



Continuously fed anaerobic digesters for biogas production from agro-industrial lignocellulosic wastes: Experimental and modeling studies

Ali Raad Talib ^{a, b, *}, Zainab Ziad Ismail ^a

^a Department of Environmental Engineering, College of Engineering, University of Baghdad, Baghdad, Iraq
^b Municipalities and Public Works, Ministry of Construction and Housing, Baghdad, Iraq

Abstract

In this study, recovery of methane-rich biogas recovery from lignocellulosic waste materials were assessed experimentally and theoretically in continuously fed anaerobic digesters under mesophilic and thermophilic conditions. Potato peels (PPs) and sunflower hulls (SSHs) were selected as abundantly available waste materials utilized in this study individually as substrates inoculated with chicken dung. The results showed that average recovered biomethane-rich biogas from PPs was 60% higher than from SSHs at steady state conditions achieved after approximately 20 days of continuous operation. Microbial growth in the biodigesters was assessed by Monod model, Halden model, and Chen- Hashimoto model in terms of methane yield and substrate utilization rate. First order kinetic model was adopted to describe the kinetic of anaerobic digestion process in the continuously operated digesters. The results predicted by Monod model significantly fitted the experimental results with correlation coefficients (R^2) > 0.93. However, the results predicted by Chen- Hashimoto model exhibited less significance with the measured results for the SSHs, whereas, those obtained by Halden model were insignificant for both substrates. The outcomes of first order kinetic model for continuously operated anaerobic digesters showed that this model produced perfect goodness of fit with the experimental data.

Keywords: Biomethane yield; Anaerobic digesters; Potato peels; Sunflower hulls; Continuous operation mode.

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1- Introduction

In the absence of oxygen, the breakdown of organic matter by bacteria is referred to as anaerobic digestion (AD) which consists of four consecutive steps including hydrolysis, acidogenesis, acetogenesis, and methanogenesis. During these stages, complex organic matters are broken down by microorganisms into simpler compounds and ultimately converted into biogas, which is mainly composed of methane (CH_4) and carbon dioxide (CO_2) [1]. Temperature conditions, pH, carbon-to-nitrogen ratio (C: N), retention duration, volatile fatty acid (VFA), and organic loading rate are all factors that can be controlled to enhance the high metabolic activity of anaerobic organisms [2]. Biodigester can be considered as a biogas production plant in which different biochemical reactions occur. Reactor configurations are also chosen based on the feeding method or operation mode whether it is batch or continuous. Typically, batch-operated biodigesters are utilized in order to assess the bio-methane potential of an organic substance. However, experimental results that come from digesters that are operated continuously are not only rare but also more reliable and dependable. This is because they replicate the conditions that exist in actual biogas plants which normally operate

in a continuous mode, and they demonstrate the long-term response of anaerobic biomass to a specific feedstock. The production of biogas in continuous stirred tank reactors (CSTRs) has become increasingly significant among the many types of digesters due to the fact that it is characterized by its simple structure and continuous operation [3]. Choosing the optimum retention time, and maintaining operational stability in the continuously-operated anaerobic digestion leads to enhance and facilitate the anaerobic digestion conversion process, and consequently, increasing the CH_4 yield [4].

On the other hand, when referring to biogas generation, lignocellulosic substrates are considered to be key feedstock option. Due to the fact that lignocellulosic materials are composing of the plants parts that are non-edible (leaves, stalks, and husks), agricultural residues are a renewable resource that does not compete with plant cultivation for food. Most of these nonedible residues are typically burned on the fields, which creates environmental problems related to the incineration of biomass in the open air [5, 6].

Numerous studies have been reported on the anaerobic digestion of the lignocellulosic waste materials for



*Corresponding Author: Email: ali.raad2301@coeng.uobaghdad.edu.iq

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biogas generation in batch or semi-continuous operated digesters. Some of them but not limited to the poultry house wastes in batch operated digesters [7], recycled medical cotton industry waste in batch operated [8], paper and paper board in batch operated digesters [9], potato peel waste and the cabbage waste in a semi-continuous operated digester [10], orange peels waste in batch operated digesters [11], marine microalgae with potato processing waste in batch operated digesters [12], alfalfa and corn silage blend in batch operated digesters [13], sunflower head and stalk in batch operated digesters [5], sheep dung with potato peels and fried chips that did not fulfill quality criteria using batch and semi-continuous mode operating digesters [14], corn stalk in batch operated digesters [15], water hyacinth in batch operated digesters [16], pineapple waste in batch operated digesters [17], rice straw and food waste in batch operated digesters [18]. Potato peels waste in batch operated anaerobic digesters [19].

For real-field applications, it is very important and more reliable to examine the performance of biogas production in a continuous mode. However, yet to the authors knowledge, studies concerning biogas production in continuously-operated anaerobic digesters (CSTR) are significantly limited. Boe and Angelidaki [20] evaluated the efficiency of biogas generation from manure in serial CSTR digester configuration versus single CSTR digester. Usack et al. [21] presented a general methodology for constructing, inoculating, operating, and monitoring a continuously-operated anaerobic digester (CSAD) system to investigate the suitability of an organic substrate for long-term anaerobic digestion. Obiukwu and Nwafor [22] investigated the performance of a continuously operated biogas digester versus a batch-mode biogas digester for biogas production from animal wastes. Results indicated maximum biogas yield of 3.603L and 2.685L were obtained in the continuous and batch processes, respectively at thermophilic conditions. Barua and Kalamdhad [23] evaluated the performance of a novel anaerobic digester operated in continuous mode utilizing untreated and thermally treated water hyacinth as the feedstock. Also, co-digestion of water hyacinth food waste was considered. Tumusiime et al. [24] developed a incorporated system for energy recovery which enables feedstock change and controlling of the operating parameters for sustainable biogas recovery continuously operating anaerobic digesters. Calise et al. [25] developed a thermal transient model using MATLAB® which can accurately predict the occurrence of heat transfer and biological phenomena in the continuously-operated anaerobic digester.

This study aimed to evaluate for the first time the performance of continuously fed anaerobic digesters for biomethane recovery from two types of abundantly available agro-industrial lignocellulosic waste materials represented by potato peels wastes (PPs) and sunflower hulls (SSHs) at mesophilic and thermophilic conditions. Also, methanogenesis growth was assessed by adopting three different models including Monod model, Halden model, and Chen- Hashimoto model in terms of substrate

utilization and biogas generation as well. Additionally, first order kinetic model was applied to describe performance of the anaerobic digestion process.

2- Materials and methods

2.1. Substrates and inoculum

Two types of agro-industrial lignocellulosic waste materials were alternatively utilized as the substrates in this study due to their abundant availability from local food industry facilities. Potato peels (PPs) waste was collected from potato-based food industry including potato chips production plants, and frozen fried potatoes industrial facility. The sunflower hulls (SSHs) waste was collected from local sunflower oil processing facilities; these hulls are readily available but have zero commercial value. Both waste materials; the PPs and SSHs were repeatedly washed to remove dirt and dust, air-dried, and then after they were ground into tiny particles. The characterization of waste samples revealed that the content of carbon (C), nitrogen (N), volatile solids (VS), and total solids (TS), were 49%, 2.1%, 89%, and 94% for PPs, whereby they are 42%, 1.4%, 76%, and 84% for SSHs, respectively.

The anaerobic digestion process of lignocellulosic materials is difficult to accomplish because of the fibrous, complicated, and inflexible structure of these materials. Furthermore, under anaerobic conditions, these materials may breakdown in a slow and ineffective manner. Additionally, the application of pretreatment to condition the lignocellulosic biomass prior to the anaerobic digestion is to improve both hydrolysis and bioenergy extraction, as stated by Li et al. [26]. Due to the fact that pretreatment is utilized to condition the biomass, this is the case. In particular, alkaline pretreatment is renowned for its ability to make lignocellulose adaptable to enzymatic reaction by a mixture of chemical, physical, and thermal activities that are performed on a biomass [27].

Accordingly, Alkaline pretreatment of PPs and SSHs was performed to improve the hydrolysis of the cellulosic content of PPs and SSHs. Cellulose and lignin are distinguished by their extremely crystalline structure due to the presence of a wide hydrogen bond and inter-chain in the structure of cellulose. In order to perform the chemical pretreatment of PPs and SSHs, Ca(OH)_2 was added to the sieved PPs and SSHs particles at concentrations ranging from 0.1 to 0.2 g Ca(OH)_2 /g waste. Then after, the mixtures were autoclaved at a temperature of 120° for twenty minutes. Through the process of flushing the autoclaved mixture with carbon dioxide, the calcium will precipitate and be extracted as CaCO_3 . The reason behind using Ca(OH)_2 among other alkalis is due to its low cost, being abundantly available, and its potential ability to break down the bond that are difficult to be destructed within the cellulose structure

Based on the results obtained by Talib and Ismail [19], chicken dung (ChD) was used as a co-substrate to inoculate the digesters content (PPs and SSHs). The

chicken dung was freshly grabbed from local slaughterhouses, and then prepared as a slurry by mixing 50g of ChD with 350 ml of distilled water. The mixtures were manually stirred with glass rods until getting a slurry of ChD ready to be added to the substrate in the bench-scale digesters.

2.2. Setup and start-up of the digesters

Two identically designed and arranged experimental systems were set up, one system for PPs and the other for SSHs. Each system consisted mainly of two Perspex borosilicate heatproof-cylindrical containers; one of the containers was considered as a holding tank, and the other container served as the anaerobic biodigester. A Peristaltic pump (Model: BT100S, GOLANDER PUMP, USA) was used to transfer the substrates slurry from the holding tank to the digester via rubber tubes. Flowrate of the substrate slurry was maintained constant at 0.125 L/d and solid retention time (SRT) was 20 days.

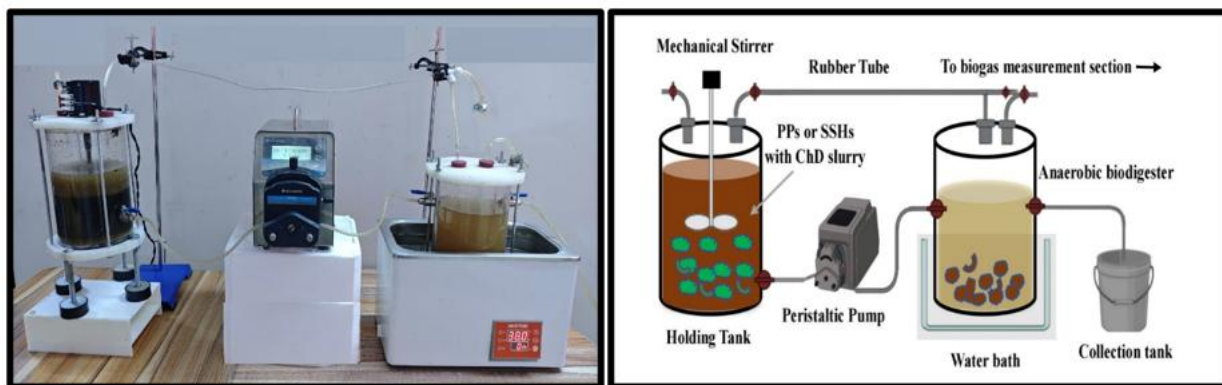


Fig. 1. Experimental system set up

2.3. Methods of analysis

Total solids (TS) and volatile solids (VS) measurements were performed in accordance with the procedure described in the *Standard Methods* [28]. pH meter (model: WTW, Inolab 720) was utilized for pH measurement. The combustion method was adopted to find the carbon content [29]. Van Soest method was used to determine the cellulose, hemicellulose, and lignin content in the PPs and SSHs before and after alkali pretreatment [30]. In accordance with the process described in the *Standard Methods*, the nitrogen concentration was estimated by a series of three primary phases, which included digestion, distillation, and titration, all of which were carried out using Kjeldahl distillation unit [28]. The ratio of carbon to nitrogen was calculated using the formula Eq. 1:

$$C/N = \frac{\% \text{ organic carbon}}{\% \text{ nitrogen}} \quad (1)$$

The generated biogas was assessed using a manometer which consisted of a U-shaped glass tube of 10 mm internal diameter filled with 40% potassium hydroxide (KOH) solution for CO₂ stripping. The U-tube was

Fig. 1 presents the setup of the experimental system. Each holding tank was provided with mechanical mixer rotated at 100 rpm to ensure homogenous mixture of substrate and inoculum slurry. Total volume of each anaerobic digester was 3L and the working volume was 2.5L. The organic loading rates (OLR) of the feed to the digesters were in the range of 1.78 and 1.52 g VS/L. d for PPs and SSHs, respectively. Before running the anaerobic digesters, they were flushed with nitrogen for 10 minutes to maintain anaerobic conditions. The ingredients of each holding tank were maintained equivalent to 2g of waste materials (PPs or SSHs): 2.5 L inoculum slurry. The digesters were immersed in a thermostatic water bath to maintain the desired temperature at mesophilic condition (38°C) and thermophilic condition (55°C). The methane yield in the digesters was continuously monitored for 60 days. The experimental systems were operated in duplicate.

permanently attached to a wooden panel, and both of its ends were maintained open. One of the ports was for the injection of gas, while the other was for the CO₂ free-gas out. A recalculation of the volume of gases was performed using the standard temperature and pressure as stated by Abdel-Hadi [31].

To assess the CH₄ volume, the generated biogas was first passed through an airtight washing bottle contain 1M caustic soda (NaOH) solution to absorb CO₂. Then after, the remaining methane transferred to a 500-ml glass container, displacing the water which overflowed into a volumetric cylinder. The volume of displaced colored water represents the CH₄ volume of [7].

Cross checking measurements of the generated biogas was performed by using gas chromatography (GC) (Model: GC1000, Yokogawa, Italy) with a flame-ionization-detector (FID) operated at a flow rate of H₂ 24 ml/ min and makeup N₂ of 30 ml/min.

3- Modeling and kinetic study

The practical application of AD process depends on the acclimation of functional microbial species and the kinetics of their biochemical reactions as well. Kinetics of

microorganisms control the desired reaction duration for the AD process. Accordingly, the kinetic models could be an efficient tool for providing meaningful valuable information for the rate of biochemical reactions and the potential transformation of the biodegradable organic carbon, which furtherly demonstrate the impasse limiting digestibility of the substrate and biomethane generation [32]. Additionally, the kinetic models can tool up key parameters for the design of AD systems like the maximum CH₄ recovery, rate of biochemical reaction, and the lag phase which are critical for the performance of system analysis in regard of the efficiency and inhibition of the system [33]. To solve the set of equations from Eq. 2 to Eq. 9, which include nonlinear algebraic equations as well as differential equations, SPSS [including IBM SPSS statistics 24] was applied.

Kinetic models' performance has been evaluated using metrics other than correlation coefficients (R²). These contain indexes like root mean square error (RMSE). The RMSE is defined as the standard deviation between predicted and measured values, with lower RMSE suggesting a better fit. R² and RMSE might be used for an overall comparison. The first-order kinetic model for anaerobic digestion process simplifies this process based on the assumption that the hydrolysis stage is the rate-limiting step which means that the reaction rate is directly proportional to the remaining biodegradable substrate concentration. The model often relates the biogas yield to the organic loading rate and can be expressed in various forms. The first order kinetic model for continuous experiments in terms of substrate utilization is given by Eq. 2 [34] as follows:

$$S = \frac{S_0}{1+k\theta} \quad (2)$$

Where: S: residual concentration of the substrate at steady state (g VS /L. d), S₀: initial concentration of the substrate (g VS /L. d), k: first-order reaction rate constant (day⁻¹), θ: solids retention time (day).

On other hands, first order kinetic model for continuous experiments in terms of biogas production is given by Eq. 3 [35]:

$$Y_{(t)} = \frac{Y_{\max} \cdot \theta \cdot k}{1+k\theta} \quad (3)$$

Where: Y_(t): Biogas yield at digestion time t days (mL/g VS), Y_{max}: Maximum biogas at steady state (mL/g VS), k: First-order reaction rate constant (day⁻¹), θ: The mean cell residence time (days).

(k) value could be negative or positive depending on whether the kinetic model describes the digestion process in terms of the substrate consumption and degradation or the biogas production. If the model is used in terms of organic substrate consumption, the value of the constant is negative, whereby it is positive if the model is applied in terms of the biogas.

For continuous AD process, Monod model in terms of substrate utilization is given by Eq. 4 [34]:

$$S = \frac{k_s(1+b\theta)}{\theta(\mu_{\max}-b)-1} \quad (4)$$

Where; S: Effluent substrate concentration for a reactor at steady state (g VS /L), b: Specific microorganism decay rate (day⁻¹), μ_{max}: Maximum specific growth rate (g VS/L.d), θ: Solids retention time (day), K_s: Half-saturation constant (g VS/L).

On the other hand, Monod model for microbial growth in terms of biogas production was adopted using a simple formula which link the rate of microbial growth (and thus biogas production) to the concentration of the limiting organic substrate, featuring a maximum growth rate (μ_{max}) and a half-saturation constant (K_s) to describe how bacteria consume the substrate (Eq. 5) [36].

$$Y_{(t)} = Y_{\max} \cdot \frac{K_s \cdot t}{1+K_s \cdot t} \quad (5)$$

Where: Y_(t): biogas yield at any time (ml /g VS/day), Y_{max}: maximum gas yield rate (ml /g VS/day), K_s: half-saturation concentration constant (day⁻¹).

Haldane model often referred to as the Haldane-Andrews substrate inhibition model is a widely used kinetic model in biogas production, in particular for describing the anaerobic digestion process where high substrate concentrations can inhibit methanogenic bacteria. Halden model represents the modified form of Monod model which consider the reduction in microbial growth rate due to toxic effects of high substrate levels, commonly occur in high-rate anaerobic digesters, such as those used for food waste or industrial wastewater. Eq. 6 represents the Halden model formula as follows [37]:

$$r_x = r_{X_{\max}} \cdot \frac{S}{K_s + S + \frac{S^2}{K_i}} \quad (6)$$

Where: r_{X_{max}}: maximum specific substrate utilization rate (g VS /L.d), r_x: specific substrate utilization rate (g VS /L.d), S: substrate concentration in the Bioreactor at steady state (g VS /L.d), K_i: inhibition constant for substrate, K_s: saturation constant for substrate (day⁻¹).

Also, Haldane model can be express in terms of biogas production by Eq. 7 [38] as:

$$Q = Q_{\max} \cdot \frac{S}{(K_s + S)(1 + \frac{S}{K_i})} \quad (7)$$

Where: Q: specific biogas yield observed at a given co-substrate ratio (mL/g VS), Q_{max}: potential of specific biogas yield (mL/g VS), S: VS ratio of a co-substrate over the total substrate VS (%), K_s: half saturation constant of the co-substrate (%), K_i: half inhibition constant of the co-substrate (%).

Chen- Hashimoto model is one of the most used kinetic models which provides reliability in predicting methane production [39]. This model was developed based on the fundamental biochemical principles and was found to be a reliable predictive tool in applications regarding digestion of wastes with substantial total solids content. It is a simple model for continuous flow digesters which predicts the substrate concentration and gas production rate at different temperatures for different loading rates

for solid wastes. The model can be represented as follows (Eqs. 8 and 9):

$$\frac{S}{S_0} = \frac{K}{t * \mu_{max} + K - 1} \quad (8)$$

Where: S: effluent substrate concentration (g/L), S_0 : influent substrate concentration (g/L), t: hydraulic retention time (days), k: dimensionless kinetic constant, μ_{max} : maximum specific growth rate (day^{-1}).

$$Y_{(t)} = Y_{max} \left(\frac{K}{t * \mu_{max} + K - 1} \right) \quad (9)$$

$Y_{(t)}$: biogas yield at digestion time t days (mL/g VS), Y_{max} : maximum biogas potential of the substrate (mL/g VS), K: the Chen-Hashimoto kinetic constant (dimensionless).

The statistical analysis was conducted using Statistica 24 to determine the variation between measured and predicted methane cumulative yields. The significance tests were calculated by one-way analysis of variance (ANOVA). In the tests, a significance level value of 0.05 was obtained.

Table 1 summarizes the models and equations used in this study.

Table 1. Summary of the models and equations

Model	Models for bacterial growth assessment	
	In terms of biogas production	In terms of substrate utilization
Monod model	$Y_{(t)} = Y_{max} * \frac{K_s * t}{1 + K_s * t}$	$S = \frac{k(1+b\theta)}{\theta(\mu_{max}-b)-1}$
Haldane model	$Q = Q_{max} * \frac{S}{(K_s + S)(1 + \frac{S}{K_i})}$	$r_x = r_{x_{max}} * \frac{K_s + S + \frac{S^2}{K_i}}{K_s + S + \frac{S^2}{K_i}}$
Chen & Hashimoto model	$Y_{(t)} = Y_{max} * \left(\frac{K}{t * \mu_{max} + K - 1} \right)$	$S_{(t)} = S_0 * \frac{K}{t * \mu_{max} + K - 1}$
	Models describe the kinetic of anaerobic digestion process	
	In terms of biogas production	In terms of substrate utilization
First order kinetic model	$S = \frac{S_0}{1 + k * \theta}$	$Y = \frac{Y_{max} * \theta * k}{1 + k * \theta}$

4- Results and discussion

4.1. Biogas production and methane yield

Profiles of the daily biomethane production from the alkali-pretreated PPs and SSHs are presented in Fig. 2 at mesophilic and thermophilic conditions.

Generally, it is well observed that biomethane yield from PPs is remarkably higher than SSHs regardless of the temperature conditions. This could be attributed to the difference in biochemical composition (fats/lipids, carbohydrates, proteins), biodegradability, and physical structure of PPs and SSHs. Materials with high-lipid and carbohydrates contents like food waste yield the most gas, whereby tough, woody, or fibrous materials like straw yield less biogas and break down slower, requiring longer digestion times for maximum energy extraction. Key factors include high lipid content, simple sugars, and a balanced Carbon-to-Nitrogen (C/N) ratio for optimal microbial activity. However, the biomethane production at mesophilic conditions was much lower than at its production at thermophilic conditions for both types of lignocellulosic waste materials; PPs and SSHs. As given in Fig. 2, at mesophilic condition the biogas gradually increased from the first day of operation until day 20, then after achieved a steady state condition until the end of the operation period (60 days). At thermophilic condition, the

biogas production achieved steady state after 16 days. The results revealed that at thermophilic conditions, the daily biogas production and methane yield increased by 66.39% and 79.19%, respectively. Similarly, for biogas production from the SSHs at mesophilic conditions, it increased gradually during the first 21 days of operation followed by achieving a steady state condition to the end of operation, while at thermophilic condition, biogas started to increase gradually from the first day of operation for 18 days before it reached a steady state region to the end of operation period. The results demonstrated that the biogas production rate and CH_4 yield increased by 34.62% and 32.69%, respectively at thermophilic conditions. The remarkable increase in the biogas generation rate and the corresponding CH_4 in the anaerobic digestion processes at thermophilic conditions compared to mesophilic conditions is due to the fact that the biochemical reaction rates and hydrolysis of organic matter increased at elevated temperatures, leading to faster biodegradation of organic matters and higher biogas yield [40]. However, in spite of the fact that thermophilic conditions remarkably enhanced the rate of biogas and methane generation, but higher temperature didn't have tangible effect on the methane percentage for both lignocellulosic waste materials; PPs and SSHs. The slight increase in $\text{CH}_4\%$ didn't exceed 1%.

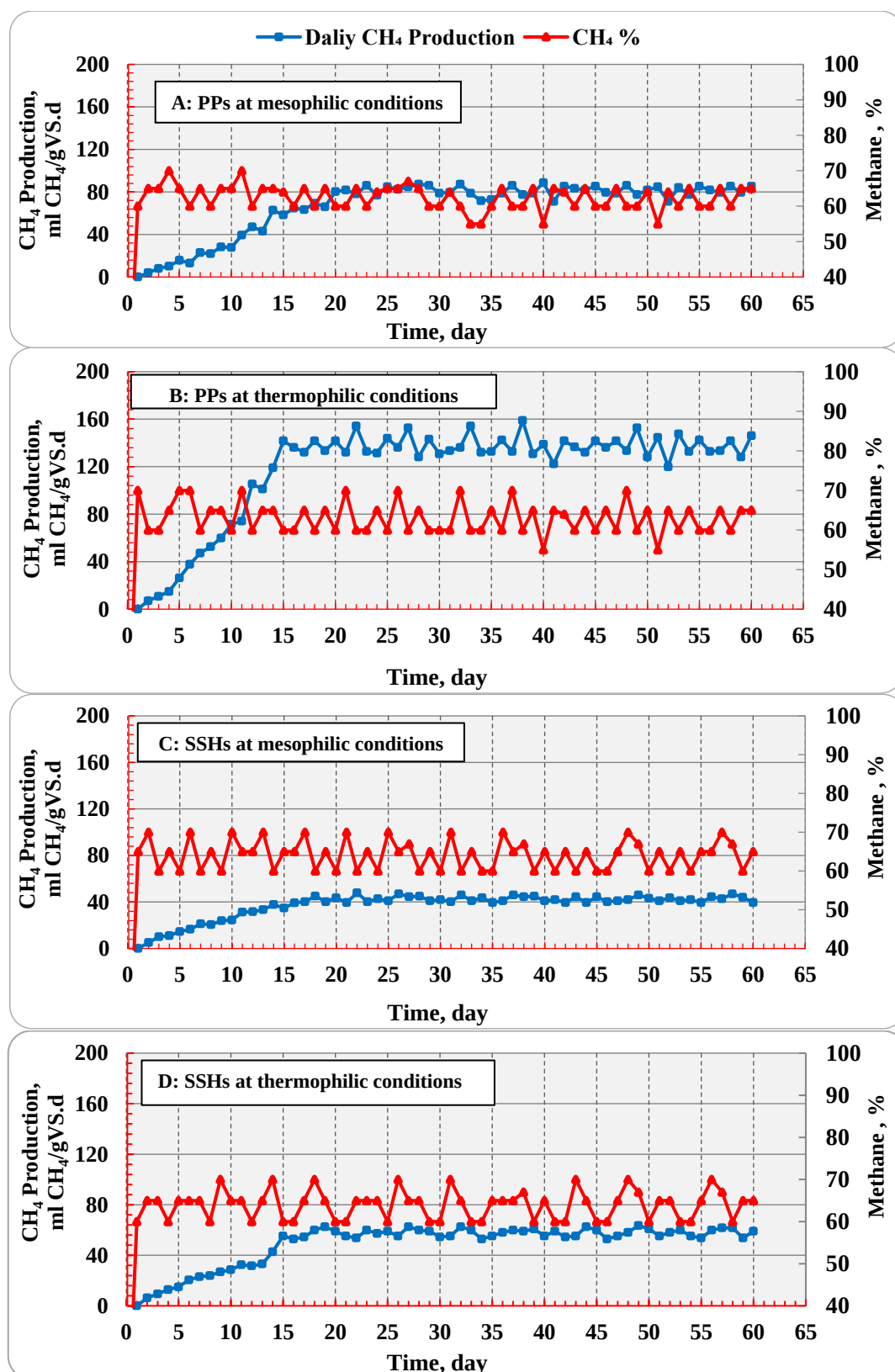


Fig. 2. Specific CH_4 production from PPs and SSHs at mesophilic and thermophilic conditions: A: PPs at mesophilic, B: PPs at thermophilic conditions, C: SSHs at mesophilic conditions and D: SSHs at thermophilic conditions

The trends of biomethane yield obtained in this study are well compatible with the previously reported studies concerned of biogas recovery from anaerobic digestion of lignocellulosic materials. Li et al. [41] revealed that under

thermophilic conditions (55°C), the anaerobic co-digestions of fat, oil, and grease produced biogas higher than its generation at mesophilic (37°C) in semi-continuous flow digesters. Ismail and Talib [7] indicated

the increase of CH₄ recovery at 55°C from that at 38°C for the co-digestion of pretreated poultry house wastes inoculated with chicken dung. Vanwonderghem et al. [42] demonstrated that shortening the solid retention time at high temperature is an effective way to drive the microorganisms towards controlled production of high levels of specific volatile fatty acids. Ismail and Talib [8] demonstrated an increase in biogas production from an alkaline-treated recycled medical cotton industry waste under thermophilic conditions from that at mesophilic conditions. Carrillo-Reyes et al. [43] demonstrated that when the temperature is high enough, the microalgae-bacteria found in wastewater treatment plants can be broken down by the anaerobic digestion process, at thermophilic circumstances, the methane concentration in the produced biogas was roughly 57% of its volume at mesophilic conditions (35°C).

Liu et al. [44] revealed that when it comes to biogas generation, thermophilic anaerobic digestion of cabbage waste and cow dung is thought to be more prolific and effective than mesophilic anaerobic digestion. This is because high temperatures accelerate the rate-limiting steps of the anaerobic digestion process, as well as the breakdown of contaminants. Kaur et al. [45] summarized that thermophilic anaerobic digestion is regarded extremely productive and more effective than mesophilic anaerobic digestion in terms of CH₄ content due to the

increased rate-limiting processes in the anaerobic digestion. Wang et al. [46] found that thermophilic anaerobic digestion promotes superior organic matter decomposition and CH₄ production, meanwhile destroying harmful microbes.

4.2. Kinetic study and statistical analysis

As mentioned earlier, the kinetic of the anaerobic digestion (AD) process refers to the rates of biochemical reactions and microbial growth occur within the AD system. It models how fast substrate is consumed and products are formed, with hydrolysis often being the rate-limiting step. According to Ma et al. [47], the structure and abundance of methanogens community significantly and closely related to methane yield during the AD process. Based on this fact, the bacterial growth during the AD process was assessed in terms of biomethane yield. Fig. 3 and Fig. 4 presents the measured and predicted profiles of bacterial growth in terms of substrate utilization and methane yield from PPs and SSHs, respectively. In Fig. 3, the profiles of CH₄ indicated significant agreement between the measured results and those predicted by Monod model and Chen- Hashimoto Model with very high determination coefficients as given in Table 2 and Table 3.

Table 2. Results of a growth models in term of methane production

Monod								
Substrate	Temperature condition	Measured CH ₄ production (mL/g VS. d)	Predicted CH ₄ production (mL/g VS. d)	Y _{max} (mL/g VS.d)	K (day ⁻¹)	R ²	RMSE	
PPs	Mesophilic	88.66	83.12	88.66	0.250	0.9280	13.386	
PPs	Thermophilic	147.53	143.09	158.88	0.151	0.9370	16.869	
SSHs	Mesophilic	44.47	42.18	47.89	0.123	0.9510	5.92	
SSHs	Thermophilic	59.01	59.17	63.55	0.225	0.9280	6.978	
Haldane								
Substrate	Temperature condition	Measured CH ₄ production (mL/g VS. d)	Predicted CH ₄ production (mL/g VS. d)	Q _{max} (mL/g VS)	K _i	K (day ⁻¹)	R ²	RMSE
PPs	Mesophilic	88.66	74.60	88.66	20	0.148	0.548	22.103
PPs	Thermophilic	147.53	137.11	158.88	40	0.175	0.775	34.771
SSHs	Mesophilic	44.47	39.59	47.89	35	0.185	0.714	7.879
SSHs	Thermophilic	59.01	39.22	63.55	18	0.655	0.850	14.373
Chen- Hashimoto								
Substrate	Temperature condition	Measured CH ₄ production (mL/g VS. d)	Predicted CH ₄ production (mL/g VS. d)	Y _{max} (mL/g VS)	μ _{max} (day ⁻¹)	K	R ²	RMSE
PPs	Mesophilic	88.66	80.38	88.66	0.051	20	0.969	9.236
PPs	Thermophilic	147.53	155.76	158.88	0.035	55	0.983	25.57
SSHs	Mesophilic	44.47	44.94	47.89	0.055	35	0.882	7.364
SSHs	Thermophilic	59.01	60.60	63.55	0.041	30	0.822	13.159

Table 3. Results of a growth models in term of substrate utilization rate

Monod model								
Substrate	Temperature condition	Measured residual substrate (g VS /L)	Predicted residual substrate (g VS /L)	b (day ⁻¹)	K _s (g VS/L)	μ _{max} (g VS /L. d)	R ²	RMSE
PPs	Mesophilic	0.534	0.553	1.000	0.415	1.780	0.976	0.048
PPs	Thermophilic	0.285	0.534	1.010	0.392	1.780	0.940	0.204
SSHs	Mesophilic	0.456	0.554	0.990	0.295	1.520	0.984	0.137
SSHs	Thermophilic	0.243	0.551	1.030	0.249	1.520	0.976	0.279
Haldane model								
Substrate	Temperature condition	Measured residual substrate (g VS /L.day)	Predicted residual substrate (g VS /L.day)	k (day ⁻¹)	k _i	S (g VS /L. d)	R ²	RMSE
PPs	Mesophilic	0.534	0.614	0.0037	0.659	1.780	0.967	0.089
PPs	Thermophilic	0.285	0.575	0.0031	0.715	1.780	0.968	0.238
SSHs	Mesophilic	0.456	0.554	0.0045	0.615	1.520	0.972	0.084
SSHs	Thermophilic	0.243	0.644	0.0047	0.945	1.520	0.984	0.338
Chen- Hashimoto model								
Substrate	Temperature condition	Measured residual substrate (g VS /L.day)	Predicted residual substrate (g VS /L.day)	K	μ _{max} (day ⁻¹)	S ₀ (g VS /L. d)	R ²	RMSE
PPs	Mesophilic	0.534	0.376	15	0.950	1.780	0.859	0.216
PPs	Thermophilic	0.285	0.454	20	0.990	1.780	0.914	0.403
SSHs	Mesophilic	0.456	0.486	17	0.620	1.520	0.850	0.317
SSHs	Thermophilic	0.243	0.427	16	0.700	1.520	0.922	0.393

However, approximately less agreement could be noticed between the results predicted by the Halden model and experimental measurements, Halden model show weak convergence with measured data. This observation could be due to many factors such as (1) when using complex non-homogeneous substrate (like food waste), the simple substrate inhibition assumption of the Halden model fails because different components of substrate affect growth differently, (2) the experimental data may not span a wide enough range of substrate concentrations to accurately define both the K_s (limitation) and K_i (inhibition) simultaneously, leading to ambiguous fits, and (3) the Halden model assumes a specific type of substrate inhibition (non-competitive), but if the inhibition is caused by other factors such as metabolite accumulation (change of pH, toxicity of the product) or if the inhibition is only partial, the Halden model will not fit properly). Regarding the current study, the poor fit of Halden model with the experimental results it is more likely due to the fact that experimental data may not span a wide enough range of substrate concentrations. Also, different components of substrate (food grade waste with chicken dung as a co-substrate) could affect growth differently which may not match the simple substrate inhibition assumption of the Halden model.

Similarly, the profiles of methanogenesis growth in terms of substrate utilization as illustrated in Fig. 4 indicate a prompt growth of methanogenesis during

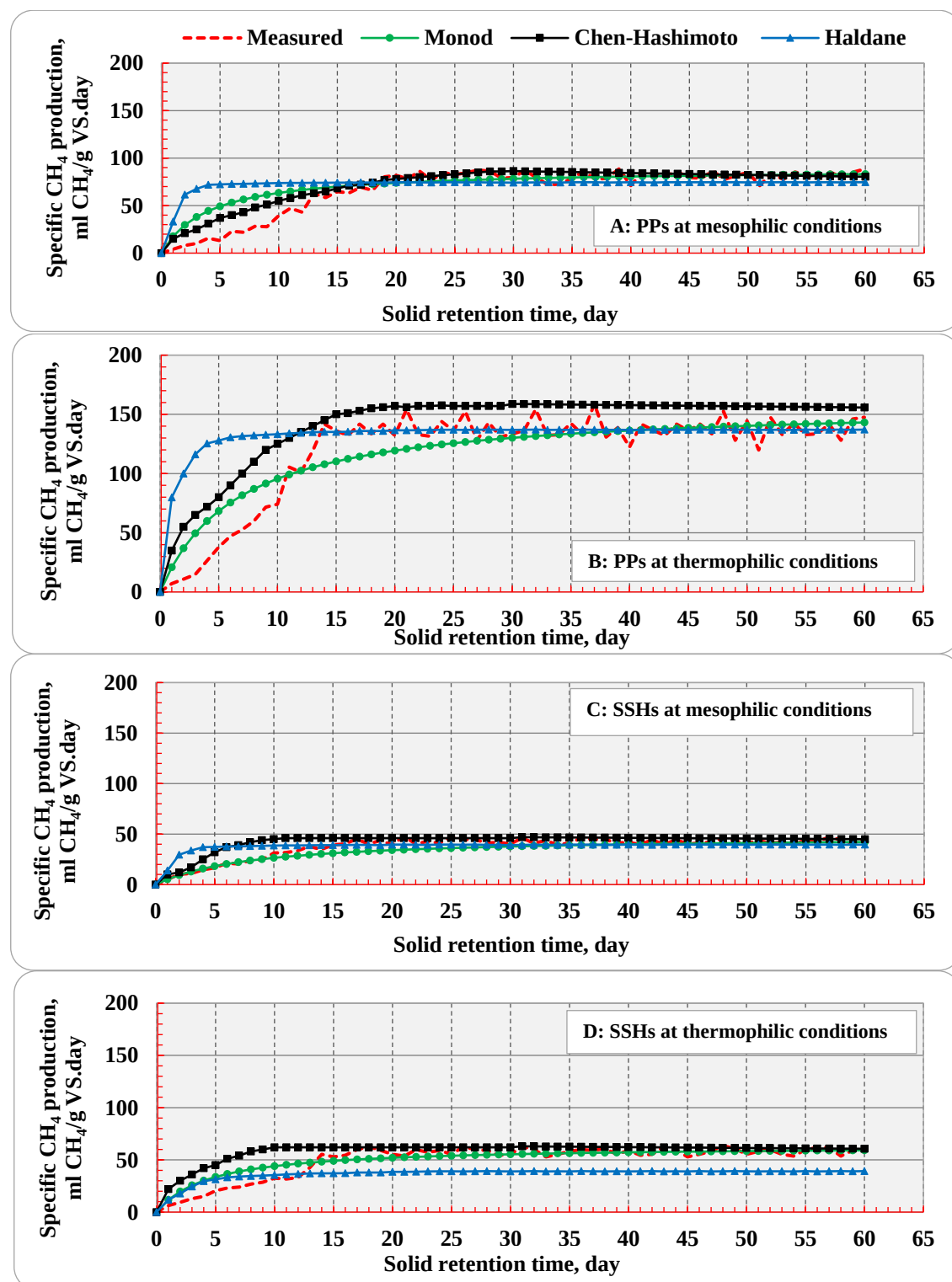
nearly the first 20 days of operations, followed by steady-state growth until the end of operation for both PPs and SSHs substrates.

Based on the trend and level of the presented profiles, it is well observed that the amount of methane yield from PPs was much higher than from SSHs at both mesophilic and thermophilic conditions. This could be attributed to the fact that the percentages of cellulose, hemicellulose, and lignin are higher in the SSHs than in PPs even after alkaline pretreatment (Table 4). It is well known that these components are not easily be decomposed or broken-down by microorganisms because they form insoluble, crystalline microfibrils, which are highly resistant to enzymatic hydrolysis [48].

Also, in general, it is well observed that the rate of methane yield from PPs and SSHs indicated higher generation at thermophilic conditions than at mesophilic conditions. This observation is identical with the previously reported studies. Trisakti et al. [49] revealed a good agreement between the experimental and predict results obtained by Monod model with 0.98 coefficient of determination (R²) for the biogas yield from the anaerobic co-digestion of palm oil mill effluent. Akbay [50] confirmed a significant matching of experimental results with those predicted by the Monod model for the biogas yield from the co-anaerobic digestion of okra waste and municipal sewage sludge by using cattle manure.

Table 4. Percentages of lignocellulosic components of the PPs and SSHs before and after alkaline pretreatment

Components	PPs			SSHs		
	Before Alkaline pretreatment	After alkaline pretreatment	Removal %	Before alkaline pretreatment	After alkaline pretreatment	Removal %
Cellulose	12.81	8.63	32.63	40.39	17.33	57.09
Hemicellulose	12.59	8.59	31.77	20.89	9.88	52.70
Lignin	5.76	2.61	54.69	20.57	9.75	52.60

**Fig. 3.** Profiles of measured and predicted bacterial growth in terms of biogas production at mesophilic and thermophilic conditions; A: PPs at mesophilic, B: PPs at thermophilic conditions, C: SSHs at mesophilic conditions and D: SSHs at thermophilic conditions

On the other hand, as mentioned earlier in section 3, the first order model was adopted to describe the kinetics of biogas production by AD process in continuously fed digesters. Normally, the first-order kinetic model for biogas production in a continuous operating digester,

typically modeled as a continuous stirred tank reactor (CSTR), assumes that the hydrolysis phase is the rate-limiting step and that the rate of substrate degradation is proportional to the remaining biodegradable substrate concentration.

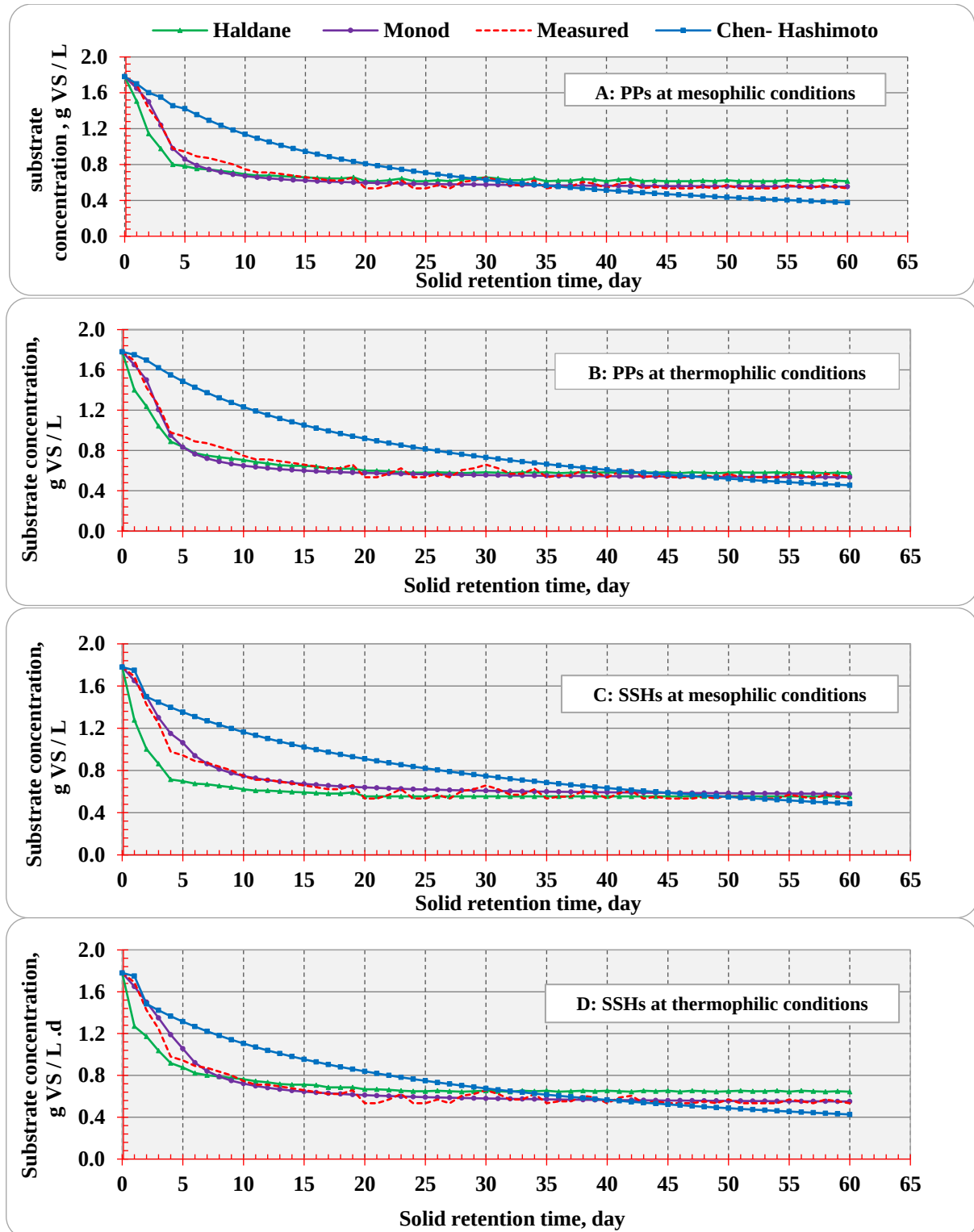


Fig. 4. Profiles of measured and predicted bacterial growth in terms of substrate utilization at mesophilic and thermophilic conditions; A: PPs at mesophilic, B: PPs at thermophilic conditions, C: SSHs at mesophilic conditions and D: SSHs at thermophilic conditions

Fig. 5 and Fig. 6 illustrates the experimental and predicted profiles for methane production in terms of substrate utilization and CH₄ production, respectively. A significant agreement was observed between the

experimental results and those predicted by the first kinetic model with affirmative determination coefficients values as given in Table 5 at mesophilic and thermophilic conditions for both types of substrates; PPS and SSHs.

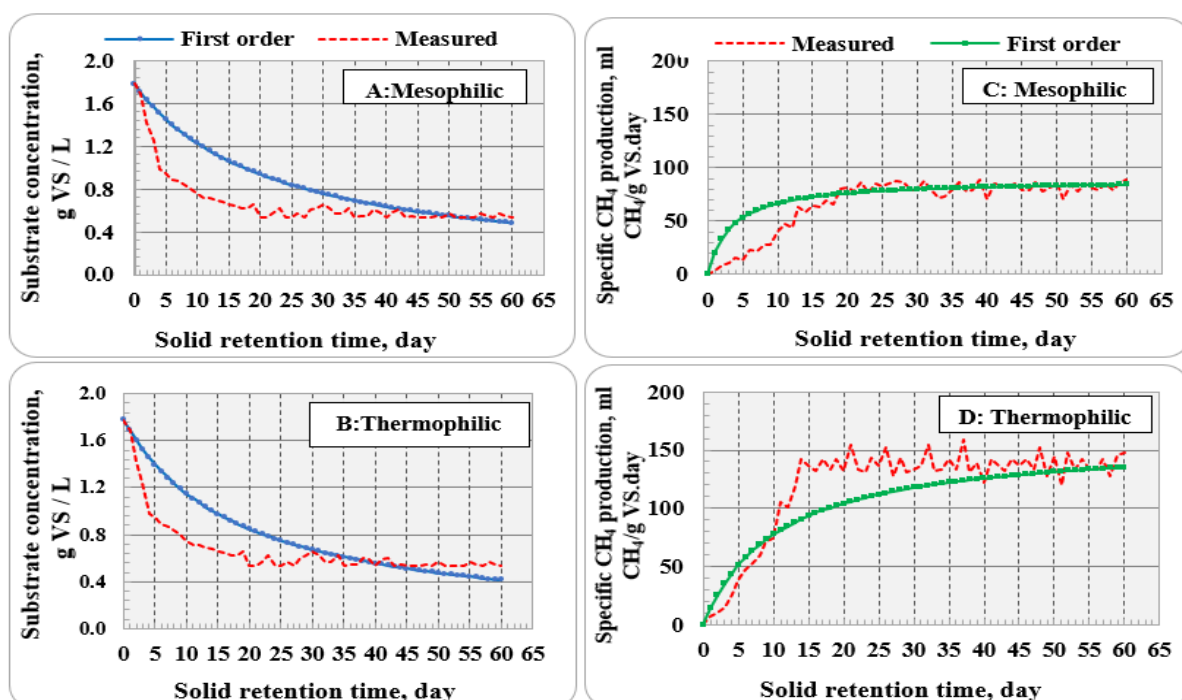


Fig. 5. Profiles of results predicted by first order kinetic model for PPs in terms of substrate consumption rate and CH₄ generation at mesophilic (upper panel) and thermophilic (Lower panel) conditions; A: in terms CH₄ generation at Mesophilic, B: in terms CH₄ generation at Thermophilic, C: in terms of substrate consumption rate at Mesophilic and D: in terms of substrate consumption rate at Thermophilic

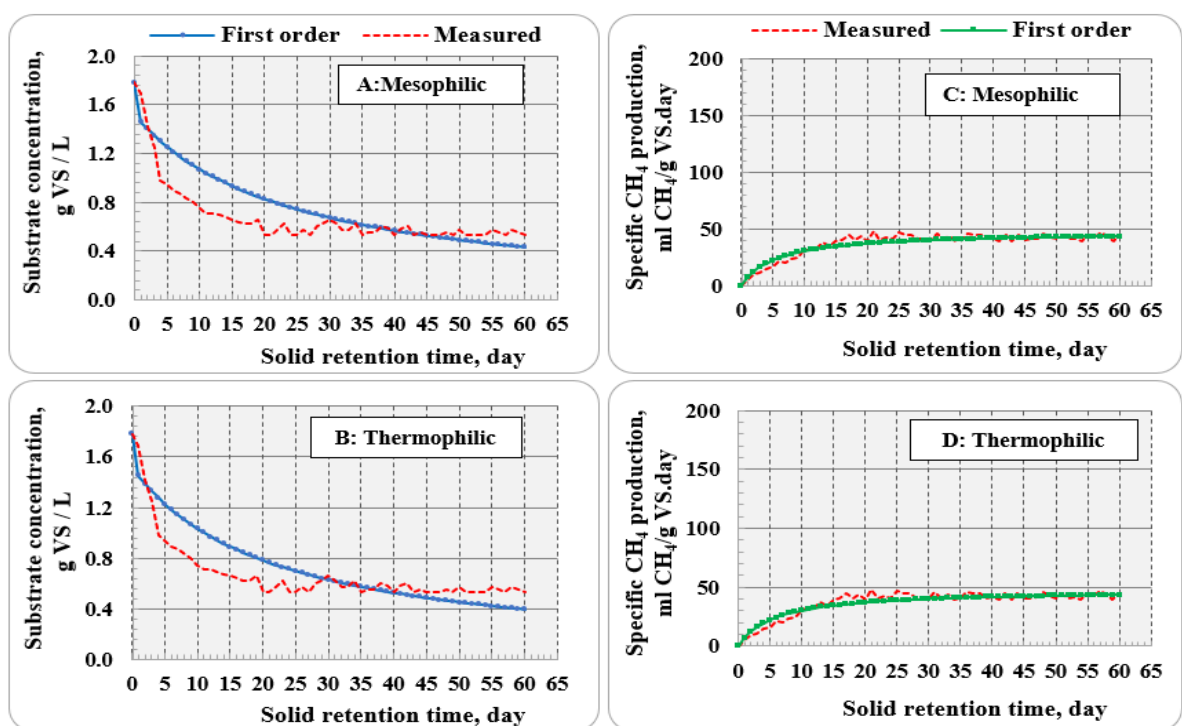


Fig. 6. Profiles of results predicted by first order kinetic model for SSHs in terms of substrate consumption rate and CH₄ generation at mesophilic (upper panel) and thermophilic (Lower panel) conditions; A: in terms CH₄ generation at Mesophilic, B: in terms CH₄ generation at Thermophilic, C: in terms of substrate consumption rate at Mesophilic and D: in terms of substrate consumption rate at Thermophilic

Table 5. Measured results versus results predicted by first order model in terms of methane production and substrate utilization

As biogas production							
Substrate	Temperature condition	Measured CH ₄ production rate (mL/g VS. d)	Predicted produced CH ₄ rate (mL/g VS. d)	K (day ⁻¹)	Y _{max} (mL/g VS)	R ²	RMSE
PPs	Mesophilic	88.66	83.99	0.300	88.66	0.923	14.839
PPs	Thermophilic	147.53	135.17	0.095	158.88	0.920	21.835
SSHs	Mesophilic	44.47	43.73	0.175	47.89	0.961	3.763
SSHs	Thermophilic	59.01	57.38	0.155	63.55	0.930	7.675
As substrate utilization							
Substrate	Temperature condition	Measured remaining substrate concentration (g VS /L)	Predicted remaining substrate concentration (g VS /L)	S ₀ (g VS /L.day)	K (day ⁻¹)	R ²	RMSE
PPs	Mesophilic	0.53	0.48	1.78	0.045	0.837	0.270
PPs	Thermophilic	0.28	0.41	1.78	0.055	0.920	0.341
SSHs	Mesophilic	0.46	0.43	1.52	0.042	0.830	0.247
SSHs	Thermophilic	0.24	0.40	1.52	0.047	0.909	0.341

The first order kinetic model normally provides the potential of biogas generation and the first-order conversion constant of the organic substrate into biogas. Therefore, this model was considered appropriate and complementary for describing the kinetics of the anaerobic digestion process. Nguyen et al. [51] demonstrated a high agreement between the measured and predicted results by the first order kinetics model for biogas yield from the co-anaerobic digestion of recycled for piggery wastewater treatment. López et al. [52] stated that the volumes of biogas produced from the cow manure by the AD process were fitted very well with the predicted values estimated by first-order kinetics in a continuous stirred digester. Wongarmat et al. [53] demonstrated that the experimentally obtained values of methane produced from the AD of effluent and sugarcane filter cake are well fitted with the predicted data using first-order kinetics model in a semi-continuous fermentation process using stirred tank bioreactor.

5- Conclusion

This study explored the feasibility of continuously operated anaerobic biodigesters for methane production using widely accessible lignocellulosic potato peels waste (PPs) and sunflower hulls waste (SSHs) of no economic value. The results demonstrated that at steady state conditions, the average methane yields from PPs and SSHs inoculated with chicken dung was found to be 158.88 ± 20.13 and 63.55 ± 16.45 mL/g VS. d, respectively. The outcomes of Monod model application excellently agreed the experimental measurements with correlation coefficients (R^2) > 0.93 indicating favorable operational conditions of the anaerobic digestion process. The results predicted by Chen- Hashimoto model showed moderate matching with the measured results for the SSHs, whereby, the outcomes of Halden model were insignificant for both PPs and SSHs. The first order kinetic model described well the digestion process

occurred in the continuously operated digesters. For future work, the effect of different particle sizes, and other mathematical models like Contois will be considered.

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المفاعلات اللاهوائية ذات التغذية المستمرة لإنتاج الغاز الحيوي من المخلفات الزراعية - الصناعية الكنوسيليلوزية: دراسات تجريبية ونمذجة

علي رعد طالب^{١،٢،*}، زينب زياد اسماعيل^١

^١ قسم الهندسة البيئية، كلية الهندسة، جامعة بغداد، العراق

^٢ وزارة الاعمار والاسكان والبلديات العامة، دائرة الاعمار الهندسي، بغداد، العراق

الخلاصة

في هذه الدراسة، تم تقييم استرجاع الغاز الحيوي الغني بالميثان من المخلفات الكنوسيليلوزية عمليا ونظريا من خلال المفاعلات اللاهوائية ذات التغذية المستمرة تحت ظروف درجة الحرارة العالية والمعتدلة. تم اختيار قشور البطاطا (PPs) وقشور بذور زهرة عباد الشمس (SSHs) باعتبارها من أكثر الموارد الطبيعية الموجودة بوفرة على وجه الأرض والتي يمكن الاستفادة منها لو تمت ادارتها بشكل صحيح ومستدام حيث تم اضافة لها روث الدجاج كمصدر للبكتريا. أظهرت النتائج ان الميثان المستخلص من (PPs) اكثر 60% من الغاز الناتج من (SSHs) عند الوصول الى حالة الاستقرار بعد ٢٠ يوم من التشغيل المستمر. النمو البكتيري في المفاعلات الحيوية تم تقييمه بواسطة موديلات (Monod, Chen- Hashimoto, Halden) من ناحية انتاج الميثان ومعدل استهلاك المواد. تم تبني موديل الدرجة الاولى لوصف حركية عملية الهضم اللاهوائي في المفاعلات اللاهوائية ذات التغذية المستمرة. بينت النتائج المخمنة بواسطة موديل (Monod) تطابق بصورة كبيرة مع النتائج المختبرية بمعامل ارتباط (R^2) اكبر من ٠,٩٣. أما النتائج النظرية التي تم احتسابها بواسطة موديل (Chen- Hashimoto) فقد اظهرت ترابط اقل مع الفحوصات المختبرية في (SSHs)، بينما كانت النتائج التي تم الحصول عليها بواسطة نموذج (Halden) ليست ذات دلالة إحصائية لكلا النوعين من المخلفات. أظهرت نتائج النمذجة الحركية من الدرجة الأولى (first order kinetic) للمفاعلات اللاهوائية التي تعمل بشكل مستمر أن هذا النموذج حقق توافقاً مثالياً مع البيانات المختبرية.

الكلمات الدالة: انتاج الميثان الحيوي، الهضم اللاهوائي، قشور البطاطا، قشور بذور عباد الشمس، التشغيل المستمر.