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# ИЗВЕСТИЯ

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РЕСПУБЛИКИ КАЗАХСТАН

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# RAPID ASSESSMENT OF ORGANIC LOADING RATE FOR A SEMI-CONTINUOUS ANAEROBIC DIGESTER

**Abstract.** This paper presents a mathematical model for analysis of biogas yield in a semi-continuous anaerobic digester. The main criteria for monitoring and evaluating the effectiveness of anaerobic digestion of different substrates in a semi-continuous anaerobic digester are the cumulative biogas yield and biogas production rate in a batch reactor. Different organic loading rates (OLR) for mono-substrates and their mixtures were analyzed for obtaining the maximum specific biogas yield in a semi-continuous digester.

**Keywords:** biomass energy; semi-continuous digester, organic loading rate, mathematical model, modified Gompertz model.

**Introduction.** Organic Loading Rate (OLR) is an important operational parameter which represents the biological conversion capacity of an anaerobic digestion system [1]. It is indeed a control parameter in semi-continuous systems. It has been established that the anaerobic digester runs inefficiently with low OLR, while with high OLR, there exists a risk of system failure due to overloading [2]. Researches in this area indicate that the methanogenic processes can be intensified by increasing the OLR and decreasing the hydraulic retention time (HRT) [3, 4, 5]. In [6] OLR increased 6 times during the digestion of olive mill solid residue. This led to an increase in the biogas productivity of more than 400%. According to literature data, the optimum OLR depends on the type of the substrate being digested, and on the total solids concentration of the substrate [3, 5, 7 - 12].

Even in modern anaerobic processes the OLR value greatly affects the performance of the digester [13-16].

Determination of the optimal OLR value for effective anaerobic digestion process in a semi-continuous digester is always based on long-term experimental studies [9, 17]. For example, in the PhD thesis of Hassan, the experimental study lasted 150 days in order to determine the yield of biogas from co-substrates with an OLR in the range from 1 to 5 kg $VS \cdot m^{-3} \cdot day^{-1}$ [3]. In study [18] two different concentrations of OLR (0.7 and 1.4 kg $VS \cdot m^{-3} \cdot day^{-1}$) were investigated to examine the effect of the change in the organic loading rate on the efficiency of the biogas production from grass and cattle slurry. The experimental study lasted 26 week. The feasibility of spent mushroom compost as a co-substrate in anaerobic digestion was investigated for 90 days [19]. 140 days of continuous experiment were required to assess the impact of OLR in the range of 1.0-5.0 kg $VS \cdot m^{-1}$ $day^{-1}$ on the biogas yield [1].

As can be seen from the above, long periods of time are required for carrying out these processes, which makes the experiment challenging. It should be noted that additional experimental studies are supposed to be conducted even for the same substrate, but with different content of volatile solids (VS). In addition, advance of the co-digestion process in biogas technology makes it necessary to study a variety of anaerobic digestion systems and assess the specific biogas yield, depending on the OLR. Thus, it becomes important to use simulation models to predict the operation of digesters. It is possible to estimate the time characteristics of the operational parameters of a biogas plant on the basis of a model for semi-continuous process for the various organic loading conditions without interfering with plant operation.

The aim of this work is to develop a mathematical model that allows to conduct a rapid assessment of the specific biogas yield in a semi-continuous digester at different OLRs, using experimentally derived equation of biogas production in a batch reactor.

**Mathematical model.** We consider the work of a semi-continuous digester under the following assumptions:

- continuous mechanical mixing is carried out in the digester assuming that in this case the mixing intensity allows us to neglect the spatial in homogeneity of concentration;
- loaded substrate has the same concentration as the liquid in the digester.

The biogas yield rate depends on the retention time in the digester. All calculating formulas are based on the function of biogas yield for batch digester $F(t)$ depending on retention time. $f(t) = dF/dt$ – function of biogas yield rate. The function $F(t)$ can be obtained experimentally or described by analytical function. For example, the Gompertz equation quite well describes the biogas yield.

Modified Gompertz model was used by many authors to describe the methane yield from various organic substrates in the batch systems [20-26]. The modified Gompertz equation has the form:

$$F(t) = P\exp\left\{-\exp\left[\frac{R_{max}\cdot e}{P}(\lambda - t) + 1\right]\right\} \tag{1}$$

Thus, the calculating formulas of the cumulative biogas yield in a batch digester are used to analyze the *uniform* and *non-uniform loading* of semi-continuous digester.

Initially, we consider the simplest case of a *uniform loading*: loading of even substrate volumes equal to $1/n$ part of the total anaerobic digester with a periodicity $\Delta t$ equal to the time interval $h_t$ (usually one day).

We get the recurrence formula for cumulative biogas yield of a semi-continuous digester $\widetilde{F}(t)$.

For $t$=0 $\quad \widetilde{F}(0) = \widetilde{F}_0 = F(0)$;

For $t = h_t$ $\quad \widetilde{F}(1\cdot h_t) = \widetilde{F}_1 = \widetilde{F}(0) + \int_0^{h_t} f(t)dt = F(0) + F(h_t) - F(0) = F(h_t) = F_1$;

For $t = 2h_t$ fraction of the loaded portion of the total volume $V_1^2 = \frac{1}{n}$, and fraction of the substrate which is in an anaerobic digester for a period of time between $h_t$ and $2h_t$ is equal to $V_2^2 = 1 - \frac{1}{n}$ then

$$\widetilde{F}(2h_t) = \widetilde{F}_2 = \widetilde{F}_1 + \frac{1}{n}\int_0^{h_t} f(t)dt + \left(1 - \frac{1}{n}\right)\int_{h_t}^{2h_t} f(t)dt = \widetilde{F}_1 + \frac{1}{n}(F_1 - F_0) + \left(1 - \frac{1}{n}\right)(F_2 - F_1) \tag{2}$$

For $t = 3h_t$ fraction of the loaded portion of the total volume $V_1^3 = \frac{1}{n}$; fraction of the substrate which is in an anaerobic digester for a period of time between $h_t$ and $2h_t$ is equal to $V_2^3 = \left(1 - \frac{1}{n}\right)V_1^2$; fraction of the substrate which is in an anaerobic digester for a period of time between $2h_t$ and $3h_t$ is equal to $V_3^3 = \left(1 - \frac{1}{n}\right)V_2^2$ then

$$\widetilde{F}(3h_t)=\widetilde{F}_3=\widetilde{F}_2+\frac{1}{n}\int_0^{h_t} f(t)dt+\frac{1}{n}\left(1-\frac{1}{n}\right)\int_{h_t}^{2h_t} f(t)dt+\left(1-\frac{1}{n}\right)^2\int_{h_t}^{2h_t} f(t)dt=$$

$$=\widetilde{F}_2+\frac{1}{n}(F_1-F_0)+\frac{1}{n}\left(1-\frac{1}{n}\right)(F_2-F_1)+\left(1-\frac{1}{n}\right)^2(F_3-F_2) \quad (3)$$

and etc.

For $t=mh_t$ $\quad V_1^m=\frac{1}{n}$; $V_i^m=\frac{1}{n}\left(1-\frac{1}{n}\right)^{i-1}V_{i-1}^{m-1}$, $i=2,3\ldots m$ or

$$V_i^m=\frac{1}{n}\left(1-\frac{1}{n}\right)^{i-1},\ i=1,2\ldots m-1,\ V_m^m=\left(1-\frac{1}{n}\right)^{m-1} \quad (4)$$

$$\widetilde{F}_m=\widetilde{F}_{m-1}+\sum_{i=1}^{m-1}\frac{1}{n}\left(1-\frac{1}{n}\right)^{i-1}(F_i-F_{i-1})+\left(1-\frac{1}{n}\right)^{m-1}(F_m-F_{m-1}) \quad (5)$$

We apply the principle of mathematical induction to verify the correctness of the obtained recurrence formulas (4)-(5).

1. $m=1$, $\widetilde{F}_1=\widetilde{F}_0+(F_1-F_0)=F_0+(F_1-F_0)=F_1$ ;

2. We get $\widetilde{F}_{m+1}$ from (3), (4):

$$V_1^{m+1}=\frac{1}{n};\ V_i^{m+1}=\left(1-\frac{1}{n}\right)V_{i-1}^m\quad i=2,3\ldots m+1\ ,$$

or taking into account (4)

$$V_i^{m+1}=\left(1-\frac{1}{n}\right)\frac{1}{n}\left(1-\frac{1}{n}\right)^{i-2}=\frac{1}{n}\left(1-\frac{1}{n}\right)^{i-1},\ i=2,3\ldots m\ ,\ V_{m+1}^{m+1}=\left(1-\frac{1}{n}\right)^m \quad (6)$$

$$\widetilde{F}_{m+1}=\widetilde{F}_m+\sum_{i=1}^{m+1}V_i^{m+1}\cdot\int_{(i-1)h_t}^{ih_t} f(t)dt$$

Using (6) we finally obtain

$$\widetilde{F}_{m+1}=\widetilde{F}_m+\sum_{i=1}^{m}\frac{1}{n}\left(1-\frac{1}{n}\right)^{i-1}(F_i-F_{i-1})+\left(1-\frac{1}{n}\right)^m(F_{m+1}-F_m), \quad (7)$$

quod erat inveniendum.

If $\Delta t\neq h_t$ then by similar reasoning we can obtain the following recurrence formula for the biogas yield in the semi-continuous anaerobic digester.

$$\widetilde{F}_m=\widetilde{F}_{m-1}+\sum_{i=1}^{IN}\frac{1}{n}\left(1-\frac{1}{n}\right)^{i-1}(F_{i+k-1}-F_{i+k-2})+(F_{IN+k}-F_{IN+k-1})\left(1-\frac{1}{n}\right)^{IN} \quad (8)$$

where $IN=\lfloor(m-1)/\Delta t\rfloor$, here $\lfloor\ \rfloor$ – denotes the operation of taking the greatest integer which is less than or equal to the number that is in parentheses.

The recurrence formula to determine the mean retention time in an anaerobic digester has the form

$$\widetilde{T}_m=\sum_{i=1}^{IN}\frac{1}{n}\left(1-\frac{1}{n}\right)^{i-1}((i-1)\Delta t+kh_t)+\left(1-\frac{1}{n}\right)^{IN}(IN\cdot\Delta t+kh_t), \quad (9)$$

here $\overline{T}_m$ – mean retention time in an anaerobic digester at the time $m\cdot h_t$.

We consider the case of *non-uniform loading* its volume and time are given in the tabular form. We denote the loading volume at the time $m\cdot h_t$ as $1/n_m$ part of the total digester volume. Then the recurrent formula for the cumulative biogas yield in the semi-continuous digester has the form

$$\widetilde{F}_m = \widetilde{F}_{m-1} + \sum_{i=1}^{m} (F_i - F_{i-1}) V_i^m \tag{10}$$

If the loading is not zero

$$V_i^m = V_{i-1}^{m-1}\left(1 - \frac{1}{n_m}\right),\ V_1^m = \frac{1}{n_m},\ V_1^1 = 1,\ i = 2,3...m \tag{11}$$

If the loading is zero

$$V_i^m = V_{i-1}^{m-1},\ V_1^m = 0,\ V_0^0 = 1,\ i = 1,2...m \tag{12}$$

The mean retention time at non-uniform loading is calculated by the following recurrence formula

$$\overline{T}_m = h_t \sum_{i=1}^{m} V_i^m \cdot i \tag{13}$$

where formulas (11) are used if the loading is not zero and if the loading is zero

$$\overline{T}_m = \overline{T}_{m-1} + h_t \tag{14}$$

For numerical calculations the program was written on Delphi. For the analysis of loading modes the function of cumulative biogas yield and biogas yield rate in the batch digester can be specified per kg of VS, kg of COD, kg of TS, kg of substrate and etc.

**Verification of a mathematical model.** For the validation of the obtained mathematical model we compared the calculated methane production rate with our experimental data and the reported by other authors [3, 17].

***Verification of a model by comparison with obtained experimental data.*** For batch and semi-continuous experiments 12-liter continuously stirred laboratory digesters were used (fig. 1). The digesters had a cylindrical shape (inside diameter is 210 mm, height is 330 mm). Chicken wastes were collected from a Poultry Farm JSC "Kazan" (Russia). It was stored in a refrigerator at ±4 °C.

Volumetric biogas production was measured using MilliGascounters MGC-1 (Ritter, Germany). The concentration of the main components of biogas was analyzed with a GA2000 gas analyzer (Keison, UK). TS is defined as the mass which remains when the water content is removed by drying in an oven at 105°C until it maintains a constant mass. The determination of VS is achieved by heating the dry matter at 550°C for 3 hours.

Figure 1 – Lab-scale reactors (DBFZ, Germany)

The VS content of the substrates was adjusted at 10.5%. The results of the experiments under mesophilic batch conditions are demonstrated in Figures 2.

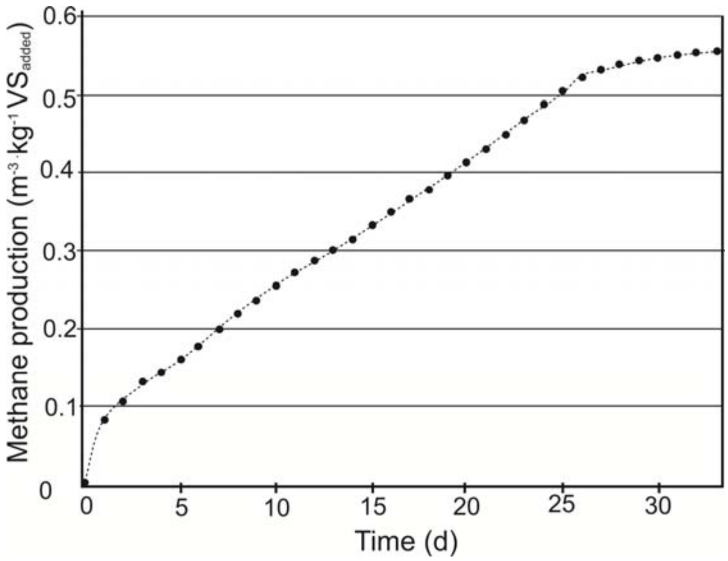


Figure 2 – Methane production potential of chicken manure

Methane production during the semi-continuous feeding experiment is shown in Figure 3.

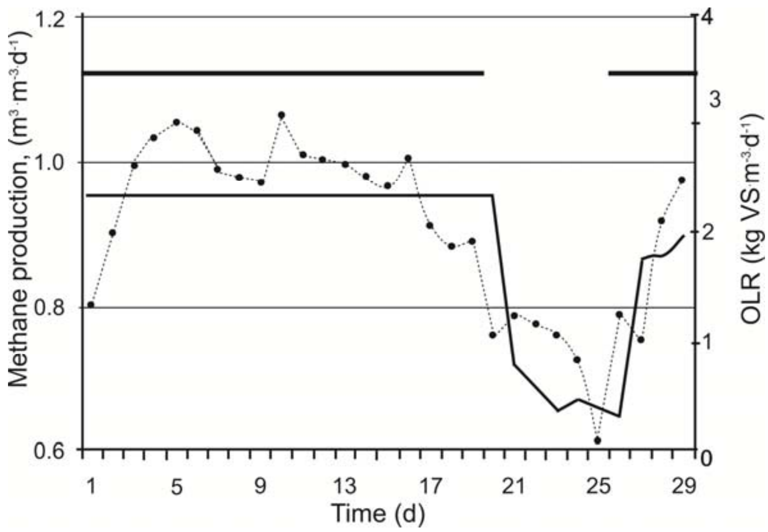


Figure 3 – Volumetric methane production: ── calculated; --●-- experimental; ▬ OLR

Experiment in a lab-scale semi-continuous digester lasted 33 days after steady-state biogas production was achieved. The organic loading rate was kept constant at 3.5 kg VS·$m^{-3}$·$day^{-1}$, except for the period from the 20$^{th}$ to 25$^{th}$ day of the experiment, when the substrate was not loaded.

The resulting calculated curve is in good agreement with the experimental curve.

***Verification of a model by comparison with experimental data reported by other authors.*** Nayono (2009) published experimental data, where press water and food waste were used as substrates [17]. Meanwhile, the organic loading mode was non-uniform. Fig. 4 shows the experimental data and the theoretical curve obtained using a mathematical model. As can be seen from these results, the calculated curves agree with the experimental data.

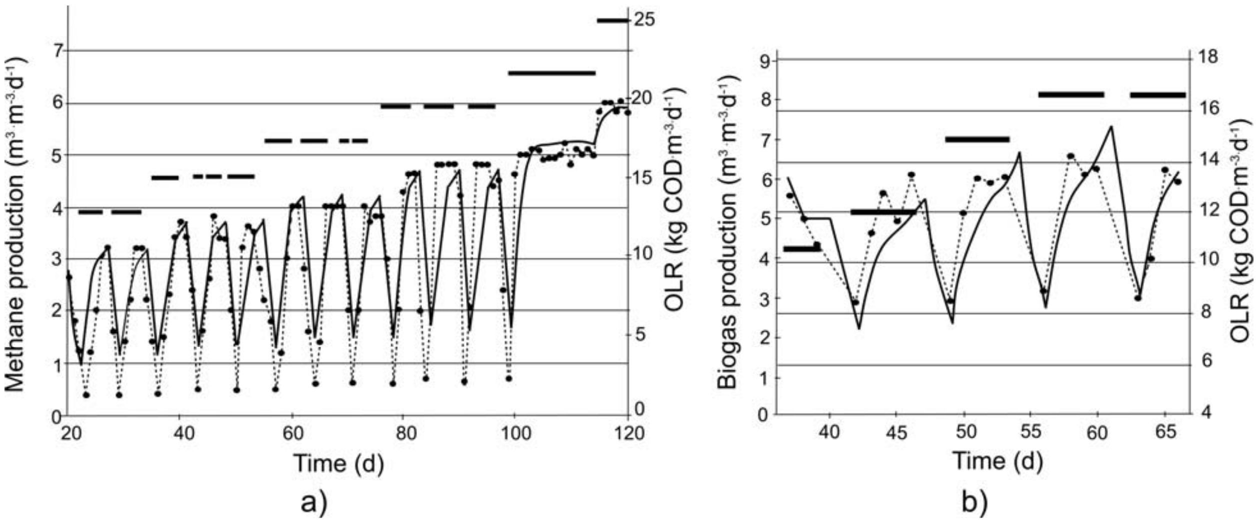


Figure 4 – Volumetric gas production:
— calculated, --●— experimental (Nayono, 2009); ▬ OLR: (a) press water; (b) food waste

Forage beets silage and forage beets silage with manure were used as substrates in Hassan (2003) [3]. Experiments were carried out under thermophilic conditions. Experimental data and theoretical calculations are compared in Fig. 5.

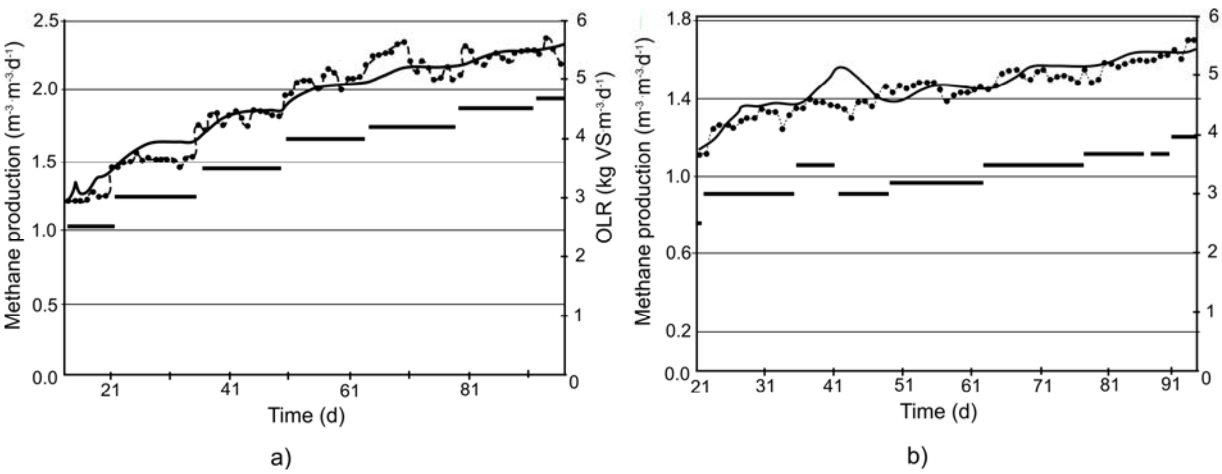


Figure 5 – Volumetric gas production:
— calculated, --●— experimental (Hassan, 2003); ▬ OLR: (a) Forage beets silage; (b) Forage beets silage with manure.

Thus, as can be seen from these graphs, the calculated curves are in quite good agreement with the experimental data, which indicates the adequacy of the developed simulation model.

**Results.** Rapid assessment of specific biogas yield in a semi-continuous digester at different OLR was carried out on the basis of the proposed mathematical model and developed software.

The purpose of calculations was to determine the value of OLR for semi-continuous digester, which will provide the maximum specific biogas yield.

Biogas production rate and its yield from mono-digestion are defined by Gompertz modified model (Table 1). A study and optimization of methane production from mono-substrates in semi-continuous digester will help to develop the process procedure for operation of biogas plants.

Some substrates give higher yield of biogas then animal waste because they contain variety growth factors (such as amino acids and reducing sugars). Actually co-digestion allows increasing the yield of biogas. The yield of biogas is determined experimentally and specific to the various farms. Table 2 shows the parameters of the Gompertz model for multicomponent organic mixtures.

Table 1 – Parameters of the Gompertz model for mono-substrates

| № | Substrate | VS, % | P, ml/g VS | $R_m$, ml/g VS/d | λ, d | Gas | Reference |
|---|---|---|---|---|---|---|---|
| 1 | Biological sludge (raw) | 5.49 | 184 | 24 | 0 | Methane | [27] |
| 2 | OFMSW (raw) | 10.51 | 308 | 11.9 | 0 | Methane | [27] |
| 3 | Grease waste (raw) | 46.82 | 489 | 30.3 | 17.6 | Methane | [27] |
| 4 | Spent grain (raw) | 23.34 | 251 | 18.7 | 0.8 | Methane | [27] |
| 5 | Cow manure (raw) | 20.85 | 317 | 19.6 | 0 | Methane | [27] |
| 6 | Food waste | 24.67 | 613 | 80 | 0.9 | Biogas | [28] |
| 7 | MSW | 30.58 | 522 | 97 | 1.2 | Biogas | [28] |
| 8 | Horse dung | 6.8 | 254.5 | 37.87 | 9.03 | Biogas | [29] |
| 9 | Swine manure | 2 | 492.36 | 21.43 | 5.68 | Methane | [30] |
| 10 | Food waste leachate | 8.64 | 218.6 | 7.1 | 16.4 | Methane | [30] |
| 11 | Chicken manure | 6.97 | 383 | 36 | 1.67 | Methane | [31] |

Table 2 – Parameters of the Gompertz model for multicomponent mixtures

| № | Substrate | VS, % | P, ml/g VS | $R_m$, ml/g VS/d | λ, d | Gas | Reference |
|---|---|---|---|---|---|---|---|
| 1 | Paper and biosolids | 35.62 | 457 | 73 | 1.1 | Biogas | [28] |
| 2 | MSW and paper | 30.77 | 487 | 94 | 1.3 | Biogas | [28] |
| 3 | MSW and biosolids | 30.3 | 562 | 99 | 1.2 | Biogas | [28] |
| 4 | Cow dung and horse dung | 6.2 | 360 | 36.99 | 8.07 | Biogas | [29] |
| 5 | Cow dung and horse dung | 5.7 | 167.85 | 18.95 | 8.71 | Biogas | [29] |
| 6 | Cattle manure and rumen fluids | 10.495 | 172.51 | 3.89 | 7.25 | Methane | [30] |
| 7 | Saw dust and cattle dung | 6.75 | 579.3 | 20.74 | 6.22 | Methane | [32] |
| 8 | Pig slurry and olive oil bleaching earth | 7.37 | 334.21 | 13.15 | 14.45 | Methane | [33] |
| 9 | Cattle dung and winemaking waste | 3.83 | 338 | 14 | 11.58 | Methane | [34] |
| 10 | Cattle dung and food waste | 3.55 | 288 | 6 | 11.8 | Methane | [34] |
| 11 | Cattle dung and biowaste | 3.7 | 387 | 13 | 14.6 | Methane | [34] |

Period of calculation lasted 100 days, the organic loading rate ranged from 0.1 kg $VS \cdot m^{-3} \cdot day^{-1}$ to 15 kg $VS \cdot m^{-3} \cdot day^{-1}$. Table 3 shows the results of the calculation: the OLR value, providing the maximum specific biogas yield in semi-continuous digester; HRT; biogas production per fresh material (FM) and the biogas yield, $m^3 \cdot kg^{-1}$ VS.

As can be seen from Table 3, the optimal OLR values for various substrates vary over a wide range, from 0.6 to 10 kg $VS \cdot m^{-3} \cdot day^{-1}$. A variety of substrates and significant duration of the experiments lead to the need for using methods of rapid assessment of the specific biogas yield, depending on the OLR in a semi-continuous digester.

Table 3 – Mean results of the calculations for a semi-continuous digester

| № | Substrate | OLR, kg VS·m$^{-3}$·d$^{-1}$ | HRT, d | Biogas production, m$^3$·m$^{-3}$ FM | Biogas yield, m$^3$·kg$^{-1}$ VS |
|---|---|---|---|---|---|
| *mono-digestion* | | | | | |
| 1 | Biological Sludge (raw) | 2 | 27 | 13.6 | 0.247 |
| 2 | OFMSW (raw) | 3 | 35 | 30.7 | 0.292 |
| 3 | Grease waste (raw) | 10 | 47 | 219.2 | 0.468 |
| 4 | Spent grain (raw) | 10 | 23 | 66.3 | 0.284 |
| 5 | Cow manure (raw) | 10 | 21 | 67.4 | 0.323 |
| 6 | Food waste | 10 | 25 | 121.7 | 0.493 |
| 7 | MSW | 10 | 31 | 140.3 | 0.459 |
| 8 | Horse dung | 3 | 23 | 10.0 | 0.147 |
| 9 | Swine manure | 0.6 | 33 | 9.7 | 0.486 |
| 10 | Food waste leachate | 3 | 29 | 10.8 | 0.125 |
| 11 | Chicken manure | 2 | 35 | 35.6 | 0.511 |
| *co-digestion* | | | | | |
| 1 | Paper and biosolids | 10 | 36 | 142.7 | 0.401 |
| 2 | MSW and paper | 10 | 31 | 131.6 | 0.428 |
| 3 | MSW and biosolids | 10 | 30 | 146.9 | 0.485 |
| 4 | Cow dung and horse dung | 3 | 21 | 11.9 | 0.192 |
| 5 | Cow dung and horse dung | 2 | 29 | 6.0 | 0.105 |
| 6 | Cattle manure and rumen fluids | 3 | 35 | 13.5 | 0.128 |
| 7 | Saw dust and cattle dung | 2 | 34 | 35.7 | 0.529 |
| 8 | Pig slurry and olive oil bleaching earth | 2 | 37 | 19.5 | 0.264 |
| 9 | Cattle dung and winemaking waste | 1 | 38 | 11.5 | 0.300 |
| 10 | Cattle dung and food waste | 1 | 36 | 6.5 | 0.183 |
| 11 | Cattle dung and biowaste | 1 | 37 | 10.7 | 0.290 |

**Conclusion.** A mathematical model was developed to analyze the biogas yield in a digester on the basis of the biogas yield in a batch reactor.

On the basis of the developed mathematical model and software, numerical calculations were carried out and OLR values, which provide maximum specific biogas yield in a semi-continuous digester, were obtained.

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## ЖАРТЫЛАЙ ҮЗДІКСІЗ МЕТАНТЕНК ҮШІН ОРГАНИКАЛЫҚ ЗАТТАР БОЙЫНША ЖҮКТЕУДЫН ЭКСПРЕСС-БАҒАЛАУ

**Аннотация.** Осы жұмыста жартылай үздіксіз анаэробты реактордаң биогаздын шығуың талдауға математикалық моделі ұсынылған.

Жартылай үздіксіз метантенк жағдайында түрлі субстраттарды анаэробты ашытудың мониторингі мен тиімділігін бағалау үшін газдың шығуы және периодты әрекет ететің реакторда биогазды өндіру жылдамдығы болып табылады. Максималды меншікті биогазды алу үшін моно-субстраттар мен олардың қоспалары үшін жартылай үздіксіз реакторда әр түрлі органикалық жүктеу жылдамдығы талданды.

**Түйін сөздер:** биомасса энергиясы; жартылай үздіксіз реакторы, жүктеудын органикалық жылдамдығы, математикалық модель, модификацияланған Гомпертц моделі.

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## ЭКСПРЕСС ОЦЕНКА НАГРУЗКИ ПО ОРГАНИЧЕСКОМУ ВЕЩЕСТВУ ДЛЯ МЕТАНТЕНКА ПОЛУНЕПРЕРЫВНОГО ДЕЙСТВИЯ

**Аннотация.** В работе представлена математическая модель, позволяющая анализировать выход биогаза в метантенке полунепрерывного действия. Основными критериями, которые используются для мониторинга и оценки эффективности анаэробного сбраживания различных субстратов в метантенке полунепрерывного действия, являются кумулятивный выход биогаза и скорость выхода биогаза в реакторе периодического действия. Проведен анализ различных вариантов нагрузки по органическому веществу (organic loading rate, OLR) для моно-субстратов и смесей, направленный на получение максимального удельного выхода биогаза в метантенке полунепрерывного действия.

**Ключевые слова:** энергия биомассы; полунепрерывного реактора, органические скорость загрузки, математическая модель, модифицированная модель Гомпертца.

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