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# A model for methane production in anaerobic digestion of swine wastewater

Hongnan Yang [a, b], Liangwei Deng [a, b, *], Gangjin Liu [a, c], Di Yang [a, b], Yi Liu [a, b], Ziai Chen [a, b]

[a] Biogas Institute of Ministry of Agriculture, Chengdu 610041, PR China
[b] Laboratory of Development and Application of Rural Renewable Energy, Ministry of Agriculture, Chengdu 610041, PR China
[c] Bioprocess Control AB, Scheelevägen 22, 223 63 Lund, Sweden

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ABSTRACT

A study was conducted using a laboratory-scale anaerobic sequencing batch digester to investigate the quantitative influence of organic loading rates (OLRs) on the methane production rate during digestion of swine wastewater at temperatures between 15 °C and 35 °C. The volumetric production rate of methane ($R_p$) at different OLRs and temperatures was obtained. The maximum volumetric methane production rates ($R_{pmax}$) were 0.136, 0.796, 1.294, 1.527 and 1.952 $L_{CH4}$ $L^{-1}$ $d^{-1}$ at corresponding organic loading rates of 1.2, 3.6, 5.6, 5.6 and 7.2 g volatile solids $L^{-1}$ $d^{-1}$, respectively, which occurred at 15, 20, 25, 30 and 35 °C, respectively. A new model was developed to describe the quantitative relationship between $R_p$ and OLR. In addition to the maximum volumetric methane production rate ($R_{pmax}$) and the half-saturation constant ($K_{LR}$) commonly used in previous models such as the modified Stover–Kincannon model and Deng model, the new model introduced a new index ($K_D$) that denoted the speed of volumetric methane production rate approaching the maximum as a function of temperature. The new model more satisfactorily described the influence of OLR on the rate of methane production than other models as confirmed by higher determination coefficients ($R^2$) (0.9717–0.9900) and lower bias between the experimental and predicted data in terms of the root mean square error and the Akaike Information Criterion. Data from other published research also validated the applicability and generality of the new kinetic model to different types of wastewater.



## 1. Introduction

Associated with the development of an intensive piggery industry, swine manure management has become an urgent problem during recent years. Anaerobic digestion is an economical and effective alternative for treating swine manure due to its operational simplicity and potential for energy recovery (Weiland, 2010; Deng et al., 2014).

Although the use of anaerobic treatment technology is widespread, optimum process performance seldom is achieved because of the high degree of empiricism that prevails in the design and operation of anaerobic digesters. As a result of increased demand for efficient digester operation and model-based design, kinetic modeling of the anaerobic digestion process has gained extensive attention. The kinetics of biological processes can be addressed using microbial growth models, substrate utilization models and product formation models, which are interrelated through the corresponding yield coefficients (Massé and Droste, 2000; Fernández-Rodríguez et al., 2013). For such a complex substrate containing dissolved and particulate organic matter as swine wastewater, the volatile suspended solids, on which an estimate of microorganism concentration typically has been based, is not a good indicator due to difficulties in differentiating between bacterial volatile suspended solids and complex biomass volatile solids (Momoh et al., 2013). In addition, the component of swine wastewater removed by sedimentation or absorption has often been neglected because of difficulty in measuring it directly. Using the microbial growth rate and the substrate removal rate as variables in models has certain limitations in fitting and evaluating models,

* Corresponding author. Biogas Institute of Ministry of Agriculture, Chengdu 610041, PR China.
*E-mail address:* dengliangwei@caas.cn (L. Deng).

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particularly for continuous microbial cultures. In contrast, the amount of biogas (methane) formed during the conversion of organic matter by microorganisms in anaerobic digestion is the most common on-line and easily performed measurement (Donoso-Bravo et al., 2011), and simultaneously reflects the activity of microorganisms and the rate and degree of biodegradation because biogas production is directly proportional to substrate degradation. In many studies, biogas or methane production has been used as the only measurement by which to estimate model parameters (Martín et al., 1994; Batstone, 2006; Mähnert and Linke, 2009; Fernández-Rodríguez et al., 2013).

Numerous types of mathematical models have been developed to describe the methane production process of animal waste digestion. Among them, the anaerobic digestion model 1 (ADM1) is the most advanced due to its precise predictability and strong generality (Girault et al., 2011). The ADM1 model reflects the major processes that are involved in the conversion of complex organic substrates into methane and carbon dioxide and inert byproducts (Batstone et al., 2002). However, the model requires a large number of constants and coefficients that should be calibrated according to the characteristics of the substrates; such calibration requires the use of special assays and computing skill, which is difficult for scientists and engineers dedicated to the plant operation and improvements (Parker, 2005; Liu et al., 2008). Therefore, simplified models that consist of only a few variables have been widely studied. The first-order rate equation (Yang et al., 2015) and the modified Gompertz model (Kafle and Kim, 2013) have been applied to batch assays and have satisfactorily predicted methane production. Unfortunately, the data obtained from batch studies lacks common, universal bases for comparison, and modeling results from batch studies are usually provided in terms of the final values of the methane yields from substrates, rather than methane yields varying with hydraulic retention time (HRT). The volumetric methane production rate, as an important parameter for optimizing the design of a digester, is difficult to obtain using batch assays (Brulé et al., 2014).

Conversely, simplified models that are calibrated in continuous operation can more accurately reflect the actual anaerobic digestion of wastewater and seem to be qualified for design and optimization of wastewater treatment plants (Batstone, 2006; Ekama, 2009). Among the kinetic models that predict methane production based on continuous testing are the modified Stover–Kincannon (Yu et al., 1998), Chen–Hashimoto (Chen, 1983) and Deng (Deng et al., 2014) models; all are derived assuming that digesters are operated at steady state conditions. The Chen and Hashimoto model was considered to be an appropriate model with which to describe the kinetics of methane production from swine wastewater and has been widely used (Pham et al., 2014). Yu et al. (1998) proposed a model to describe the kinetics of methane production based on the Stover–Kincannon model. The modified Stover–Kincannon model for methane production has been applied to soybean wastewater (Yu et al., 1998), synthetic milk wastewater (Ramakant et al., 2002) and synthetic wastewater containing *para*-nitrophenol (Kuşçu and Sponza, 2009), but has been rarely used in the study of swine wastewater anaerobic treatment. To describe the variation in the volumetric methane production rate ($R_p$) as a function of the organic loading rate (OLR) in the temperature range of 15–35 °C, Deng et al. (2014) developed a reliable model capable of closely matching observed methane production rates ($R^2 = 0.989–0.999$). However, the lack of widespread verification and comparison of the fitting results of these models limits their application in biogas engineering.

In this study, the anaerobic digestion of swine wastewater was conducted at incremental OLRs by increasing the feed flow-rate while maintaining a constant influent substrate concentration and at temperatures of 15, 20, 25, 30, and 35 °C. The aims were: (1) to evaluate the methane production performance at gradually increasing OLR and to obtain the maximum volumetric methane production rate at each temperature, (2) to create a rational and suitable model with which to quantify the effect of OLR on the volumetric methane production rate, and (3) to evaluate the quantitative effect of temperature on methane production.

## 2. Materials and methods

### 2.1. Swine wastewater and inoculum

The swine wastewater used in this study was collected from a farm located in Jianyang, Sichuan, China, 35 km away from the laboratory. Samples were transported back to the laboratory immediately after collection and stored at 4 °C. The concentration of swine manure was adjusted to a volatile solids (VS) content of 0.80% by adding a certain amount of water before the start of an experiment.

The inoculation sludge for the anaerobic digestion experiments was obtained from a full-scale digester that treated swine wastewater from the same pig farm that served as the source of the wastewater.

### 2.2. Anaerobic digestion experiments

As shown in Fig. 1, the methane fermentation experiments were performed in 1000 mL gas-tight glass reactors with a rubber plug and attached to an influent port, an effluent port and a pipe for venting biogas. A 1000 mL wide-mouth glass bottle was used as a biogas gasholder, which was fitted with an influent-effluent port to allow the entrance of biogas and the discharge of water. The digesters were connected by rubber tubes to the gasholder (Deng et al., 2012). Each digester was inoculated with 500 mL of anaerobic sludge at the beginning of the experiments. The digester was operated in draw-and-fill mode twice a day. Experiments were conducted at 15, 20, 25, 30 and 35 °C, and five water baths were used to maintain the temperature of the digesters. The anaerobic digesters were mixed manually twice a day.

The OLRs in experiments were increased by reducing the HRT at a constant influent concentration until the maximum volumetric methane rate ($R_{pmax}$) was achieved (when the $R_p$ stopped rising or the deviations of the last two $R_p$s were less than 5%). The difference of methane production rate under different temperatures resulted in different initial and final OLRs and loading intervals for the five temperatures that were studied. The OLRs applied were increased by small increments in order to minimize any adverse effects of sudden increases in loading to obtain the $R_{pmax}$. The operating load range in the anaerobic digestion experiments at different temperatures is listed in Table 1. There were different experimental runs for different operation temperatures. A steady-state condition during each run was achieved when the deviations between the observed values of daily methane production were less than 5% and each run had a duration of 2–3 times the corresponding HRT (in the range of 5–40 days) or of 10 days (in the HRT range 1.1–3.3 days) at steady-state condition. All treatments were conducted in duplicate. The amounts of released biogas and the concentrations of methane were recorded on a daily basis. The gas produced in each digester was measured using a water displacement device.

### 2.3. Analytical methods

Analyses of chemical oxygen demand (COD), total solids (TS), and VS were carried out according to standard methods (APHA, 1998), The determination of COD was accomplished by digesting