Environ Res Tec, Vol. 4, Issue. 4, pp. 308–316, December 2021

Environmental Research and Technology
https://ert.yildiz.edu.tr - https://dergipark.org.tr/tr/pub/ert
DOI: https://doi.org/10.35208/ert.916002

Research Article

Which kinetic model best fits the methane production on pig farms with covered lagoon digesters?

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ARTICLE INFO

Article history
Received: 20 April 2021
Revised: 23 September 2021
Accepted: 06 October 2021

Key words:
Anaerobic digestion; Biogas; modeling; Pig farming

ABSTRACT

The volumetric production of biogas can be estimated through kinetic models, although many of them have not been validated adequately in full-scale systems with specific operational conditions in tropical countries. This study aimed to evaluate the applicability of these kinetic models to estimate methane production in pig farming operated with covered lagoon digesters (CLD, to inform: Chen-Hashimoto, First-order, Cone, Modified Gompertz, Modified Stover-Kincannon and Deng. The input data were obtained through the monitoring of two CLD in pig farming located in Minas Gerais-Brazil. The analyzed parameters were methane composition, the temperature of the substrate, chemical oxygen demand (COD), and volatile solids. The real production of methane (Pactual) was determined in relation to the electric power production at the internal combustion engine. The results obtained for Pactual and the models were compared through regression analysis (t-test, $\alpha=1\%$). All of the evaluated models overestimate the methane production in comparison with Pactual. The smallest difference between the CH4 production and the measurement on the pig farm was obtained with Chen model, overestimating approximately 16.3%, while the highest estimate was 38.5% obtained with the Modified Stover-Kincannon model. The results showed the absence of statistical differences among the real data (monitored system) and the simulated data (p-value>0.01). The mathematical kinetic models are considered a reliable tool to evaluate the energetic potential of biogas in pig farming with CLD from operational simplicity and low cost.

Cite this article as: Lopes JO, Rosa AP, Sousa IP, Melo SM, Almeida AA, Borges AC. Which kinetic model best fits the methane production on pig farms with covered lagoon digesters? Environ Res Tec 2021;4:4:308–316.

INTRODUCTION

Agribusiness is one of the most important sectors of the Brazilian economy. Among the many sectors in it, pig farming plays a prominent role [1]. Confined animal breeding produces high volumes of manure, which contains a high content of organic matter, nutrients, and metals. The lack of proper treatment for the effluent can contaminate water bodies, soil, and the atmosphere [2]. Because manure treatment is required, covered lagoon digesters have been widely used in Brazil as an alternative treatment on pig farms [3].

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This paper has been presented at EurAsia Waste Management Symposium 2020, İstanbul, Turkey

Published by Yıldız Technical University Press, İstanbul, Turkey

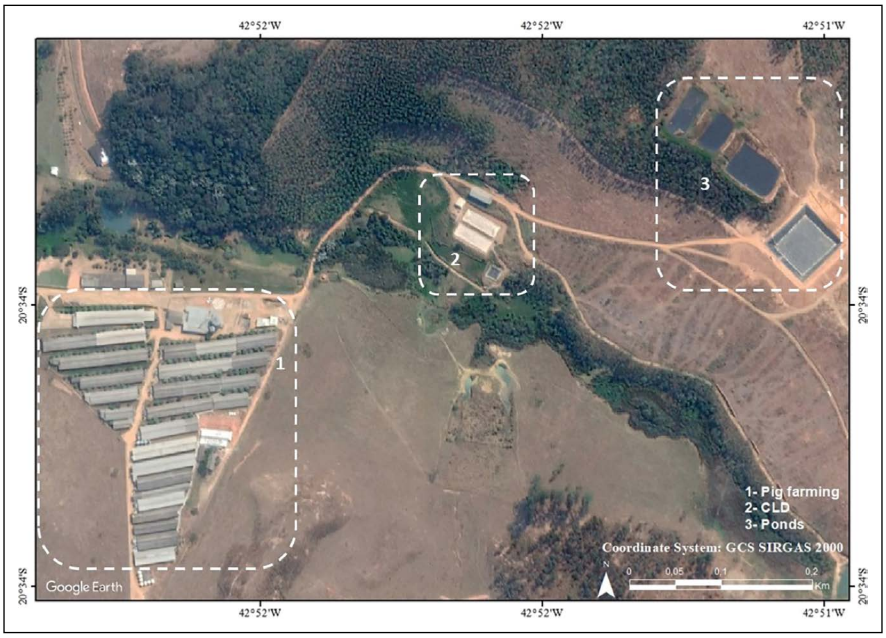

Figure 1. Aerial photography from the studied pig farming.

In Brazil, the covered lagoon digesters (CLD) are widely used to treat manure in pig farms and their use has many benefits such as lower implementation and maintenance costs as well as biogas energy recovery [4]. The use of mathematical modeling is an important tool for estimating the volumetric production of biogas. Among the models, kinetics have been widely used to assist in understanding about the breakdown of organic matter, to estimate biogas production, and to provide data for projects, operation, and control of the performance of the anaerobic digestion [5]. According to Neto [6], kinetic studies are aimed at evaluating a phenomenon or process, through the quantification of parameters as time and substrate concentration in a gradual process to obtain a known product.

The use of kinetic models to estimate methane production for different types of manure has been done by several authors on a laboratory-scale. Zhang et al. [7] used the first-order kinetic model and the modified Gompertz model to estimate the methane production through the co-digestion of pig manure with dewatered sewage sludge in batch reactors. Nguyen et al. [8] evaluated four kinetic models (Cone model, a first-order Kinetic model, modified Gompertz model, and dual pooled first-order kinetic model) to obtain the model that best fits the methane production from nine different types of manure. Yang et al. [9] applied the Chen-Hashimoto model, modified the Stovere-Kincannon model, and Deng model in the treatment of swine manure using batch anaerobic reactor in laboratory-scale. The Chen-Hashimoto model exhibited well-fitting results.

The kinetic studies are in its majority, used in controlled conditions by laboratory-scale. It is possible to identify the existence of some gaps related to the application of these kinetic models on a full scale, particularly when using covered lagoon digesters. In this way, assure the reliability of kinetic models to methane production can contribute to the improvement of energetic sustainability in the farms. This study aimed at evaluating and comparing the fit of kinetic models to estimate methane production in pig farming with covered lagoon digesters. The differential of this study is the proposal to transition from the laboratory-scale to full, considering the use of kinetic models from the use of an operational parameter with easy determination (volatile solids).

MATERIALS AND METHODS

Study Area

Monitoring was carried out on a pig farm located in Teixeiras (State of Minas Gerais/Brazil) (Fig. 1). The farm works in a complete cycle system for the raising of animals in confinement, from birth to completion. The unit has an average of 10,695 animals, of which 1,631 are sows and 14 boars.

The effluent treatment system consists of an equalization tank that receives the manure by the gravity action. Then the influent is pumped in a semi-continuous manner and applied in two CLD operating in parallel. After the treatment in the digesters, the effluent is sent to a stabilization pond, being used after treatment as organic fertilizer in pasture areas on the farm.

The digesters were built in trenches, inverted pyramid-shaped trunks covered on the bottom and walls with flexible PVC geocomposite and covered with another blanket of the same material, forming the dome (biogas reservoir). Each anaerobic digester has a volumetric capacity of 1.250 m^3. The details of the main dimensions of the digesters are shown in Figure 2.

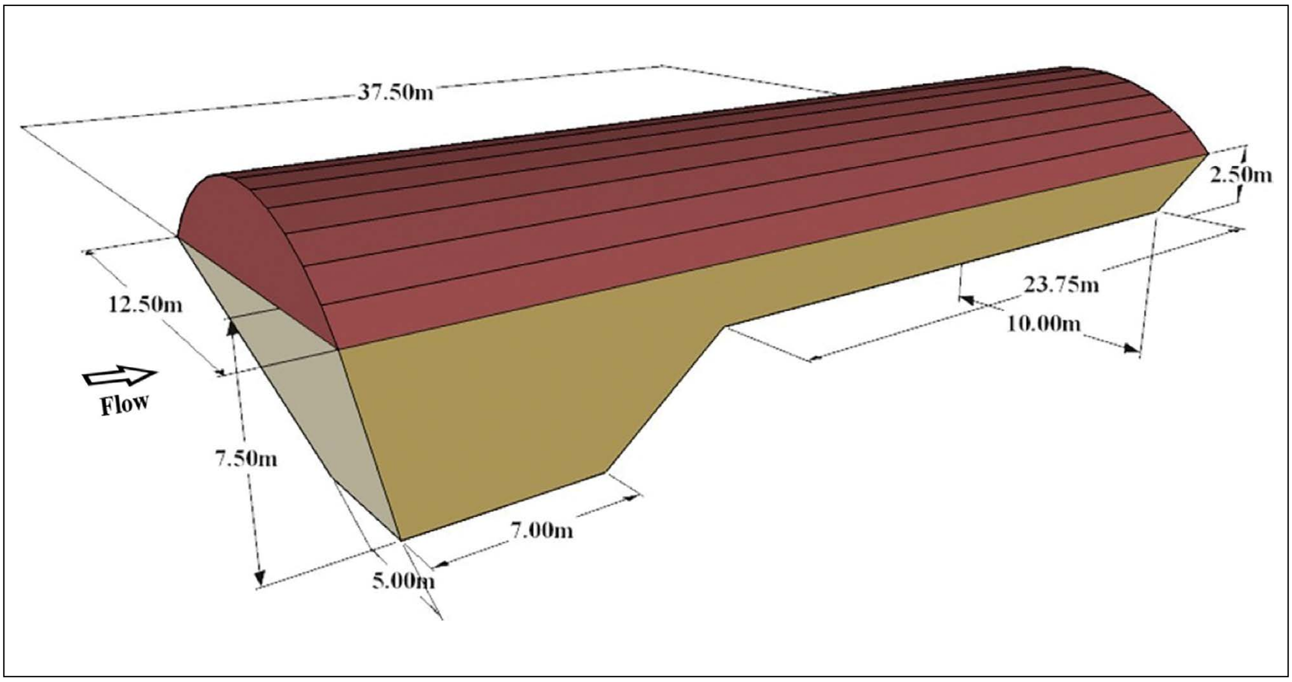

Figure 2. Details of the external and internal dimensions of the digesters.

The biogas produced by the anaerobic process inflates the dome of the digester where it remains stored. Then, the biogas is channeled to a temperature meter and later converted into electricity in a generator engine model GMWM120 with a power of 120 kVA.

Monitoring of the Covered Lagoon Digesters

The monitoring was carried out from September 2018 to August 2019. The parameters methane composition, temperature of the substrate, chemical oxygen demand (COD), and volatile solids were analyzed, which are the main input parameters of the evaluated methodologies (Fig. 3). The influent samples were collected weekly.

The monitoring of the temperatures in the digester was obtained from the generation of a database with average temperature values collected every 15 min. Then, the temperature data were organized into daily averages, followed by monthly averages.

Quantification of the biogas composition (around 10 liters) was performed using a gas analyzer (Online Infrared Gas Analyzer, model Gasboard, # 3100). The manure campaigns were carried out on a weekly basis and the results were analyzed following the procedures described in Standard Methods for the Examination of Water and Wastewater APHA [17]. The monthly water consumption and a coefficient of 65.0% were used to determine the manure flow [18]. The hydraulic retention time (HRT) was calculated using manure flow and digester volume ratio.

Mathematical Models to Estimate the Volumetric Methane Production

After a comprehensive evaluation, the most useful kinetics models to estimate the biogas production in covered lagoon digesters were selected, as follows: Chen-Heshimoto [10], First-order [11], Cone [12], modified [13], Modified Stover-Kincannon [14] and Deng [15]. Table 1 shows the input data of the mathematical models evaluated in terms of volumetric methane production. These methodologies have not yet been evaluated jointly considering input data from full-scale plants in pig farms.

Chen-Hashimoto Model

$$B = \frac{B_0 \text{ x } VS}{HRT} \text{ x} \left(1 - \frac{K}{\mu m \text{ } HRT - 1 + K}\right) \tag{1}$$

in which

B - methane production (m^3 CH_4 kg^{-1} VS);

B^0 - ultimate methane yield (0.36 m^3 $_{CH4}$ kg^{-1} VS m^3 CH_4 kg^{-1} VS);[1]

VS - volatile solids in the influent (kg VS m^{-3})

HRT - hydraulic retention time (d);

μm - maximum specific growth rate (d^{-1});

K - indicator for the overall performance.

$$K=0.6+0.006e^{(0.1185 \text{ x } VS)} \tag{2}$$

$$\mu m=0.013 \text{ } T-0.129 \tag{3}$$

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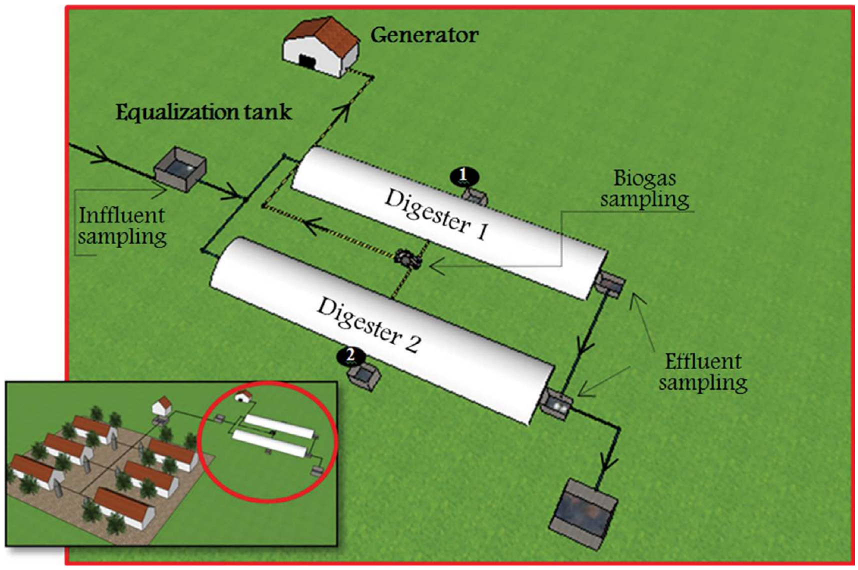
[1] 10.36 m^3 CH_4 kg^{-1} VS - 25 °C [15].



Points 1 and 2 – sensors of biomass temperature.

Figure 3. Schematic representation of the treatment system in the pig farm.

Table 1. Input dada of the mathematical models to estimate the potential of CH4 production

Kinectic models	Kinetic parameters reported in the literature						
	Scale/Reactor type	**Influent**	**Organic volumetric load**	**Reaction time (d)**	**T (ºC)**	**Source**
Chen-Hashimoto	Anaerobic digesters of laboratory and pilot-scale	Swine manure	13-65 $kg_{SV}\ m^{-3}$	5-40	30-60	[10]
First-order	Anaerobic biodigester of laboratory scale, in batches	Swine manure solids	16.12 ± 0.16 $kg_{SV}\ m^{-3}$	26	55±2	[8]
Cone						
Modified Gompertz						
Deng	Anaerobic biodigester of laboratory scale, in sequential batches	Swine wastewater	1.21-3,87 $kg_{ST}\ m^{-3}\ d^{-1}$	2.78-8.93	15-35	[15]
Modified Stover-Kincannon	Anaerobic filter of laboratory experiment, pilot, and full scale	soybean wastewater	4.41 – 22.25 $kg_{DQO}\ m^{-3}\ d^{-1}$	4.41 – 22.25 $kg_{DQO}\ m^{-3}\ d^{-1}$	34-36	[16]

in which

T - biomass temperature (ºC).

$$Q_{CH_4}=Bx\ Q\ x\ VS \qquad (4)$$

in which

Q - effluent flow ($m^3\ d^{-1}$);

Q_{CH_4} - methane production ($m^3\ CH_4\ d^{-1}$).

First-Order Model

$$B=B_0x(1—e^{(-k*HRT)}) \qquad (5)$$

$$Q_{CH_4}=Bx\ Q\ x\ VS \qquad (6)$$

in which

B_0 - ultimate methane yield (0.369 $m^3{}_{CH4}\ kg^{-1}$ VS $m^3\ CH_4\ kg^{-1}$ VS);

k - indicator for the overall performance (0.113 d^{-1}).

Cone

$$B = \frac{B_0}{1+(k*TRH^{-n})} \tag{5}$$

in which

B_0 - ultimate methane yield (0.376 $m^3{}_{CH4}$ kg^{-1} VS);

k - indicator for the overall performance (0.168 d^{-1});

n- shape factor (1.56).

$$Q_{CH_4} = Bx\ Q\ x\ VS \tag{6}$$

Modified Gompertz

$$B = B_0\ x\ \exp\left\{-\exp\left[\frac{R_{max}x\ e}{B_0}\ (\lambda - HRT) + 1\right]\right\} \tag{7}$$

in which

B_0 - ultimate methane yield (0.327 $m^3{}_{CH4}$ kg^{-1} VS);

R_{max} - maximum methane production rate (0.034 m^{-3} kg^{-1} d^{-1});

λ - lag phase time (0.531 d).

$$Q_{CH_4} = Bx\ Q\ x\ VS \tag{8}$$

Deng

$$R_p = \frac{R_{pmax}}{1+e^{(K_{LR}-Lr)}} \tag{9}$$

in which

R_p - volumetric yield of methane production ($m^3{}_{CH4}$ m^{-3} d^{-1});[2]

R_{pmax} - maximum volumetric yield of methane production (m3 $_{CH4}$ m^{-3} d^{-1});[3]

K_{LR} - constant of saturation (kg_{VS} m^{-3} d^{-1});[3]

Lr - organic volumetric loads (kg VS m^{-3} d^{-1}).[2]

$$R_{pmax} = 2.760 - 7.181\ e^{(0,067T)} \tag{10}$$

$$K^{LR} = 3.469 - 13.676\ e^{(-0,101T)} \tag{11}$$

$$Lr = \frac{SV\ x\ Q}{V} \tag{12}$$

in which

V - digester volume (m^{-3}).

$$Q_{CH_4} = R_p\ x\ Q \tag{13}$$

Modified Stover-Kincannon

$$M = \frac{M_{max}\ x\ Q\ x\frac{SV}{V}}{M_B\ x\ Q\ x\frac{SV}{V}} \tag{14}$$

in which

M - yield methane production (m^3 m^{-3} d^{-1});

M_{max} - maximum methane production (19. 23 m^3 m^{-3} d^{-1});

M_B - constant (53.46 kg m^{-3} d^{-1}).

$$Q_{CH_4} = M\ x\ V \tag{15}$$

The actual methane production (Pactual) from September 2018 to August 2019 was determined using the equivalent of electricity production in an internal combustion engine as shown in Eq 16-.18.

$$P = \frac{E}{m\ x24} \tag{16}$$

in which

P - available electric power (kW);

E – the amount of electricity produced per month, obtained from energy bills (kWh);

m - the number of days in the calculated month (d);

24 - number of hours the generator runs in one day (h);

$$PCL_d = PE\ x\ PCL\ x\ \frac{4.19}{3.600} \tag{17}$$

in which

PCL_d - lower caloric potential available (kWh m^{-3});

PE - specific weight (kg Nm^{-3}) (interpolated values according to Zilotti [19];

PCL - lower caloric potential (kcal kg^{-1}) considering interpolated values according to Avelar [18];

4.19/3,600 - conversion factor from kcal to kWh.

$$PTB = \frac{P}{PCI_d\ x\ Ef\ x\ \%}\ x\ 24 \tag{18}$$

in which

PTB = Total amount of produced methane ($m^3{}_{CH4}$ d^{-1});

Ef= worldwide efficiency of thermal machines (0.25);

$\%CH_4$ = Percentage of methane in the biogas;

24 – conversion factor h d^{-1}.

The P_{actual} and the mathematical models were compared by using a T-test for a significance level of 1%, the comparison was carried out using monthly average values. The methane production in all cases was estimated considering the models and their input data as they were conceived.

RESULTS AND DISCUSSION

Monitoring of Covered Lagoon Digesters

Over the experimental period, the manure flow ranged from 98.0 to 107.2 m^3 d^{-1} with an average of 102.3 m^3 d^{-1}.

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[2] R_p and L_r: according to [15].

[3] R_{pmax} and K_{LR}: according to [16].

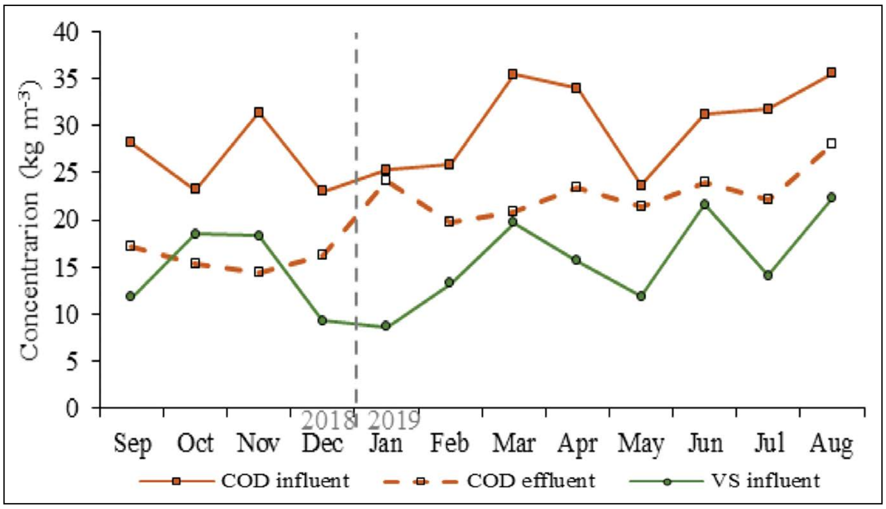

Figure 4. Monthly average of COD, volatile solids (VS).

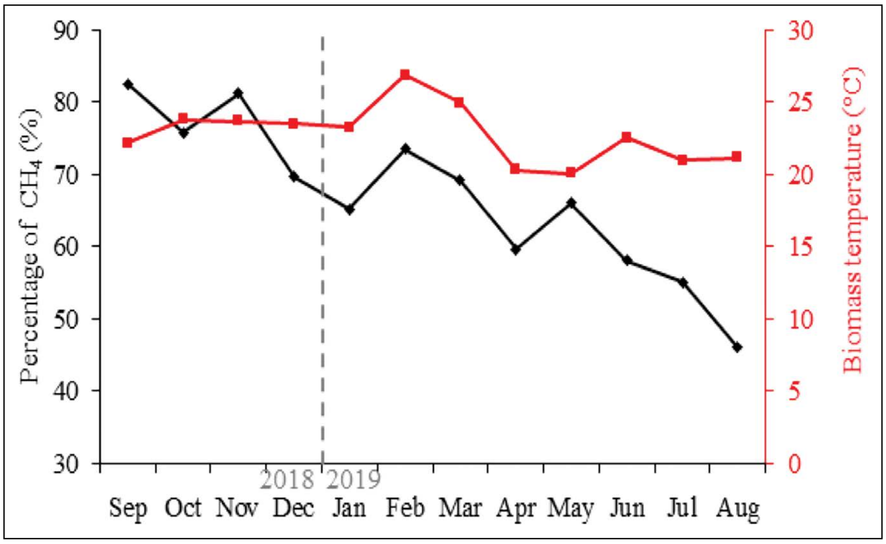

Figure 5. Monthly average of the percentage of methane in biogas and internal temperature.

In pig farms, the manure flow, COD, and volatile solids could have been influenced by several factors such as the number of animals, environmental conditions as well as pig handling [20].

The COD concentration in the influent and effluent ranged from 23.0 up to 35.5 kg m^{-3} and 14.3 a 28.0 kg m^{-3}, respectively (Fig. 2). The COD efficiency was around 30.6%, which is compatible with the results pointed out by Fernandes et al. [21] (28.0% and COD affluent of 30.0 kg COD m^{-3}). Biogas production has a direct correlation to COD removal efficiency and volatile solids compound in anaerobic digestion. However, variations of manure flow can influence the COD removal and then the biogas production. The organic component of manure is associated with VS and contributes to biogas production. According to Figure 4, the VS ranged from 8.0 to 22.3 kg m^{-3}. Veloso et al. [22] obtained 9.9 kg m^{-3} on average of VS, in turn, Silva et al. [23] obtained an average of 18.9 kg m^{-3}, both in accordance with the monitoring data in the pig farm evaluated.

Figure 5 shows the methane composition in biogas. The values ranged from 43.6 to 81.9%. A downward trend was observed after March (beginning of winter). In addition, the biomass temperature inside the CLD varied from 20.1 to 26.8 °C. The decrease of methane composition over the period could be associated with operational variances as well as the hydraulic retention time, pH, and alkalinity [24].

Comparison of Kinetic Models by Considering the Methane Production

The methane production mean (actual and simulate data) according to the kinetic models are shown in Figure 6. The volumetric methane production ranged from 470.8 to 560.9 m^3 CH_4 d^{-1}, while the actual data was 405.0 $m^3{}_{CH4}$ d^{-1}.

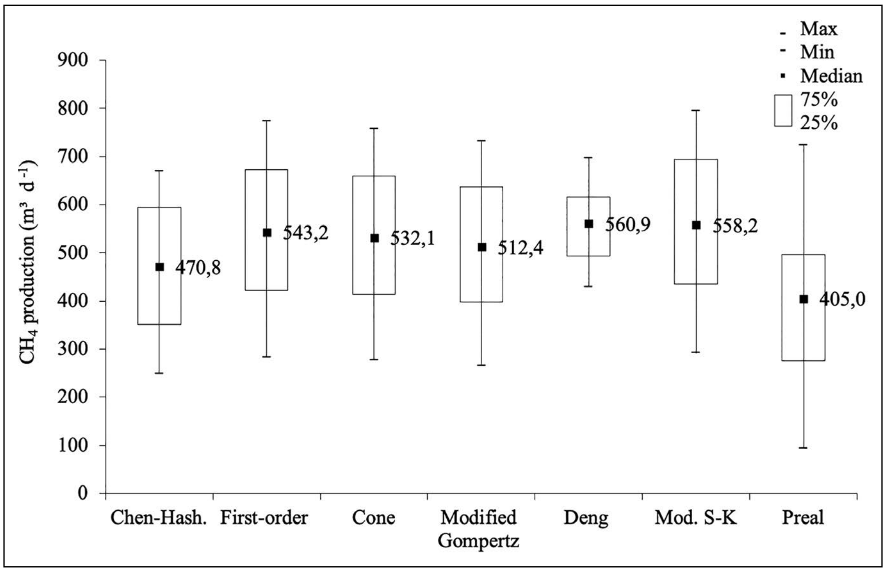

Figure 6. Box plot of methane production for evaluated models and the monitored system (P_{actual}) (Sep. 2018 - Aug. 2019).

Table 2. Statistical analysis of methane production for the models

Models	Average methane Production (m^3_{CH4} d^{-1})	$t_{calculate (1\%)}$
Chen-Hashimoto	470.8	-0.1^{ns}
First-order Kinetic	543.2	0.7^{ns}
Cone	532.1	0.6^{ns}
Modified Gompertz	512.4	0.4^{ns}
Deng	560.9	1.2^{ns}
Modified Stover-Kincannon	558.2	0.8^{ns}

H0: β1 = 1 (μmodel = μ real data) and H1: β1 ≠ 1 (μmodel ≠ μ real data); *: Difference between each value with significantly level of 1%; ns: No difference between each value; ttab 1%(11) 3.11.

The mathematical model results (Fig. 4) indicate the similarity of the results and the real data. However, all models overestimate the methane production value. The smallest difference was obtained for the Chen-Hashimoto model (higher than 16.3%), while the highest gap was higher than 38.5% obtained for the Modified Stover-Kincannon model.

Yang et al. [9] compared some kinetic models (Chen-Hashimoto, modified Stover-Kincannon, and Deng) with the actual methane production in batch digesters treating swine manure, operated in laboratory-scale with controlled temperature. The authors reported that for the range of 20–30 °C, the three models used to estimate the methane production presented a determination coefficient higher than 0.96. On the other hand, at 15 °C, only Chen-Hashimoto could predict methane production.

Several studies at laboratory-scale when comparing the Cone model, the first order and the modified Gompertz for different types of manure, such as, swine manure [8], fruit residues [25], co-digestion of chicken, dairy, and pig manure with durian shell [26] reported high determination coefficients. Table 2 shows the statistical analysis of the mathematical models in comparison with the methane production measured from the pig farm.

It can be seen in Table 2 that there were no statistical differences between the real data (monitored system) and the simulated data. The models based on volatiles solids present a strong association with biogas production [27, 28]. According to Mito et al. [28], the kinetic models best fit the monitored data in comparison with other mathematical models based on operation conditions (IPCC). The study was carried out on a pig farmand aimed at evaluating models to estimate methane production in CLD.

All assessed methodologies were reliable to estimate the methane production in CLD. Further studies are suggested to consider kinetic coefficients that best fit the operational conditions of tropical countries, despite the reliable results showed by the evaluated models.

CONCLUSIONS

The kinetic models evaluated to estimate the methane production did not differ statistically from the the actual production observed in full-scale covered lagoon digester.

The kinetic models stands out as interesting and reliable tools to estimate methane production, which is obtained from an operational parameter with easy determination (volatile solids).

The use of mathematical models to estimate methane production may be a useful tool for energy sustainability studies and contributes to the decision-making in pig farming.

ACKNOWLEDGMENTS

This study was partially funded by the Coordination for the Improvement of Higher Education Personnel - Brazil (CAPES) - Finance Code 001, National Council for Scientific and Technological Development - Brazil (CNPq) – Grant No. 140417/2020-6 and Minas Gerais State Research Foundation (FAPEMIG), Grant No. APQ-01109-18.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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