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Estimation of methane production for batch technology – A new approach

Rafał Mulka [a,*], Wiesław Szulczewski [b], Józef Szlachta [a], Mariusz Mulka [c]

[a] University of Enviromental and Life Sciences, The Faculty of Life Sciences and Technology, Institute of Agricultural Engineering, Wrocław, Poland
[b] University of Enviromental and Life Sciences, The Faculty of Enviromental Engineering and Geodesy, Department of Mathematics, Wrocław, Poland
[c] Wrocław University of Technology, Faculty of Computer Science and Management, Wrocław, Poland

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ABSTRACT

In the case of agricultural biogas plants it is the living microorganisms (mainly archaea) that determine the amount of methane produced. If the conditions in the digester are not adequate or the substrates are selected incorrectly, the microorganisms will not be able to develop properly and methane production will also be low or none. Therefore, in the first place the influence of individual factors on the production of methane was analysed. Next, based on the conclusions drawn from the analysis of the factors, a mathematical model was developed that will facilitate the selection of appropriate substrates and process parameters by future investors building agricultural biogas plants. The aim of the study was to demonstrate the impact of the factors on the production of methane and to present a mathematical model for estimating methane production for batch technology used in agricultural biogas plants (this kind of production is also used in laboratories for testing specific substrates). The model presented in the paper has been developed and tested on a group of over seventy substrates of agricultural origin. The inclusion of many factors determining methane production in the model is not complicated as each of the factors is easy to measure.

1. Introduction

Energy consumption and environmental pollution are constantly growing. Besides, one of the many problems that mankind will soon have to face is the depletion of natural resources – major energy carriers such as coal or oil. Furthermore, the commitment of the European Union countries to the implementation of renewable energy sources resulted in a recent revival of interest in cleaner energy sources such as wind, solar and geothermal energy or biomass (e.g. Poland has committed to build 2000 biogas plants by 2020 [6] and to increase biogas power capacity to 3000 MW [31]). The cost of producing energy, which is very high in comparison to conventional sources, is a big problem associated with green energy. In this case, an alternative solution may be offered by agricultural biogas plants which can use agricultural waste such as manure to produce energy [24]. Additionally, apart from energy production, agricultural biogas plants significantly contribute to the reduction of methane emissions. This gas is much more aggressive to the Earth's atmosphere than carbon dioxide. At the same time the biogas produced can be used to produce biofuels [5]. However, a notable drawback of agricultural biogas plants is their unstable energy production level. Depending on the substrate, the conditions in the fermentor and the microorganisms involved in hydrolysis and fermentation, the production of methane can vary [18]. With the application of a mathematical model, it is possible to make an initial estimation of methane production for appropriately selected substrates and process parameters. Moreover, the risk of the project, that is the construction of biogas plants, would be reduced. In relation with the above, the authors made an attempt at the development of a mathematical model that would permit the estimation of methane production for two technologies – the batch technology and the continuous technology. The model permits the simulation of methane production on the basis of

* Corresponding author.
E-mail address: rafalletto@yahoo.de (R. Mulka).

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a number of factors determining the process, easy to determine at the stage of its application. The construction of the model was based on the analysis of methane production process for a group of over seventy substrates of agricultural origin. This paper presents the first part of the model, concerning the batch technology. However, it should be emphasised that the equations allowing the estimation of methane production for that type of technology constitute a basis for an estimation tool applicable to any type of methane production technology.

2. Literature review

During the formation of biogas, which is a mixture of gases (mainly methane and carbon dioxide [28]) there are many different, often closely related, biochemical processes taking place due to microbial activity. A number of external factors, such as temperature, affect these processes. The literature concerning the modelling of the process of methane production is abundant, but there are few reports presenting models that would be effective and easy to use. Starting with the model developed by Benjamin Gompertz in 1825, through the leading mathematical models of Chen, Hashimoto (1978) [1] and Minott (2002) [38], to the model of 2015 created by Latinwo [19] who based his model on the Gompertz model. At the same time the literature provides many reviews offering a synthesis of a part of those models, as for example in the paper by Batstone [2]. For this reason in the further part of this review we will focus on those factors affecting methane production that are incorporated in the model presented herein. Although sometimes the information is of a handbook level, it permitted appropriate – in relation to the scale of impact on methane production – inclusion of those factors in the model developed.

2.1. Temperature

Temperature is the most important parameter determining the process of methane formation. This is due to the microorganisms that live and develop in temperature ranges specific for their species. Taking into account that methane is produced by archaea (obligate anaerobes), the process temperature is adjusted specifically to the requirements of those microorganisms. There are three temperature ranges used in agricultural biogas plants [3]:

- psychrophilic <25 °C
- mesophilic 30 °C–45 °C
- thermophilic 45 °C–55 °C

The influence of that factor was included e.g. in the model created by Safelty and Wasterman in 1992 [38]. The model does not take other factors into account, so it is impossible to conduct an in-depth analysis. Apart from that, temperature was used in the model developed by Minott. Unlike the previous model, Minott took a lot more factors into account [38].

2.2. Humidity

With regard the moisture of the substrate it is assumed that dry fermentation occurs when the moisture drops below 84%, while wet fermentation takes place when the moisture is equal to or higher than 84%. Consequently, agricultural biogas plants very often use livestock manure in combination with energy crops or waste from agricultural sources. Water is used very rarely to achieve proper moisture because it does not have appropriate cultures of bacteria and water does not produce any energy gain [16].

2.3. Reaction pH

In agricultural biogas plants pH is adjusted to methanogenic microorganisms (e.g. *Methanosarcina mazei* archaea species live at pH between 5 and 7 [23]). According to [11], the optimum pH is about 7, whereas for the bacteria involved in hydrolysis pH is between 4.5 and 6.3. These are not, however, strictly defined boundaries because the bacteria can survive e.g. at slightly lower or higher pH [16].

The use of an appropriate inoculum is also important for pH. If its pH is low, as in the case of liquid manure, it will lower the overall pH of the mixture, whereby the efficiency of methane production will decrease or the process will not even start. It is also important to regularly test the fermentation process as regards the inoculum to substrate ratio [12].

2.4. The composition of volatile solid

Methane is mainly formed from carbohydrates, proteins and fats (the last produce the most energy, but also their decomposition takes the longest [3]). In addition, microorganisms need the following elements for their adequate development: nitrogen, carbon, sulphur, phosphorus and trace elements. If dry matter contains irreducible compounds, such as lignin, then without adequate preparation of the substrate the production will be lower [17]. Apart from that, mixing is also very important for microorganisms. In the case of the non-mixing mode (very often used in laboratory), the microorganisms will not be deployed well in the digester. There will be places in the digester where microorganisms cannot live [22].

The chemical composition was taken into account in the models developed by Buswell and Muell, as well as by Boyle. Buswell and Muell developed a model for the estimation of methane production in 1962 [13]. The model calculated the production of methane based on the chemical composition (carbon, oxygen and hydrogen). In contrast, Boyle, drawing on the model by Buswell and Muelle, expanded their model and took into account the content of sulphur and nitrogen in the substrate [13].

Also noteworthy is the paper by Batstone in which the author presents models based on mass balance (as a fundamental parameter of all models) [2]. Whereas, in the case of the work by Monayeri [10] the factor determining biogas production is normalised organic dry matter.

Table 1
Hydraulic retention time of selected substrates (by Myczko 2011 [25]).

Substrate	*HRT* [*day*]
Pig manure	10–20
Cow manure	10–15
Chicken manure	30–50
Corn silage	25–60
Sorghum silage	25–50
Potato juice	14–25
Molasses	20–40