxide (CO₂)   | 30 – 40%   |
| Hydrogen (H₂)          | 5 – 10%    |
| Nitrogen (N₂)          | 1 – 2%     |
| Water vapor (N₂O)      | 0.3%       |
| Hydrogen sulfide (H₂S) | residues   |

Biogas can be transformed into heat, electricity, light and mechanical energy [3,11,15].

Figure 1. General drawing of experimental unit: 1 – digester; 2 – flanged socket for raw substrate; 3 – flanged socket for digestate discharge; 4 – flanged socket for biogas; 5 – pressure sensor; 6 – thermostatic controller; 7 – heat tape; 8 – stirrer; 9 – supporting foot; 10 – gas holder; 11 – connection hose; 12 – motor; 13 – belt drive; 14 – parallel-shaft reducer [13].
In some cases, it is not necessary to convert all of organic carbon to methane — organic acids can also be produced and used as a food source for oil-producing yeast. Producing oils are similar in composition to vegetable oils that are used in many industrial processes, including cosmetics and soaps [15,16].

Without enough nitrogen, bacteria will not be able to utilize all of the carbon present therefore process will be less efficient. In general, the C/N ratio ranges from 20 to 30. The C/N ratio should never exceed 35, since nitrogen will be consumed quickly and the reaction rate will decrease. If the C/N ratio is very low, nitrogen will be released and accumulate in the ammonia form, which is toxic under certain conditions [3,17].

Livestock waste, in particular cattle manure, has an average C/N ratio of about 27. In human feces the C/N ratio is only 8, while the specific biogas yield per kilogram of human excrement is 20-28 ml/g [3,5,8,17].

During anaerobic digestion, about 30% of organic materials decompose, and, therefore, the amount of dry matter in the substrate is reduced to 7% [3].

While disposing of organic waste by anaerobic digestion, a fermented mass is also formed that called digestate. Digestate is rich in organics, nutrients, almost odorless. Moreover, pathogenic microorganisms are partially inactivated while digestion process. Due to the rich organics and nutrients in digestate, it is used as fertilizer or for vermicomposting in order to breed worms and obtain vermicompost. Numerous studies [7,10,11,12] have shown that, digestate is a valuable organic fertilizer (with the exception of total phosphorus content, which is in excess).

4. Materials and methods

A model laboratory experiment was carried to determine the general characteristics of initial waste according to the following parameters: pH, organic carbon, total nitrogen and dry matter (Table 2). There are limiting parameters for anaerobic digestion process.

The following samples were taken for the study: faecal sludge (FS) from pit latrine, sewage sludge (SS) from wastewater treatment plant, cattle manure (CM), poultry manure (PM).

Digestion was carried out in 500 ml sealed vessels (flasks), in anaerobic, thermophilic conditions. Process temperature is 55°C. Period is 14 days with constant stirring. The hydraulic seal was used to collect and measure the generated gas volume by the displaced water volume. The moisture content of sample materials is 95% (adjust to this value with tap water. All mixtures were prepared in a 1:1 ratio of different types of organic waste.

4.1. Method for determining operating parameters:

1. To determine pH, a pH-meter “pH-410” and a water extract from substrates in a ratio of 1:5 by weight were used [18]. For liquid waste the pH was determined directly in the waste.
2. The organic carbon content was determined in accordance with the ISO 14235:1998 method [19]. Method principle is the oxidation of organic carbon with potassium dichromate (in excess) and concentrated sulfuric acid at 135°C. Dichromate ions upon reduction change the solution colour from orange-red to green. The intensity of the green colour was measured using a spectrophotometer. The organic carbon content is determined using a glucose calibration scale.
3. The total nitrogen content was determined by the Kjeldahl method as modified by ISO 11261:1995 [20]. Method principle is based on determining the ammonium nitrogen content obtained as a wet ciefaction result of a sample with sulfuric acid. After ciefaction, ammonia nitrogen was converted into ammonia form by adding alkali (sodium hydroxide) and distilled off with steam on an automatic distiller and “VELP UDK” titrator. Steam-distilled ammonia was collected in a titration cell, into which a boric acid solution was previously poured. Concentration of the producing ammonium borate solution was determined by titration by the color change of indicators.
4. Determination of dry organic matter (DOM) in dry matter (DM) was calculated as:

\[ oTS = \frac{m_{TS} - m_{wTS}}{m_{TS} - m_T} \times 100 \]
oTS is organic dry matter content in wastewater, %; mTS is the crucible mass with dry matter mass contained in the substrate, g; moTS is the crucible mass with ash, g; mT - crucible mass, g.

5. Required dose determination of raw materials daily loading depends on the total reactor volume and substrate retention time in anaerobic digester:

\[
o LR = \frac{oDM}{V_p}
\]

oLR - organic substrate loading rate, %; oDM - content of organic dry matter in dry matter, %; Vp - installation volume, liters.

6. Determination of retention time for complete substrate processing in anaerobic digester:

\[
D = \frac{V_p}{o LR}
\]

D is the optimal number of days required for complete processing of the substrate; V_p - installation volume, liters; oLR - organic substrate loading rate, liters.

Table 2. Operation parameters of organic wastes digestion.

| Waste | Dry matter | pH       | N_{total} % | C_{organic} % | C/N  |
|-------|------------|----------|-------------|---------------|------|
| SS    | 3.4 ± 0.5  | 7.7 ± 0.5| 3.1 ± 0.3   | 27.3 ± 1.3    | 7    |
| FS    | 12.6 ± 0.2 | 7.4 ± 0.2| 15 ± 4.8    | 31.6 ± 2.7    | 8    |
| CM    | 15.3 ± 3.8 | 7.6 ± 0.5| 0.5 ± 0.7   | 38.3 ± 3.2    | 27   |
| PM    | 22.6 ± 2.1 | 6.8 ± 0.6| 2.9 ± 0.3   | 29.2 ± 0.2    | 12   |

As can be seen from the table, the acidity indicators of the waste correspond to the data presented in the literature data. According to [21,22], poultry manure (PM) is classified as alkaline waste due to the high content of ammonia. The pH of alkaline waste fluctuates in the range of 6.2-8.1, as a result of which it is dangerous to use it as fertilizer in an unprocessed form.

Sewage sludge (SS), most commonly, has a neutral pH value, in the range of 6.3-7.6 for domestic wastewater [23,24,25].

The moisture content of substrate has an important role in anaerobic digestion. The process of anaerobic digestion is carried out with a moisture content of more than 80% [8,26].

The main waste characteristics for anaerobic digestion process are carbon to nitrogen (C/N) content. Maximum content of organic carbon (Corg) was found in cattle manure (38%) and faecal sludge (31%) (Table 2). Other of organic waste contains 27-30% of organic carbon. The content of total Nitrogen (Ntot) is from 0.05% (cattle manure) to 3.1% (sewage sludge). The results obtained are agree with the literature data [3,24,25].

After the model experiment, the studies were repeated in an experimental digester. There was ensuring the required technological mode, leak resistance and equipment cleanliness. Accomplish this the following action sequence was applied:

- Washing the digester with hot water (T=90°C), checking the operation of the thermal stabilization system, drying;
- Loading the digester with fresh substrate to 2/3 of the height of the working reactor level;
- Checking the digester for leaks and closing all branch pipes;
- Heating the substrate up to 33°C;
- Periodic mixing of the digested substrate, as well as discharge of digestate and loading of fresh substrate;
- Assessing of biogas produced volume.
5. Results and discussion
At the first stage, the possibility of anaerobic digestion of fecal sludge without adding other organic waste was investigated. Biogas yield was 13 ml/g (dry matter) in 14 days (Fig. 5). The relatively low biogas yield during anaerobic digestion of faecal sludge is associated with a low C/N ratio. Besides, it must be considered that in most cases, digestion of one type of organic waste is economically unprofitable, due to the low biogas yield, including, for example, digestion of poultry manure, since all parameters are outside the optimal range. At the same time, digestion of cattle manure may be advisable due to optimal values for all parameters. There are parameters (pH, C/N ratio, dry matter content) for types of organic waste in Fig. 2,3,4.

![Figure 2. C/N ratio of organic waste.](image2)

![Figure 3. pH of organic waste.](image3)

![Figure 4. Dry matter content in organic waste (%).](image4)
As can be seen from the above, in order to optimize pH level of digestion mixtures, C/N ratio and dry matter content, various types of organic waste must be used simultaneously. As a result, at the second stage of investigation, the optimal ratio of waste components in mixture was determined so that C/N ratio was optimal for the methanogenesis process [3,21, 27].

![Figure 5](image)

**Figure 5.** Biogas yield while organic waste digestion within 14 days (ml/g dry matter).

As seen from Fig. 5, digestion of mixture of fecal sludge, poultry manure, cattle manure and sewage sludge (FS + PM + CM + SS) provides biogas yield of 18 ml/g (dry matter) in 14 days. Such biogas yield is not optimal, but exceeds biogas yield while mono-digestion of faecal sludge.

Application of other types of organic waste to faecal sludge significantly increases the biogas yield. So, while digestion a mixture of faecal sludge and poultry manure (FS + PM), the maximum biogas yield is provided – 28 ml/g of dry matter in 14 days.

In other cases digestion of the FS + CM and FS + SS mixtures, has a lower biogas yield, which was, respectively, 22 ml/g and 25 ml/g of dry matter in 14 days.

6. **Conclusions**

1. Based on characteristics of initial organic waste, it has been established that various waste is characterized by a wide range of acidity values (from 6.8 to 7.7), organic carbon content (from 27% to 38%) and total nitrogen (from 0.5% to 5 %). Differences in waste characteristics make it possible to create artificial systems that are optimal for the functioning of microbial communities and to control processes by forming mixtures for anaerobic digestion without additional reagents.

2. The optimal ratio and optimal parameters for waste processing by anaerobic digestion have been determined. The method for determining parameters includes modeling digestion processes, compiled taking into account moisture, carbon and nitrogen content, followed by results elaboration. The volume of released biogas for 14 days was determined as one of parameters.

3. The highest digestion potential and biogas yield is ensured by the co-digestion of following mixtures: fecal sludge and poultry manure – biogas yield was 28 ml/g (dry matter); and faecal sludge and sewage sludge – biogas yield was 25 ml/g (dry matter).

4. It has been shown that co-digestion mixtures of organic waste: sewage sludge and faecal sludge, cattle manure and faecal sludge, poultry manure and faecal sludge – leads to a significant biogas yield increase in comparison with mono-digestion of faecal sludge by 1.2-2 times.

7. **References**

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