Eco-Energetics: technologies, environment, law and economy
2019 · Vol. 2 · pp. 105–112 ISSN 2657-5922 · Annual
DOI 10.24426/eco-energetics.v2i2.115

Piotr Sakiewicz[1*], Jan Cebula[2], Krzysztof Piotrowski[3], Jolanta Bohdziewicz[4]

[1] Institute of Engineering Materials and Biomaterials, Faculty of Mechanical Engineering, Silesian University of Technology, Gliwice, Poland
[2] Institute of Environmental Protection and Engineering, Faculty of Materials and Environmental Sciences, University of Bielsko-Biala
[3] Department of Chemical Engineering and Process Design, Faculty of Chemistry, Silesian University of Technology, Gliwice, Poland
[4] Institute of Water and Wastewater Engineering, Faculty of Energy and Environmental Engineering, Silesian University of Technology, Gliwice, Poland
[*] piotr.sakiewicz@polsl.pl

Kinetics of methane fermentation of selected post-processed poultry beddings — possibilities of process intensification and limitations

Abstract
The kinetics of methane fermentation of selected post-processed poultry beddings was analyzed. A modified nonlinear Gompertz model was applied for the calculations. The presented kinetic parameter may be useful for design or optimization calculations of agricultural-biogas installations integrated with industrial-scale poultry breeding.

Keywords: poultry breeding manure, methane fermentation, process kinetics, batch biogas production process, modified Gompertz model.

1. Introduction

Methane fermentation processes of substrates including side-products of industrial--scale poultry breeding are nowadays highly important issue for biogas plant producers. The anaerobic fermentation of post-processed poultry-beddings premixed with poultry-metabolism products is a very attractive (environmentally and economically) alternative of their neutralization due to related with these wastes environmental problems, uncontrolled odours, ammonia, CO_2 and CH_4 emissions and problems with storage or other forms of its recycling (Webb et al., 1985; Pechan et al., 1987; Ojolo et al., 2007; Dalkılıc et al., 2015; Karaalp et al., 2015; Recebli et al. 2015; Leppikorpi et al., 2016; Miah et al., 2016; Al-Masalha et al., 2017). The poultry breeding manure is characterized by high nitrogen content in a chemical form of uric acid $C_5H_4O_3N_4$ and proteins. During anaerobic fermentation NH_3 and NH_4^+ are produced in amounts inhibiting the process, limiting the fermentation already at concentrations 5 mass % or less. To counteract these problems one uses, among others, mixing of poultry manure of high N content with different substrates with high C content, in order to reach the technologically required C/N ratio. Some of such co-substrates may be represented by post-processed poultry beddings — subject of research presented in this work.

2. Research subject and methodology

Laboratory stand designed for experimental identification of batch methane fermentation process is demonstrated in Figure 1. The plant consisted of 12 thermostated bioreactors where isothermal (38°C) anaerobic fermentation process ran (applied substrate concentrations: 1–10 mass % of dry mass). As the inoculum a digestate from working agricultural biogas plant was used. Cumulative volumes of the produced biogas were controlled and measured every several hours, while reading frequency was dependent on the process course intensity in a given stage. The poultry-breeding manure premixed with bedding biomaterial represented by: sawdust, straw (collected in two different poultry breeding farms), poultry manure premixed with the straw derived from the room with installed floor heating (raw substrate, after 6 and after 12 weeks of temporary storage on a aerated compost prism), as well as — for comparison — samples of pure straw being the subject of steam explosion process in different process-technological conditions were used as substrates.

Fig. 1. Laboratory stand with model bioreactors for the tests of batch isothermal anaerobic fermentation process

For kinetic analysis of the batch fermentation process in samples of the poultry beddings commonly used in industrial-scale poultry breeding premixed with poultry manure, the modified Gompertz model (1) was used (Bolado-Rodriguez et al., 2016; Kafle et al., 2016; Phukoetphim et al., 2017; Syaichurrozi, 2018; Batista et al., 2018):

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

where:

H — cumulative biogas volume produced from the process beginning up till given time t, m^3/Tdm (ton of dry mass),
H_{max} — the highest model-predicted H value (model asymptote), m^3/Tdm,
R_{max} — maximum biogas production rate, m^3/Tdm/h,
λ — process incubation time (*lag-time*), h,
t — test time, h.

3. Results

Kinetic parameter corresponding to methane fermentation processes of post-processed poultry beddings under study are presented in Table 1.

Table 1. Kinetic parameter values of methane fermentation process of the analyzed post-processed poultry beddings — modified Gompertz model

No.	1 process stage				2 process stage				3 process stage			
	H_{max} m³/Tdm	R_{max} m³/Tdm/h	λ h	R^2	H_{max} m³/Tdm	R_{max} m³/Tdm/h	λ h	R^2	H_{max} m³/Tdm	R_{max} m³/Tdm/h	λ h	R^2
Poultry manure with sawdust												
1	290.8	3.97	7.51	0.993	384.3	0.54	–	0.998	829.2	0.10	–	0.997
2	290.3	3.49	8.61	0.993	385.8	0.48	–	0.999	447.5	0.18	–	0.998
3	322.1	2.97	1.68	0.996	452.8	0.65	–	0.999	514.4	0.34	–	0.999
Poultry manure with the straw (poultry breeding farm 1)												
4	441.7	4.69	–	0.968	641.3	1.27	–	0.996	1295	0.22	–	0.997
5	484.4	5.06	7.25	0.996	649.5	1.15	–	0.999	758.6	0.38	–	0.999
6	502.4	3.56	5.15	0.996	554.0	1.39	–	0.999	675.0	0.26	–	0.998
Poultry manure with the straw (poultry breeding farm 2)												
7	405.0	1.54	92.46	0.999								
8	810.3	2.10	81.10	0.998								
9	624.9	2.56	78.98	0.998								
Straw samples preprocessed in temperature 180°C during 1 h												
10	68.68	5.77	23.09	0.999								
Straw samples preprocessed in temperature 180°C during 0,5 h												
11	86.88	14.33	16.21	0.999								
Poultry manure with the straw — heated floor — "dry", fresh												
12	78.84	1.07	1.23	0.986	520.8	1.18	–	0.996	540.6	1.17	–	0.994
13	83.31	1.15	2.60	0.990	506.1	1.03	–	0.996	543.9	1.18	–	0.998
14	82.15	1.64	3.44	0.992	517.9	1.18	–	0.991	524.6	1.13	–	0.991
Poultry manure with the straw — heated floor — after 6 weeks of composting												
15	125.0	0.91	–	0.978	651.3	0.99	–	0.996	551.8	1.17	–	0.994
16	142.8	0.90	–	0.979	592.1	1.11	–	0.998	569.4	1.10	–	0.996
Poultry manure with the straw — heated floor — after 12 weeks of composting												
17	568.6	1.98	45.52	0.999								
18	565.6	2.14	41.35	0.998								

Poultry manure premixed with sawdust used as a substrate in agricultural biogas production demonstrates both: lower maximum biogas production rate R_{max}: 2.97–3.97 m^3/Tdm/h for sawdust, Table 1, No. 1–3, Fig. 2 when compared with straw 1.54–5.06 m^3/Tdm/h, Table 1, No. 4–9, Fig. 3, and smaller maximal predictable biogas yield — H_{max}: 290.3–322.1 m^3/Tdm for sawdust; 405.0–810.3 m^3/Tdm for the straw. One should also notice significant differences in incubation time which for sawdust is 1.68–8.61 h, whereas 5.15–92.46 h for the straw bedding. Both for sawdust and straw one can distinguish three stages, which are characterized by gradual deceleration of the process. For the sawdust these stages are characterised by three different values of parameters: H_{max}: 290.3–322.1, 384.3–452.8 and 447.5–829.2 m^3/Tdm and the corresponding R_{max}: 2.97–3.97, 0.48–0.65 and 0.10–0.34 m^3/Tdm/h, whereas for the straw these parameters are as follows: H_{max} — 441.7–502.4, 554.0–649.5 and 675.0–1295 m^3/Tdm as well as R_{max} — 3.56–5.06, 1.15–1.39 and 0.22–0.38 m^3/Tdm/h.

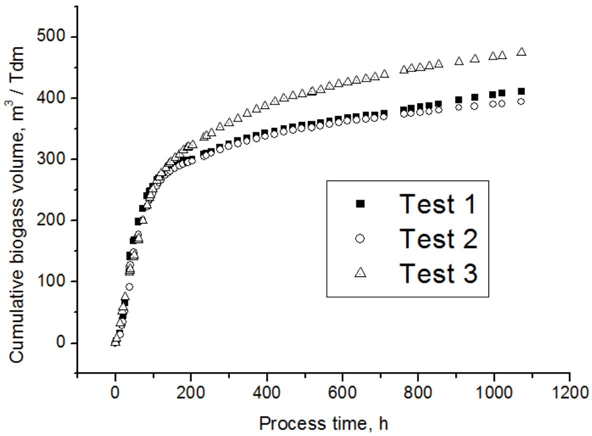

Fig. 2. Time-course of batch methane-fermentation of poultry manure premixed with sawdust

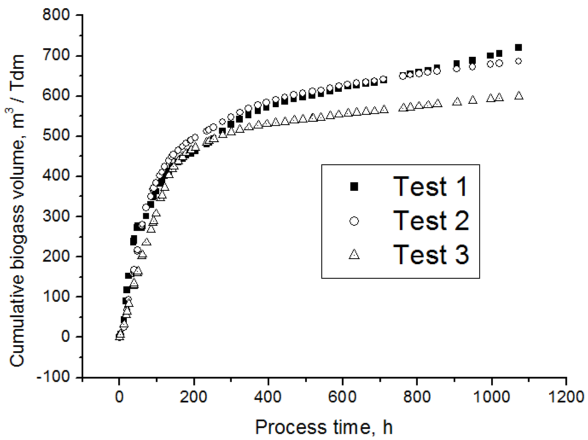

Fig. 3. Time-course of batch methane-fermentation of poultry manure premixed with the straw

Presence of multistage process suggests complex kinetic and a system of consecutive chemical and biochemical conversions. Parallel course of some biochemical reactions in the analyzed system is also confirmed by practical lack of clearly visible *lag-phase* periods between consecutive stages of the complex methane fermentation process, where smooth transition between one stage and beginning of the second one is observed without clear, temporary slowing down of the process course. It should be also emphasized that poultry manures with the straw derived from two different industry-scale poultry breeding farms — driven in identical measurement conditions — differ both in number of stages of methane fermentation process (3 stages and 1 stage), and process incubation time (λ: 5.15–7.25 h, 78.98–92.46 h). It proves complexity of the process, resulting mainly from chemical compositions of the substrates. This in turn, results directly from general breeding conditions, straw quality, proportions of post-processed bedding components (C/N), bedding exchange frequency (decay degree), quality and chemical composition of the fodders, as well as other factors. An important for the earliest, but also to main fermentation process stages (hydrolysis, substrates dissolution) is crumbling of post-processed poultry beddings, particularly sawdust or straw, their storage conditions, preliminary decomposition degree in conditions provided by microenvironment of breeding process, etc.

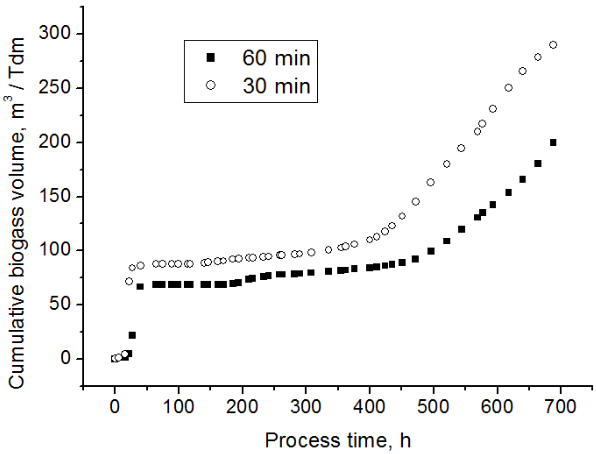

Fig. 4. Time-course of batch methane-fermentation of straw samples being subjected to preliminary steam-explosion process in temperature of 180°C

One of the important factors influencing hydrolysis and dissolution rates of components, being in water subjected to further conversion towards methane biosynthesis, is biological structure of bedding biomaterial — sawdust or straw. Previous extraction of valuable compounds from the biological lignocellulosic construction may be key-element impacting the whole process kinetics, directly influencing the biogas production economy. Increase in biogas production rate by preliminary preprocessing and oriented action on straw — a component of the post-breeding mixture — may advantageously affect the whole manure-straw mixture conversion. Therefore, the tests with the straw preprocessed with high-temperature (180°C) steam explosion were also carried out.

The results are presented in Table 1, No. 10 and 11 and Fig. 4. It is clearly seen, that shortening of steam explosion process time from 60 to 30 min results in advantageous growth of H_{max} from 68.68 to 86.88 m^3/Tdm, significant increase (already satisfactory high after 60 min of preprocessing) of R_{max} from 5.77 to 14.33 m^3/Tdm/h, as well as shortening of *lag-time* period from 23.09 to 16.21 h. Moreover, it was observed that the straw is a subject of further bioconversion towards biogas, which should be the subject of more thorough tests (Fig. 4).

One of the factors responsible for prevention of too early, uncontrolled decomposition of bedding biomaterial (unfavourable for poultry breeding) is application of heating floor system. Produced under such conditions substrate for biogas plant, with different quality parameters resulting from decay processes inhibition, may be the subject of additional technological preprocessing like exposition to air on a prism — under aerobic conditions (partial composting).

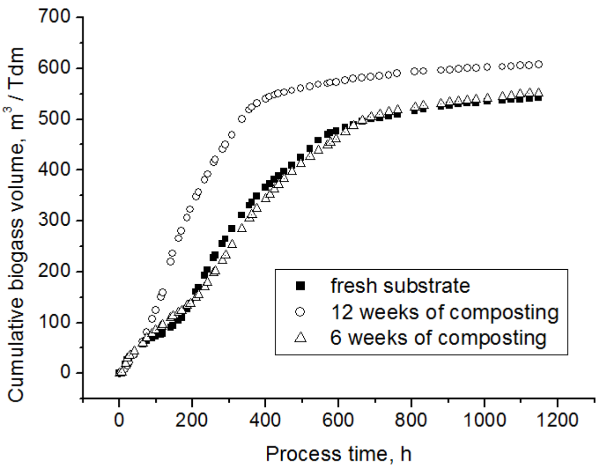

Fig. 5. Time-course of batch methane-fermentation of poultry manure premixed with the straw (room with floor heating system) — “fresh” substrate, after 6 and after 12 weeks of composting (aeration)

The results connected with the analysis of such substrate type are presented in Table 1, No. 12–18 and in Fig. 5. Dry, fresh poultry-breeding manure in the room with the heated floor, No. 12–14, during anaerobic fermentation undergoes biotransformation into biogas in 3-stage process. Maximal biogas yields H_{max}, according to stages sequence, are: 78.84–83.31, 506.1–520.8 and 524.6–543.9 m^3/Tdm. Corresponding to these stages maximal process rates R_{max} are: 1.07–1.64, 1.03–1.18 and 1.13–1.18 m^3/Tdm/h, respectively. The difference in H_{max} between first and second process stage is clearly observable, whereas the R_{max} values practically stabilize on identical level. After 6 weeks of exposition on a prism (partial composting), during methane fermentation of such preprocessed substrate increase in biogas yield and equally clear three process stages were observed. Maximal biogas yields increased up to: 125.0–142.8, 592.1–651.3 and 551.8–569.4 m^3/Tdm, while maximal biogas production rates stabilized on practically unchanged level, appropriately for each of the process stage: 0.90–0.91, 0.99–1.11 and 1.10–1.17 m^3/Tdm/h. Interesting observation is, that dry mixture of poultry manure with the straw collected in chicken coop with heated floor, without any preprocessing, showed incubation time (*lag-time*) before first process stage 1.23–3.44 h, whereas 6 weeks of exposition to aeration in a compost prism made, that methane fermentation process started instantly. This observation confirms advantageous effect of such, practically costless, preliminary preprocessing of the substrate, increasing the economic parameters of agricultural biogas plant (shortening of each batch methane fermentation process time).

It should be added, that between 1 and 2, as well as 2 and 3 stage no clear time-breaks were observed, what suggests complex interconnections within the consecutive process stages, as well as mixed consecutive-parallel character of these complex gradual biotransformations. Elongation of air exposition time (partial composting) from 6 to 12 weeks produces, however, essential change in the kinetic course of the batch methane fermentation process (Table 1, No. 17–18). In this case one-stage process is observed, with distinctly increased process rate (R_{max}: 1.98–2.14 m^3/Tdm/h), whereas maximum available biogas yield H_{max} 565.6–568.6 m^3/Tdm is comparable with the yield of the last, third process stage corresponding to substrate after 6 weeks of aeration. Nevertheless, in this case incubation period elongated significantly (41.35–45.52 h), what must be also considered in design and economical calculations of agricultural biogas plant where batch methane fermentation process will be carried out (productivity).

4. Conclusions

Based on obtained results one can conclude, that mixed substrates, blending metabolism products of poultry breeding and partly decayed bedding biomaterials may represent attractive substrate in agricultural biogas production. These may be subject of anaerobic fermentation together, thus their separation is not necessary what could influence the overall biogas production economy. Problem of C/N ratio correction and recycling of large mass streams of waste product of industrial-scale poultry breeding is simultaneously solved, what is an important environmental aspect of technology compatible with sustainable development strategy. The results suggest high complexity of the process, thus should be used in design-calculation works as the rough and estimated values only, necessary to verify based on the samples of the biomass which is planned to be in future important substrate for the designed biogas plant.

References

Al-Masalha, I., Elayyan, M., Issa, H.A.B. (2017). Use of biogas energy in poultry farming heating. *The International Journal of Engineering and Science* (IJES), *6*(3), 58–63.

Batista, A.P., Gouveia, L., Marques, P.A.S.S. (2018). Fermentative hydrogen production from microalgal biomass by a single strain of bacterium Enterobacter aerogenes — Effect of operational conditions and fermentation kinetics. *Renewable Energy, 119*, 203–209.

Bolado-Rodriguez, S., Toquero, C., Martin-Juarez, J., Travaini, R., Garcia-Encina, P.A. (2016). Effect of thermal, acid, alkaline and alkaline-peroxide pretreatments on the biochemical methane potential and kinetics of the anaerobic digestion of wheat straw and sugarcane bagasse. *Bioresource Technology, 201*, 182–190.

Dalkılıc, K., Ugurlu, A. (2015). Biogas production from chicken manure at different organic loading rates in a mesophilic-thermopilic two stage anaerobic system. *Journal of Bioscience and Bioengineering, 120*(3), 315–322.

Kafle, G.K., Chen, L. (2016). Comparison on batch anaerobic digestion of five different livestock manures and prediction of biochemical methane potential (BMP) using different statistical models. *Waste Management, 48*, 492–502.

Karaalp, D., Doruk, N., Dizge, N., Keskinler, B., Azbar, N. (2015). A novel solution for biogas applications in poultry industry: CLAMBS approach. *Journal of Bioprocessing and Biotechniques, 5*(2), 1–6.

Leppikorpi, M., Virkajärvi, I. (2016). Unlocking the potential of poultry manure. *Biogas Journal, 5*, 40–42.

Miah, M.R., Rahman, A.K.M.L., Akanda, M.R., Pulak, A., Rouf, M.A. (2016). Production of biogas from poultry litter mixed with the co-substrate cow dung. *Journal of Taibalh University of Science, 10*, 497–504.

Ojolo, S.J., Oke, S.A., Animasahun, K., Adesuyi, B.K. (2007). Utilization of poultry, cow and kitchen wastes for biogas production: a comparative analysis. *Iranian Journal of Environmental Health Science and Engineering, 4*(4), 223–228.

Pechan, Z., Knappova, O., Petrovicova, B., Adamec, O. (1987). Anaerobic digestion of poultry manure at high ammonium nitrogen concentrations. *Biological Wastes, 20*, 117–131.

Phukoetphim, N., Salakkam, A., Laopaiboon, P., Laopaiboon, L. (2017). Kinetic models for batch ethanol production from sweet sorghum juice under normal and high gravity fermentations: Logistic and modified Gompertz models. *Journal of Biotechnology, 243*, 69–75.

Recebli, Z., Selimli, S., Ozkaymak, M., Gonc, O. (2015). Biogas production from animal manure. *Journal of Engineering Science and Technology, 10*(6), 722–729.

Syaichurrozi, I. (2018). Biogas production from co-digestion Salvinia molesta and rice straw and kinetics. *Renewable Energy, 115*, 76–86.

Webb, A.R., Hawkes, F.R. (1985). The anaerobic digestion of poultry manure: variation of gas yield with influent concentration and ammonium-nitrogen levels. *Agricultural Wastes, 14*, 135–156.

Acknowledgement

This work is part of research and development project: "Utilization of waste from poultry farming and poultry industry for the purpose of biogas production as a source of renewable energy and mineral-organic fertilizer" (WFOS/RX-15/19/2017) co-financed by the Regional Fund for Environmental Protection and Water Management in Gdansk.