Features of sewage sludge degradation being involved in biomethanogenesis

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Abstract. Recycling waste into biogas not only provides energy source material, but also reduces the concentration of organic matter in the recycled raw material. The paper studies energy potential and rate of sewage sludge digestion, once combined at municipal plants with chicken manure and sugar beet pulp. A laboratory biogas plant with batch reactors was used for trials. A specific yield of biogas from activated sludge was 597.97±154.75 ml/g OM, specific yield of methane – 9.93±3.16 ml/g OM. The rate of organic matter digestion was 19.31%. Adding broiler chicken manure and sugar beet pulp into the bioreactor had a positive effect on fermentation. The specific yield of biogas increased to 978.39±166.32, bagasse – up to 1089.12±195.26 ml/g OM. The specific yield of methane increased, respectively, to 44.75±12.9 and 16.24±8.16 ml/g OM. The organic matter degradation rate increased to 30.61%, bagasse – to 33.94%. Thus, chicken manure and sugar beet pulp added into the bioreactor increases the efficiency of sludge treated into biogas, which is most likely due to increased mass fraction of organic matter and normalized carbon-nitrogen ratio in the bioreactor.

1. Introduction
Urban wastewater treatment plants are commonly equipped with aeration tanks. The main by-product from wastewater treatment plants is a type of sludge that, once filtered, degrade in sludge beds in vivo. With this disposal method, there is a need for large areas, in addition, the environment is polluted with degradation products.

The raw sludge at treatment facilities is an alliance of microorganisms and protozoa with partially oxidized suspended solids and can be subject to further degradation, e.g. during biomethanogenesis. This not only improves the environmental friendliness of treatment systems (since methanogenesis occurs in closed containers), but also provides an additional energy source material in the form of biogas. According to the data given in reference books and obtained by various researchers, the specific output of biogas from surplus activated sludge from wastewater treatment plants is from 400 to 700 liters per 1 kg of organic matter (l/kg OM), its methane content can reach 60% (with a mass fraction of dry matter (DM) of 4%, organic matter in dry residue (OM) – 70%) [1, 2].

Using sewage sludge as raw material for biogas production, every attempt is made to enhance treatment efficiency – mainly, to increase the yield of methane. Many authors note a positive effect when activated sludge and other raw materials, often represented by plant or animal waste, are jointly processed in biogas plant. Thus, N.N. Atta et al. found that co-fermentation of activated sludge and rice straw contributes to the C/N ratio in the bioreactor and allows 4 times higher biogas yield...
compared to the options without straw [3]. In their studies, A. Björn et al. found that introducing 25% (in terms of dry solids) of solid municipal waste into the bioreactor, the synthesis of biogas increased 4 times, the specific yield of methane was 420±30 ml/g OM [4]. In laboratory experiments by A. Wriege-Bechtold, a fairly high yield of biogas was obtained in co-fermentation of activated sludge and fat from grease traps – 800-1200 l/kg OM [1].

The waste biodegradation rate is also important for the environment. B.R. Szűcs et al. found that adding cut grass and food waste to activated sludge increased organic degree biodegradation rate compared to activated sludge monofermentation [5]. Biogas is formed resulting from the degradation and transformation of organic matter in substrates by microorganisms, therefore, there is a direct relationship between biogas productivity and substrate destruction rate. Besides preparing mixtures of substrates these indicators are improved through different fermentation regimes and preparations with active forms of certain microorganisms or their enzymes. Thus, S. Kolbl found that MicropanBiogas and Novozymes enzyme preparations increased the yield of methane by 8.00 and 45.00%, respectively (up to 319.00±11.00 ml/g om) [6]. With a two-stage fermentation of sewage sludge in a thermophilic mode, the organic matter degradation rate is 13.00% higher than with a single-stage procedure; the methane yield increases from 303.74 to 450.02 ml/g om [7]. M. Lebiocka et al. found that sewage sludge treatment in semi-batch reactors resulted in 370.00 to 400.00 ml of biogas from 1 g of OM with a methane content of 55.22-56.56% [8]. In batch reactors, the microflora showed a higher resistance to an increased COD level. However, a specific yield of methane was 273.00-483.00 ml/g OM, its content in biogas ranged from 65.00 to 68.00% [9].

Sludge treatment sites and a biogas plant constructed to utilize surplus sewage sludge are located near Kursk (Russia). The recycled mass is separated, the solid fraction is used as fertilizer, while water is returned to the treatment plant. For the employees, an urgent task is to search and test additional substrates to increase the efficiency of the plant. The energy generated by the plant can be spent on its own needs, the needs of treatment facilities, or fed to the mains. A biogas plant integrated into the technological chain for processing this type of waste plays an important role in improving the ecological situation in the region. It is an ecological impact allowed by this technology that is of paramount importance in the conditions of most constituent entities of the Russian Federation.

Earlier, the authors explored the biogas productivity of surplus activated sludge taken from the above treatment facilities, as well as available cosubstrates that were supposed to be additionally treated at this biogas plant. The papr aims to determine organic matter biodegradation rate from surplus sewage sludge, including in a mixture with other cosubstrates, once treated into biogas.

2. Materials and methods
The studies were provided at the Laboratory for Biogas Technologies of Belgorod State Agricultural University named after V. Gorin (Belgorod region, Russia).

Research material is surplus activated sludge from urban treatment facilities, broiler chicken manure, sugar beet pulp.

The substrates were fermented in batch bioreactors with a working volume of 250 ml each, placed in a water bath equipped with temperature sensors and a universal meter-regulator OVEN TRM 138 (Russia). Incubation lasted 35 days at a temperature + 37±0.5 °C. Biogas was drained through pipes into polyethylene gas tanks with a volume of 5 liters each. The volume of biogas was determined weekly using a glass cylindrical flask with a piston, the composition – using a gas analyzer Optima - 7 Biogas (Germany). Each substrate was three-fold tested.

The trials were set up and conducted and the results were processed in accordance with the methods of D. Pfeiffer and M. Dittrich-Zechendorf, DIN 38 414 (S8) and VDI 4630 [10 – 12].

To ensure comparability of the findings, the gas volume was normalized according to the equation (1):

\[ V_0 = \frac{PVT_0}{TP_0} \] (1)

where:

\( V_0 \) is the volume of dry gas under normal conditions, ml,
V is the registered volume of gas, ml,
P is the gas pressure at the time of measurement, mbar,
\( P_0 \) is the atmospheric pressure at normal conditions; \( P_0 = 1013 \) mbar,
\( T_0 \) is the air temperature at normal level; \( T_0 = 273 \) K,
T is the biogas temperature, K.

The organic matter biodegradation rate was calculated by the formula (2):

\[
M_{\text{biogas}} = V_{\text{biogas}} \left( 1.96 \frac{C_{\text{CO}_2}}{100} + 0.73 \frac{C_{\text{CH}_4}}{100} + 1.54 \frac{C_{\text{H}_2\text{S}}}{100} + 1.43 \frac{C_{\text{H}_2\text{O}}}{100} + 0.77 \frac{C_{\text{NH}_3}}{100} \right)
\]

where:

- \( M_{\text{biogas}} \) is the biogas mass;
- \( V_{\text{biogas}} \) is the biogas volume;
- \( C \) is the concentration of the suitable gases in the gas mixture;
- 1.96; 0.73; 1.54; 1.43 and 0.77 are densities of the suitable gases.

The results obtained were processed by the method of variation statistics using the Microsoft Excel program. Data are presented as mean and standard error.

### 3. Results and Discussion

Mass fraction of dry matter and organic matter in substrates are the main parameters that benefit biogas productivity. They allow the loading rates of reactors to be calculated: the ratio of the mass of the inoculum OM to the substrate OM in the reactor should tend to 2:1. In the said experiment, the initial substrates had the following DM and OM values: inoculum – 7.32±0.03 and 71.95±0.40%, respectively, activated sludge – 0.28±0.07 (very low value) and 72.78±6.83%, broiler chicken manure without bedding – 26.28±0.17 and 87.45±0.15%, sugar beet pulp – 9.81±0.63 and 93.92±1.93% respectively.

The experimental options were represented by a mixture of substrates and inoculum in a given proportion, attributed to the amount of substrates available at the wastewater treatment plant, the “zero” option was inoculum. The gross yield of individual biogas components from substrates and their mixtures for 35 days of incubation is shown in Table 1.

As expected based on the data on the mass fraction of DM and OM, chicken manure and sugar beet pulp had the highest productivity. The gross yield of biogas from activated sludge during its monofermentation was the smallest. Activated sludge mixed with pulp and manure yielded average biogas productivity.

**Table 1.** Gross output of gases from 1 reactor (ml)

| Options        | CH₄     | H₂S     | CO₂     | O₂     | NH₃     |
|----------------|---------|---------|---------|--------|---------|
| Chicken manure | 485.75±116.82 | 0.2150±0.0172 | 272.29±139.36 | 141.17±27.03 | 397.34±73.88 |
| Sewage sludge  | 5.93±1.36  | 0.0001±0.00005 | 2.01±0.43 | 56.52±13.56 | 233.60±57.00 |
| Pulp           | 352.76±46.64 | 0.0003±0.00005 | 20.72±3.55 | 213.49±10.94 | 646.02±24.03 |
| Manure+Sludge  | 25.38±6.85  | 0.00004±0.00005 | 2.81±0.75 | 112.03±17.91 | 439.47±69.47 |
| Pulp+Sludge    | 16.48±2.94  | 0.0001±0.00005 | 2.30±0.38 | 125.23±23.69 | 496.18±82.80 |

The specific yield of biogas in the experiment was: from litter – 63.89±12.94 ml/g OM, fromactivated sludge – 597.97±154.75, from pulp – 193.23±15.87, from a mixture of manure and activated sludge – 978.39±166.32, from a mixture of pulp and activated sludge – 1089.12±195.26 ml/g OM; the specific yield of methane was 26.28±6.45, 9.93±3.16, 66.02±9.23, 44.75±12.97 and 16.24±8.16 ml/g DM, respectively. Despite the fact that this indicator in the activated sludge option is quite high and surpasses the options that include manure and pulp alone, the specific yield of methane is very low.
In the experiments conducted by other researchers, the specific yield of biogas during monofermentation of activated sludge is lower, and methane – much higher. In the experiments of S. Maamri and M. Amrani, the specific yield of methane from activated sludge in various combinations with cattle manure during processing in a thermophilic mode ranged from 135.00 to 168.00 ml/g OM [13]. P. Caballero et al. after thermal and enzymatic pretreatment of the activated sewage sludge obtained 425.00 ml of CH4/g OM [14]. T. Dokulilová et al. reached, at different temperature conditions of fermentation (from +36 to +50 °C), the specific yield of methane from 33.00±2.00 to 45.00±3.00 ml/g OM; the volume fraction of methane in biogas ranged from 57.5 to 58.3% [15]. M. Elsayed et al. noted that combined processing of activated sewage sludge with plant waste contributes to the growth of biogas productivity: the specific yield of biogas during mono-fermentation of activated sludge was 119.00 ml/g OM, and when processing a mixture of activated sludge with fruit and vegetable waste (ratio 1:1) – 141.00 ml/g OM; the methane content in biogas increased from 29.00 to 63.00-73.00% (with different ratios of activated sludge and plant raw materials) [16]. A.L. Aski et al. obtained 117.00±7.00 ml CH4/g OM from the activated sewage sludge of the pharmaceutical industry without any pre-treatment [17].

Based on the methods given in [11, 12], the mass of degraded organic matter in a sealed system corresponds to the mass of the resulting biogas. Subsequent upon the gross volume of the gases formed in the biogas composition, the volume fraction of each gas in % in one reactor was calculated on average for the options. Using formula (2) given in the research technique, the authors here calculated the mass of the gas mixture. The organic matter degradation rate is the amount of decomposed organic matter, expressed in % of the weight of the organic matter added (Table 2).

The organic matter degradation rate in substrates in the present experiment is quite low, especially when they are mono-fermented. The lowest value of this indicator was found to be present with mono-fermentation of chicken manure and sugar beet pulp. Surplus activated sludge had an average value. The highest degradation rate was found at combined processing of activated sludge with manure and activated sludge with sugar beet pulp. This may be due to an increase in the mass fraction of organic matter in bioreactors in general and the optimization of the C/N ratio, which has a favorable effect on the activity of microflora. M. Elsayed et al. noted the same tendency: the maximum degradation rate of the contents of the bioreactor was achieved with the combined fermentation of activated sludge and fruit and vegetable waste – with different ratios of substrates, it ranged from 63.00 to 73.00%. Provided that activated sludge or plant waste alone was digested, this indicator was much lower – 29.00 and 46.00%, respectively [16].

**Table 2. Volume fraction of resultant gases and organic matter degradation rate in substrates (%)**

| Options       | CH4 | H2S | CO2 | O2 | NH3 | Digested OM, mg | Input OM, mg | Degradation rate OM |
|---------------|-----|-----|-----|----|-----|----------------|--------------|---------------------|
| Manure        | 37.46 | 0.02 | 21.00 | 10.89 | 30.64 | 1396.43 | 23720.97 | 5.89 |
| Sludge        | 1.99 | 0.00 | 0.67 | 18.96 | 78.37 | 268.97 | 1392.67 | 19.31 |
| Pulp          | 28.61 | 0.00 | 1.68 | 17.31 | 52.39 | 1100.84 | 15325.17 | 7.18 |
| Manure+ Sludge| 4.38 | 0.00 | 0.48 | 19.33 | 75.81 | 522.63 | 1707.18 | 30.61 |
| Pulp+Sludge   | 2.57 | 0.00 | 0.36 | 19.56 | 77.51 | 577.67 | 1702.17 | 33.94 |

The organic matter degradation rate in substrates in the present experiment is rather low, especially when they are mono-fermented. The lowest value of this indicator was achieved when chicken manure and sugar beet pulp were mono-fermented. Surplus activated sludge produced an average value. The highest rate of degradation occurred when activated sludge was fermented with manure and activated...
sludge was fermented with sugar beet pulp. This may be due to an increase in the mass fraction of organic matter in bioreactors in general and the optimization of the C/N ratio, which has a favorable effect on the activity of microflora. M. Elsayed et al. note the same tendency: the maximum degradation rate of the contents of the bioreactor is achieved with the combined fermentation of activated sludge and fruit and vegetable waste – with different ratios of substrates, it ranges from 63.00 to 73.00%. Provided that activated sludge or plant waste alone is digested, this indicator is much lower – 29.00 and 46.00%, respectively [16].

In the experiments of S. Şahinkaya and M.F. Sevimli, the degradation rate of activated sewage sludge was 25.80%, and after heat pretreatment and sonication increased to 31.10-37.80%; the yield of biogas increased by 3.50-14.00, and methane – by 4.20-13.60% [18]. D. Bolzonella et al. found the organic matter degradation rate of activated sludge to differ from our results both upward and downward. With different durations of the substrate in the bioreactor (hydraulic retention time (HRT) – from 20 to 40 days), degradation ranged from 13.00 to 27.00% (average 18.00%) [19]. When activated sewage sludge of the pharmaceutical industry, containing residues of some preparations and increased concentrations of heavy metals, was treated, its biodegradation rate was 29.00%; specific yield of methane – 117.00±7.00 ml/g OM [17].

According to Handreichung. Biogasgewinnung- und Nutzung (FNR), the degradation rate of chicken manure can reach 67.00% [2]. In research by M.R. Miach et al. the degradation rate of chicken manure was 46.10%; once treated in a mixture with cattle manure in a ratio of 3:1 it increased this indicator to 51.99% [20]. Y. Li et al. found the rate of organic matter biodegradation in chicken manure to be 49.00% [21]. According to the data provided in the Handreichung. Biogasgewinnung- und Nutzung (FNR), the degradation rate of sugar beet pulp can range from 27.48 to 36.31% [2], and according to L. Brooks et al. the value of this indicator reached 75% [22], which is much higher than our results.

4. Conclusion
The paper establishes that broiler chicken manure and sugar beet pulp added into the bioreactor contributes to an increase in the efficiency of activated sewage sludge from municipal treatment facilities. Comparing the process of mono-fermentation of activated sludge with the joint treatment of these wastes, in the latter case the organic matter biodegradation rate increases by 11.30-14.63%, and the specific yield of methane – 1.64-4.51 times. A similar effect can be attributed to an increase in the content of dry matter and organic matter in the processed mixture and the optimization of the ratio of carbon and nitrogen therein.

References
[1] Wriege-Bechtold A 2015 Anaerobe Behandlung von Braunwasser und Klärschlamm unter Berücksichtigung von Co-Substraten (Technische Universität Berlin)
[2] 2013 Handreichung. Biogasgewinnung- und Nutzung (Fachagentur Nachwachsende Rohstoffe e.V. (FNR))
[3] Atta N N, El-Baz A A, Said N et al 2016 Journal of Fundamentals of Renewable Energy and Applications 06(02)
[4] Björn A, Shakeri Yekta S, Ziels R M et al 2017 Euro-Mediterr. J. Environ. Integr. 2 21
[5] Szűcs B R, Simon M, Fileyke G 2012 Management of Organic Waste 97–112
[6] Kolbl S 2015 Acta hydrotechnica 28(48) 65–76
[7] Lu J 2007 Optimization of Anaerobic Digestion of Sewage Sludge Using Thermophilic Anaerobic Pre-Treatment (Technical University of Denmark)
[8] Lebiocka M, Montusiewicz A, Cydzik-Kwitowska A 2018 Int. Journal of Env. Res. and Public Health 15(8) 1717
[9] Girault R, Bridoux G, Nauleau F et al 2012 Bioresource Technology 105 1–8
[10] Pfeiffer D, Dittrich-Zechendorf M 2012 Messmethodensammlung Biogas: Methoden zur Bestimmung von analytischen und prozessbeschreibenden Parametern im Biogasbereich
(Deutsches Biomasseforschungszentrum gemeinnützige GmbH (DBFZ))

[11] 1985  *DIN 38 414 (S8): Deutsche Einheitsverfahren zur Wasser-, Abwasser- und Schlammuntersuchung; Schlamm und Sedimente (Gruppe S); Bestimmung des Faulverhaltens (S 8)* (Beuth Verlag)

[12] 2016  *VDI 4630: Vergärung organischer Stoffe - Substratcharakterisierung, Probenahme, Stoffdatenerhebung, Gärversuche* (Beuth Verlag)

[13] Maamri S, Amrani M 2014  *Energy Procedia* 50 352–359

[14] Caballero P, Ágabo-García C, Solera R et al 2020  *Sustainable Energy & Fuels* 4 5072–5079

[15] Dokulilová T, Vířez T, Chovanec J et al 2018  *Acta universitatis agriculturae et silviculturae mendelianae brunensis* 66(1) 23–28

[16] Elsayed M, Diab A, Soliman M 2021  *Biomass Conv. Bioref.* 11 989–998

[17] Aski A L, Borghei A, Zenouzi A et al 2020  *Fermentation* 6(1) 34

[18] Şahinkaya S, Sevimli M F 2013  *Ultrasonics Sonochemistry* 20 587–594

[19] Bolzonella D, Pavan P, Battistoni P et al 2005  *Process Biochemistry* 40(3) 1453–1460

[20] Miach M R, Md Lutfur Rahman A K, Akanda M R et al 2016  *J. Taibah Univ. Sci.* 10(4) 497–504

[21] Li Y, Zhang R, Liu X et al 2013  *Energy Fuels* 27(4) 2085–2091

[22] Brooks L, Parravicini V, Svardal K et al 2008  *Water Sci. Technol.* 58(7) 1497–1504