Pilot-scale Anaerobic Digestion of Food Waste: Evaluation on the Stability, Methane Production, and Kinetic Analysis

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Abstract

Food waste was massively disposed at landfills daily, and this method is no longer effective in managing waste due to the limited space and environmental issues. An alternative solution was explored in managing the food waste, and anaerobic digestion serve as the best solution. Food waste was digested anaerobically in a lab-scale and pilot-scale anaerobic digester. The performance of a batch pilot-scale anaerobic digestion of food waste, on the other hand, is less documented. The goal of this research is to look into a batch pilot-scale anaerobic digester for food waste, with a focus on methane potential and kinetic studies. A single-stage anaerobic digestion of food waste was carried out with an inoculum to substrate ratio (I/S) of 2.0. A variety of tests were carried out to identify the properties of the food waste and the inoculum employed. Effluent was collected daily for the monitoring process. The pH and volatile fatty acid to total alkalinity ratio (VFA/TA) were monitored daily to ensure that the anaerobic digestion process remained stable. The VFA/TA ratio suggested that the anaerobic digestion process was stable throughout the anaerobic digestion process. The methane accumulation for 26 days monitoring is 463250 mL. The ultimate methane yield of 5103.6 mL CH_4/gVS was observed. The maximum removal efficiency for TS, VS, and COD in this investigation was 85.32, 94.15, and 93.52 %, showing that food waste was efficiently decomposed for biomethane conversion. The Modified Gompertz (GM) and Logistic function models were used to conduct the kinetic analysis. The results reveal that the GM model provides a higher R^2 value than the logistic function model, thus the GM model is more suited in explaining the performance of the anaerobic digestion process.

1. Introduction

The fast growth of the world economy and growing population in the past few years has extensively generated the amount of municipal solid waste (MSW) [1]. Developing countries such as Malaysia, facing significant environmental pollution annually due to the increment of MSW [1]. Solid Waste Corporation Management of Malaysia (SW Corp) reported disposing of 16 687 tonnes of food waste every day [2]. According to the SW Corp, about 55% of MSW discarded at the landfill are food waste [2]. Traditional methods such as composting, landfilling, and incineration were regularly used in handling food waste [2]. However, the traditional methods trigger some environmental impacts such as greenhouse gases emission, and groundwater pollution [2, 3].

According to Leung & Wang [4], anaerobic digestion is the most efficient technique to handle food waste. Anaerobic digestion results in many environmental benefits such as the production of soil amendments, generation of renewable energy (methane and hydrogen), and the reduction of greenhouse gases emission [3]. Anaerobic digestion is a biological process that uses anaerobic bacteria to decompose organic waste into biogas in the absence of oxygen [5]. Biogas is produced in an anaerobic environment, and the major part of biogas is methane [4]. Food waste is classified as waste with a high potential for biological treatment due to its high organic content [6]. Food waste was recorded to have a VS/TS ratio above 90%, indicating the high organic content [6, 7]. Furthermore food waste inherits high moisture content and high degradability traits, making them suitable for biological treatment (aerobic or anaerobic) [8]. Food waste comprises of complex components and organic material such as protein, carbohydrate polymers, lipid, and organic acids [1]. Food waste rich in protein also has a high potential of methane production [4].

Anaerobic digestion can be applied in a laboratory-scale reactor and a pilot-scale reactor [9]. In the laboratory-scale reactor, a small amount of raw material is used, and specific aspects of the digestion process was studied [10]. Several testing (thermodynamic and chemical kinetics) that are independent of size were studied, and the operating conditions during the digestion process were determined [10]. While in the pilot-scale reactor, different parameters were studied, such as duration of operation, control parameters, and equipment reliability [10]. The physical and chemical analysis of the digestion process can be evaluated, and scale-up problems were studied [10].

A single-stage anaerobic digestion system as well as a two-stage anaerobic digestion system can be used for anaerobic digestion [11]. Single-stage anaerobic digestion is the most straightforward system [12]. Moreover, the single-stage anaerobic digestion system is low cost, requires a simple design, and less technical failure [13]. The single-stage anaerobic digestion system is defined as all the biochemical reaction occurs in one reactor [11]. The biochemical process can be separated and utilised in more than one reactor in a two-stage anaerobic digestion system [11].

Dong et al., [14] experimented a batch anaerobic digestion system in a 35L of the pilot-scale reactor. Throughout the experiment, pH, volatile fatty acid (VFA), and ammonia nitrogen were monitored at various points during the digestive process. During the batch anaerobic digestion process, Haider et al. [15] measured pH, VFA, alkalinity, and the VFA/alkalinity ratio. This metric was found to indicate the anaerobic digestion system's stability. According to Van et al., [11], in a single-stage digestion system, the healthy bacteria may weaken the weak bacteria (methanogen) when working in the same reactor. This may cause pH, VFA, and alkalinity changes in the reactor, compromising the stability of the anaerobic digestion process.

Kinetic analysis can be used to evaluate the performance of anaerobic digestion of a specified substrate in a laboratory-scale and pilot-scale digester [2, 16]. Kinetics analysis describes food waste degradation as well as methane production [17]. Kinetic study was conducted using several mathematical kinetic models such as first-order kinetic model, modified Gompertz model, and Logistic function model [18]. Li et al., [17] stated that different models obtain varies kinetic parameters (methane production and methane yield). Deepanraj et al. [16] used the modified Gompertz model and the Logistic function model to compare the kinetic study of anaerobic digestion of food waste. According to the findings of Deepanraj et al., [16], modified Gompertz models work better in anaerobic digestion and explain the kinetic characteristics of the anaerobic digestion system better than the logistic function model. According to Pramanik et al., [2,] the modified Gompertz model elucidates anaerobic digestion performance better than the first-order and logistic function models. The results obtained by using modified Gompertz models are more complement with the data receive from the laboratory process [2].

The pilot-scale single-stage anaerobic digestion system requires an intricate design to establish. Several parameters such as digester size, type of anaerobic system, operating and monitoring parameter in enhancing the biogas production and ensuring the stability of the anaerobic digestion system, need to be selected and monitored carefully [11, 19]. There are also limited resources in explaining the performance of batch pilot-scale anaerobic digestion of food waste [20, 21]. As a result, this research will look into the performance of a pilot-scale single-stage anaerobic digestion system that treats food waste. Before the anaerobic digestion process, operating parameters such as inoculum to substrate ratio (I/S) and mixing were chosen. This research looked at how well food waste degraded in terms of total solids (TS), volatile solids (VS), and chemical oxygen demand (COD) (COD). The organic components of the substrate and inoculum employed in this study were assessed by examining the substrate and inoculum's properties. The methane production potential, maximum methane production rate, and lag time of the anaerobic digestion process were displayed using two mathematical kinetic models (modified Gompertz model and Logistic function model).

2. Materials And Methods

2.1.Substrate and inoculum

The substrate used in this study was food waste. Food waste was collected from the UTHM cafeteria. The food waste collected undergo a separation process where the impurities such as bone, tissue, and plastic were manually removed [22]. Next, the food waste was diluted with tap water with a ratio of 1:2 (food waste: tap water) [22]. After the dilution process, the food waste was mixed and disintegrated using a kitchen blender [23].

Anaerobically digested sludge was collected from the anaerobic digester treating POME and was used as the inoculum for this study. Each sample was kept under refrigeration at 4°C to prevent biodegradation [24].

2.2.Experimental design

A 105 L pilot-scale single-stage anaerobic digester with 84 L working volume was used and operated at batch mode to allow all the biochemical reactions of the anaerobic digestion processes happened simultaneously. A batch single-stage anaerobic digestion system was also employed by Sitorus & Panjaitan [25]. The schematic diagram of the pilot-scale single-stage anaerobic digester employed in this investigation is shown in Fig. 1. The system is also equipped with a purification system and water displacement. The anaerobic digester was connected with a feed tank where the mixture (food waste and inoculum) at specific inoculum to substrate (I/S) ratio was poured into the feed tank (A). Then the mixture from the feed tank was pumped into the anaerobic digester. The anaerobic digester was connected with an effluent sampling point (SP 1), where the effluent was collected, and the pH probe was connected to the SP 1 for pH measurement. Biogas from the anaerobic digester flows into the NaOH solution to remove gases except for methane (C). Then the methane from the NaOH solution flows through the water displacement to measure the volume of methane (D). The NaOH solution was made according to the instructions in the AMPTS II manual [26].

The suitable I/S ratio aids in enhancing the hydrolysis rate and improves the anaerobic digestion process [27]. In an experiment with various I/S ratios for the anaerobic digestion of food waste, Shahbaz et al. [28] found that the I/S ratio of 2.0 produced the maximum methane production. Fadzil et al. [22] also carried out batch-scale anaerobic digestion of food waste with an I/S of 2.0. The food waste and inoculum used in this investigation were 9.6 L and 74.4 L, respectively, based on the I/S ratio of 2.0.

Prior to the anaerobic digestion process, the digester was flushed with nitrogen to provide anaerobic conditions and eliminate air from the headspace [29]. The digester was operated at ambient temperature, and the digester was agitated at 70 rpm [2, 30]. The effluent from the digester was collected to monitor the digester performance [2]. The effluent was stirred to achieve homogeneity before testing [2]. The monitoring parameter involves pH, VFA, TA, VFA/TA ratio, removal efficiency (COD, TS, and VS), and methane production [30]. The monitoring parameter was monitored daily.

2.3.Analytical methods

The influent and effluent in this study were collected, and various testing was conducted. The tests were conducted to characterize the food waste, inoculum, influent, and monitor the monitoring parameters of the anaerobic digestion process daily. Triplicate sample was prepared to undergo the testing, and the mean value was calculated. Table 1 summarize the methods of characterization conducted in this study.

Table 1
Methods of characterization

Parameters	Method of measurement	Reference	Purpose
Protein	Lowry method	[22]	**Characterization**
Carbohydrate	Phenol-Sulphuric acid method	[8]	
Chemical oxygen demand, COD	Hach™ 2011 procedure method 8000	[8]	**Characterization & performance monitoring**
Total Solid, TS	Method 2540G (APHA 2005)	[8]	
Volatile Solid, VS	Method 2540G (APHA 2005)	[8]	
pH	Method 4500-H + B (APHA 2005)	[22]	
Alkalinity / Total alkalinity, TA	Titration method	[22]	
Volatile fatty acid, VFA	Titration method	[30]	

2.4.Kinetic Analysis

The performance of batch single-stage anaerobic digestion of food waste was evaluated using kinetic analysis. To complement the cumulative methane production obtained from the actual experiment data, modified Gompertz modelling and a Logistic function model were adopted [2]. Furthermore, kinetic analysis was also used to evaluate the efficiency of the anaerobic digester [32]. This model provides additional information such as maximum specific methane production rate and lag phase [2]. Eqs. (1) and (2) were used to calculate the Modified Gompertz modelling and Logistic function model.

$$M(t) = M \quad exp\left\{- \; exp\left[\frac{R.e}{M} \quad (\lambda - t) + 1\right]\right\} \qquad \text{(Eq 1)}$$

$$M(t) = \frac{M}{1+exp\{\frac{4.R.(\lambda - t)}{M}+2\}} \qquad \text{(Eq 2)}$$

Where M(t) = cumulative methane production at time t (mL CH_4/gVS added), M = methane production potential (mL CH_4/gVS), R = methane production rate (mL /gVS day), λ = lag phase (day), t = duration of the assay (day), and e = 2.7183.

2.5.Removal Efficiency

The removal efficiency were studied in this study to describe the organic degradation during the anaerobic digestion process. Every day, the removal efficiency of TS, VS, and COD was investigated. The organic inside the food waste degrades every day during the anaerobic digestion process, causing fluctuations in TS, VS, and COD concentrations [2]. The removal efficiency of TS, VS, and COD was determined using Eq. (3).

$$\text{Removal efficiency (\%)} = \frac{(Cin - Ceff)x100}{Cin} \qquad \text{(Eq 3)}$$

Where C_{in} = TS, VS, and COD influent, and C_{eff} = TS, VS, and COD effluent.

3. Results And Discussion

3.1. Characteristics of food waste and inoculum

The pH, organic content (TS & VS), COD, and macromolecular components (protein & carbohydrate) of food waste and inoculums were measured, and the results were presented in Tables 2 and 3.

Table 2

The characteristics of food waste

Characteristics	This study	[40]	[2]	[35]
pH	6.2	-	4.91	6.7
Total solid, TS (g/L)	85.67	158	66	295
Volatile solid, VS (g/L)	77.78	151	63	280
VS/TS	0.91	0.96	0.96	0.95
Chemical oxygen demand, COD (mg/L)	68750.00	157000.00	110000.00	394000.00
Total Protein (mg/L)	4403.33	-	-	-
Soluble Protein (mg/L)	3890.33	-	-	-
Total Carbohydrate (mg/L)	36074.00	99000.00	-	-
Soluble Carbohydrate (mg/L)	21034.67	54000.00	-	-

Table 3
The characteristics of inoculum

Characteristics	**This study**	**[40]**	**[42]**	**[41]**
pH	7.80	7.50	7.9	7.8
Total solid, TS (g/L)	36.78	26.70	39.0	79.06
Volatile solid, VS (g/L)	20.78	18.90	26.60	62.74
VS/TS	0.56	0.71	0.68	0.79
Chemical oxygen demand, COD (mg/L)	30000	-	29200.00	-
Total Protein (mg/L)	3789.67	-	-	
Soluble Protein (mg/L)	1910.33	-	-	
Total Carbohydrate (mg/L)	4680.67	-	-	
Soluble Carbohydrate (mg/L)	1600.33	-	-	

Food waste used in this investigation appears to have an acidic pH. Li et al. [33] investigated anaerobic digestion of food waste, and the pH of the waste employed in his study was also acidic. Zhang et al., [34], also reported a pH of 6.5 for the food waste utilised in the experiment, which is acidic. The food waste employed as a substrate for anaerobic digestion was acidic, as shown in Table 2.

TS represents the organic content of the substrate while the VS represents the biodegradable volatile solids and refractory volatile solids [35]. VS/TS ratio was determined to express the organic contents of the matter [35]. The total solid and volatile solid content of food waste reported in this study is slightly higher than that of Pramanik et al., [2], but lower than that of Rajagopal et al., [36]. Table 2 shows that the VS/TS ratio of all food waste utilised is greater than 90%. According to Qiao et al., [35], the VS/TS ratio of food waste utilised in anaerobic digestion was typically 80 percent or higher.

COD was conducted on the substrate to measure the amount of oxygen needed to oxidised matter [32]. The COD concentration observed in this study was 68 750 mg/L. Wijayanti et al., [37] stated that feedstock which the COD concentration above 20 000 mg/L is considered as a high degradable feedstock. Food waste had a high COD concentration in this study, indicating that it is a highly degradable feedstock. Table 2 shows the COD content of food waste in several experiments, indicating that food waste is a highly degradable feedstock. High degradable feedstock is suitable to be used in anaerobic digestion as it is easier for the matter to be converted into biogas [38].

The testing for carbohydrate and protein were conducted in total and soluble form. The total and soluble form of food waste represents the particulate fraction and soluble fraction of food waste [39]. The carbohydrate content of food waste and inoculum reported in this study is higher than the protein level. Yeshanew et al., [39], reported a similar pattern in the anaerobic digestion of food waste. In comparison to this study, Yeshanew et al., [39] found a larger level of carbohydrate and protein content.

The pH of the inoculums employed in this work is alkali, as shown in Table 3, and the inoculum was taken from an anaerobic digester processing palm oil mill effluent (POME). POME is a highly polluted wastewater if it is directly discharge without any treatment to it [40]. Kumar et al., [41], stated that the pH of inoculums utilised for anaerobic digestion of food waste was 7.5, and that the inoculum was acquired from a wastewater treatment plant. Parra-Orobio et al., [42] and Forster-Carneiro et al., [43] investigated anaerobic digestion of food waste using inoculum from a wastewater treatment plant. Inoculum pH was 7.8 and 7.9, according to Parra-Orobio et al., [42] and Forster-Carneiro et al., [43]. The pH level that is measured may vary. The inoculum employed in the anaerobic digestion of food waste ranges from 7.5 to 7.9, according to the data in Table 3. In this investigation, the pH of the inoculum was 7.8.

The total solid and volatile solid content of the inoculums employed in this investigation were higher than those reported by Kumar et al., [41]. The TS and VS results in this study is quite similar with the results observed by Forster-Carneiro et al., [43]. Wang et al., [7] stated that a biomass with VS/TS above 50% is considered as a biomass with high organic content. This study obtain a VS/TS ratio of 56% which indicates the inoculum used was slightly rich in organic content. Based on the results tabulated in Table 3, all the inoculums has high organic content and the inoculums are used in the anaerobic digestion of food waste.

The inoculum used in this study resulted in COD concentration of 68 750 mg/L. The result obtained in this study is slightly lower than the COD concentration reported in Chan et al., [30]. Chan et al., [30] studied anaerobic digestion by using POME as inoculum and the COD concentration reported was 70 000 mg/L. Chan et al., [30] also specified a COD concentration range in inoculum that could be used in the anaerobic digestion process. The COD content of inoculum must be between 65 900 and 85 300 mg/L [30]. The COD concentration of the inoculum employed in this investigation remained within the acceptable limit for anaerobic digestion. According to Table 3, the measured COD concentration is lower than the reported COD concentration in other literatures. Despite that, all the reported COD concentration were higher than 20 000 mg/L indicating that the inoculum usually used in the anaerobic digestion process is also highly degradable.

3.2.Characteristics of influent

Table 4 shows the characteristics of the influent for this study. The mixture of food waste and inoculum fed into the batch pilot-scale anaerobic digester is referred to as influent in this study. The pH of the influent was measured at 7.2, which is within the anaerobic digestion process's permitted range. According to Saragih et al., [23], the ideal pH range for anaerobic digestion is between 7 and 8.5. In addition the pH of mixture ranging from 6.8–7.4 is also acceptable [13, 44]. The COD of influent in this study is slightly higher by 2.04 g/L than what reported by Alizadeh et al., [45]. The VFA of influent in this study was below 500 mg/L. Chan et al., [30] also observed a VFA value for influent to be below 500 mg/L and the VFA in this study is considered to be low and less inhibition may occur.

Table 4
The characteristics of influent

Characteristics	**Influent**
pH	7.2
Total solid, TS (g/L)	48.44
Volatile solid, VS (g/L)	32.33
VS/TS	0.67
Chemical Oxygen demand, COD (mg/L)	44266.67
Alkalinity (mg $CaCO_3$/L)	150.00
Volatile fatty acid, VFA (mg/L)	118.67

3.3.Process stability

The pH, VFA concentration, and VFA/TA ratio were all evaluated to determine the stability of the anaerobic reactor [46]. On a daily basis, pH, VFA, and the VFA/TA ratio were measured and monitored [3, 32]. Daily effluent was collected and mixed before monitoring tests were performed [2]. The monitoring process were conducted to overcome early instability [33].

Throughout the anaerobic digestion process, the monitoring parameters will be evaluated to detect any inhibitions and to maintain a stable anaerobic digestion process. For 26 days, the pilot-scale anaerobic digestion of food waste was run constantly. Figure 2 depicted a graph of pH and VFA concentration versus day.

As depicted from Fig. 2 throughout the anaerobic digestion process the pH regularly changes. The lowest and highest pH recorded during the anaerobic digestion process were 6.71 and 7.45. Despite the changes in pH, the pH of the effluent was still within the optimum range which is from 6.30 to 7.80 [47]. The pH began to drop from day 1 to day 2, and the VFA concentration remain constant for 6 days. This is due to the high amount of VFA produce in the anaerobic digester in which during the early digestion process, many organics in food waste is rapidly converted into VFA causing the pH to drop [6, 48]. Then the pH start to increase from day 3 to day 7 while the VFA concentration drop significantly at day 7. According to Pramanik et al., [2,] the rising pH was caused by a low VFA concentration and a high ammonia concentration. From day 8 to 9, the pH drops, then rises until the anaerobic digestion process is completed. When the protein in the food waste is degraded, it also resulting in high ammonia concentration, high amount of hydrogen sulphide, as well as producing long chain of fatty acid, causing the pH to increase [6, 49]. In addition the increase pH may resulted because of the digester foaming when the food waste is digest [50].The VFA concentration began to decrease from day 8 to day 26. Although VFA concentrations began to rise on days 15 and 16, they remain low when compared to VFA concentrations during the first eight days of the anaerobic digestion process. The low VFA concentrations indicate a high biomethane conversion efficiency [51]. In this investigation, the final VFA concentration was low, and the final pH was within the ideal range. A similar trend has been observed by Li et al., [51], when the final VFA content is low and the final pH is suitable at the end of the anaerobic digestion process.

Table 5 tabulates the measured pH and VFA/TA ratio for 26 days. VFA/TA is also used as a tool in analysing the stability of the anaerobic digestion process along with pH, and VFA [33]. The highest VFA/TA ratio obtain is at day 2 and day 5 where early digestion stage takes place in which VFA is produced when the food waste is degraded. The highest VFA/TA ratio obtained in this study was 0.35. The anaerobic digestion process is deemed stable when the VFA/TA ratio is less than 0.35, according to Chan et al., [30], Li et al., [33], and Li et al., [52]. When the VFA/TA ratio is less than 0.4, according to Raposo et al., [27], the anaerobic digestion process works successfully without the risk of acidification. The highest VFA/TA ratio reported during this investigation was 0.35, which was still within the optimal range, indicating that the anaerobic digestion process remained steady for the whole 26-day period. The digester remain stable throughout the anaerobic digestion process aid in active microbial activity thus enhancing methane production.

Table 5
The pH and VFA/TA ratio throughout the anaerobic digestion process

Days	VFA/TA	Days	VFA/TA	Days	VFA/TA
1	0.33	**11**	0.08	**21**	0.08
2	0.35	**12**	0.08	**22**	0.08
3	0.34	**13**	0.08	**23**	0.08
4	0.34	**14**	0.08	**24**	0.08
5	0.35	**15**	0.15	**25**	0.08
6	0.30	**16**	0.14	**26**	0.08
7	0.24	**17**	0.08		
8	0.16	**18**	0.08		
9	0.17	**19**	0.08		
10	0.14	**20**	0.12		

3.4.Pilot-scale anaerobic digester performance

Next removal efficiency was studied to visualize the rate of the organic degradation throughout the anaerobic digestion process. The removal efficiency was calculated using the parameters TS, VS, and COD, where TS, VS, and COD indicate the solid content of the food waste [34]. Figure 3 depicts the removal efficiency data collected every day for 26 days.

The removal efficiency was estimated to determine the rate of organic decomposition and to assess the anaerobic digestion process' effectiveness [2]. The food waste inside the digester is decomposed and biogas is created during the anaerobic digestion process, generating changes in TS, VS, and COD concentrations [2]. The maximum removal efficiency for TS, VS, and COD in this investigation was 85.32, 94.15, and 93.52 %, respectively. Lin et al. [53] used a single-stage anaerobic digestion of food waste to achieve the greatest COD removal rate of 74 %. Kumar et al., [41] also claimed to have achieved the greatest COD elimination rate of 74 %. This study obtained greater COD removal than Lin et al., [53] and Kumar et al., [41]. Pramanik et al. [2] investigated single-stage anaerobic digestion of food waste and measured the average TS, VS, and COD removal efficiency. Pramanik et al. [2] observed removal rates of 72.20, 78.90, and 80.0 % for TS, VS, and COD, respectively. The average removal of TS, VS, and COD in this investigation was 78.39, 85.95, and 86.23 %, respectively. In this study, the average removal of TS, VS, and COD was slightly higher than the results obtained by Pramanik et al., [2].

The results of this study's TS, VS, and COD removal efficiency showed that there were active microorganisms present in the inoculum, in which the food waste was digested and anaerobic digestion was carried out [54]. In this study, COD resulted has the highest average organic degradation followed by VS, and TS. In addition, similar with what observed by Pramanik et al., [2] the COD removal has the highest average removal followed by VS removal and lastly TS removal.

3.5.Methane Accumulation

Figure 4 depicts the accumulation of methane during the anaerobic digestion of food waste. In this investigation, the methane accumulation was monitored for 26 days. The experiment ceased when the methane production was consistently low and reach plateau. For this study, the methane accumulation started to reach the plateau at day 19. The methane accumulation for this study was 463250 mL or 463.25 L respectively. Methane was increasingly produced proportional with the organic degradation [33]. High organic degradation proven an active microbial activity thus more organic is converted into methane each days [33]. Stable anaerobic digestion system with low inhibitions contributes to high methane production [11].

3.6.Methane Yield

The methane yield is measured to determine the effectiveness of anaerobic digestion of food waste [2]. The methane yield for anaerobic digestion of food waste is tabulated in Table 6. Methane gas production begins on day 1 according to the statistics shown. The methane gases start to produce on day 1 similar with what reported by Huang et al., [55] and Li et al., [51]. For this study, the methane production increase from day 1 until day 10 and then the methane production slowly decreases until day 26. The ultimate methane yield for this study was 5103.6 mL CH_4/gVS respectively.

Table 6
The methane yield ($mLCH_4/gVS$) for anaerobic digestion of food waste

Days	**Methane yield ($mLCH_4/gVS$)**	**Days**	**Methane yield ($mLCH_4/gVS$)**	**Days**	**Methane yield ($mLCH_4/gVS$)**
0	0	**10**	3503.4	**20**	4830.9
1	293	**11**	3864.7	**21**	4881.0
2	837.8	**12**	4122.5	**22**	4925.1
3	1314.9	**13**	4247.5	**23**	4968.1
4	1649.8	**14**	4363.2	**24**	5009.9
5	1893.2	**15**	4462.4	**25**	5060.6
6	2203.9	**16**	4571.4	**26**	5103.6
7	2479.9	**17**	4659.6		
8	2823.6	**18**	4727.3		
9	3103.4	**19**	4786.8		

This study obtained high removal efficiency of TS, VS, and COD (84.64, 92.79, and 93.52%), which were above 50% indicating high organic degradation [33]. The methane yield of food waste may be influenced by the rate of removal efficiency [33]. The removal effectiveness of TS, VS, and COD increased the methane production dramatically [33]. The carbohydrate content of the food waste used in this investigation is higher than the protein content. When food waste rich in carbohydrate was degraded, it tend to produce high methane yield [38].

According to the VFA/TA ratio, this study remains stable throughout the digestion process and providing a suitable working environment for the microorganisms to produce methane [12]. In this study, the anaerobic digester was semi-continuously mixed for 30 minutes at 70 rpm [2]. In a semi-continuously mixed digester, high methane yield can be obtained [57, 58]. Semi-continuously mixing during the anaerobic digestion process can provide effective microbial activity that can enhanced the methane production [29, 58].

3.7.Kinetic Analysis

The performance of anaerobic digestion of food waste was described using kinetic analysis [2]. Modified Gompertz (GM) modelling and a Logistic Function Model were used in this investigation.

Table 7 lists the expected parameters for anaerobic digestion of food waste, such as ultimate methane yield, methane production rate, and lag phase. The graph of methane yield between real data and estimated data from Modified Gompertz modelling and Logistic function modelling for this investigation is shown in Figs. 5 and 6. The figures depicted can be explained and divided into three section [2]. The first section elaborates the relationship of lag phase to establish the biogas production [3]. The second section was the exponential phase where the biogas production will be peak [3]. Lastly the third section is called death phase or steady phase where the biogas production became lesser and the graph became plateau [2].

Table 7
The kinetic analysis of anaerobic digestion of food waste

Model	Kinetic parameters	Laboratory (Actual)	Estimated
Modified Gompertz	Ultimate methane yield (mlCH_4/gVS)	5103.56	4858.10
	Methane production rate, (mlCH_4/gVS/day)	293.00	453.09
	Lag phase (day)	0.00	0.87
	R^2	-	0.85
Logistic function	Ultimate methane yield (mlCH_4/gVS)	5103.56	4632.25
	Methane production rate, (mlCH_4/gVS/day)	293.00	526.54
	Lag phase (day)	0.00	1.84
	R^2	-	0.79

For this study in the first section according to the Modified Gompertz modelling, this setup required approximately 1 day of lag phase for methane production. While Logistic function modelling required about 2 days of lag phase for methane production. The second section display the sharp increase of methane production from day 2 to day 17 for modified Gompertz modelling. Meanwhile, the methane production significantly increase from day 2 to day 15 for logistic function model. The significant increase during this period were due to the rapid development of microbial community and effective degradation process [2]. The steady phase (Sect. 3) was from day 18 to day 26 and from day 16 to day 26 for modified Gompertz model and Logistic function model correspondingly. In the steady phase, the methane production was gradually slow and slowly stopped due to the reduction of active microbial community and low degradation process [56]. The estimated data from Modified Gompertz modelling and Logistic function model were lower than the actual experimental data. These results were similar with what reported in Pramanik et al., [2].

The experimental data and kinetic parameters of the Modified Gompertz model and Logistic function model [2] were used to determine the methane production rate. A high R^2 value (above 0.5) suggests that the model used fits the experimental data well [2]. The modified Gompertz model and the Logistic function model used in this study had excellent R^2 values of 0.85 and 0.79, respectively, and were well fitted to the experimental data. The modified Gompertz model had a higher R^2 value than the logistic function model in this investigation. This demonstrated that the modified Gompertz model provided a more exact estimate and could explain more than 85% of the variation in the results [2]. According to earlier studies [16, 59], the modified Gompertz model fit the data better than the logistic function model.

4. Conclusions

This study investigate the performance of pilot-scale of single-stage anaerobic digestion of food waste. The food waste used in this study is acidic which the pH result is below 7. The food waste used in this study resulted in a VS/TS ratio of 91% which is more than 50% indicating the food waste used has high organic content. The food waste used in this study is classified as a biodegradable waste because its COD is higher than 20 000 mg/L. Food waste is composed of solids and macromolecular compound (carbohydrate and protein).

The anaerobic digestion process were monitored daily to maintain a stable anaerobic digestion process. In this study, pH, VFA, and VFA/TA were measured and the parameters were used as tool to detect instability or inhibitions during the anaerobic digestion process. During the anaerobic digestion process, the pH fluctuate daily and the highest pH and lowest pH was recorded. The highest and lowest pH were 6.71 and 7.45 which is still within the optimum range (6.30–7.80). The pH during the digestion process regularly change, due to the amount of VFA and ammonia present during the digestion process. The VFA/TA ratio recorded in this study is below 0.35 which is considered stable. VFA/TA ratio above 0.4 is consider to be unstable and digester failure may occur.

The performance of the anaerobic digestion of food waste was studied in terms of the organic degradation. The TS, VS, and COD removal efficiency were measured daily. In this study, the maximum TS, VS, and COD removal efficiency were 85.32, 94.15, and 93.52% respectively. The results shows that the organic in the food waste was highly degraded for biomethane conversion. This study recorded the average removal efficiency of TS, VS, and COD of 78.39, 85.95, and 86.23%. Based on the results obtain, COD obtain the highest removal efficiency followed by VS, and lastly TS.

The methane accumulation for this study was 463250 mL or 463.25 L respectively and the highest methane yield of 5103.6 ml CH_4/gVS was observed. This study remains stable throughout the anaerobic digestion process resulting in high microbial activity. High microbial activity indicates more organic can be converted into methane. By providing suitable environment for the microorganism to work, a good end-product can be predicted. High removal efficiency indicates high organic degradation thus more organic is converted into methane gas.

The kinetic study was carried out utilising the Modified Gompertz model and the Logistic function model. The dynamics of the anaerobic digestion process are well explained by the Modified Gompertz and Logistic function model. The Modified Gompertz and Logistic Function Model can be used to improve the design and operation of the anaerobic digestion process by optimising process parameters. The ultimate methane yield, methane production rate, and lag phase may all be calculated using the modified Gompertz and logistic function model. The modified Gompertz model is better adapted to characterise the performance of the anaerobic digestion process than the logistic function model, according to the kinetic study. This was determined by comparing the R^2 value in which the modified Gompertz model obtain higher R^2 value.

Declarations

Availability of data and materials

All data generated or analyzed during this study are within the submitted manuscript.

Competing interests

The authors declare they have no competing interests.

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Authors' contributions

All authors read and approved the final manuscript.

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Figures

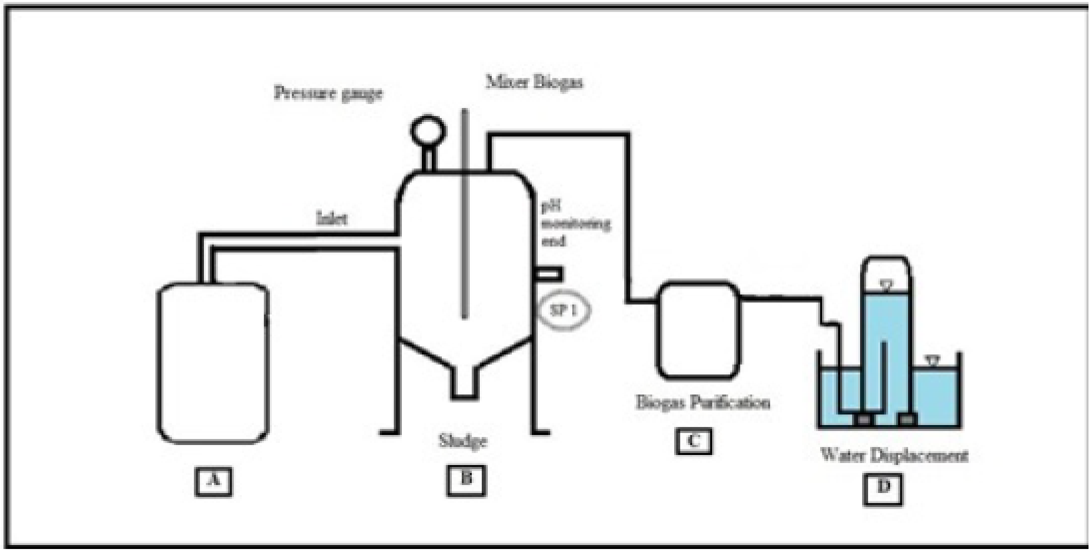

Figure 1

The schematic diagram of pilot-scale digester (batch mode)

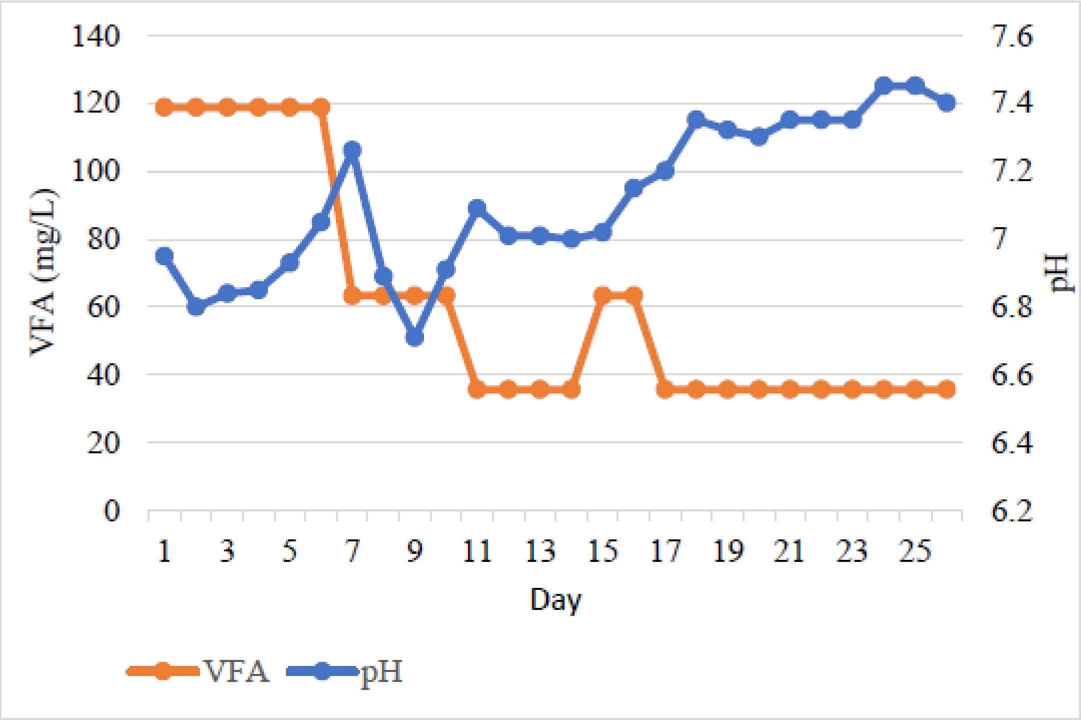

Figure 2

pH, VFA versus day

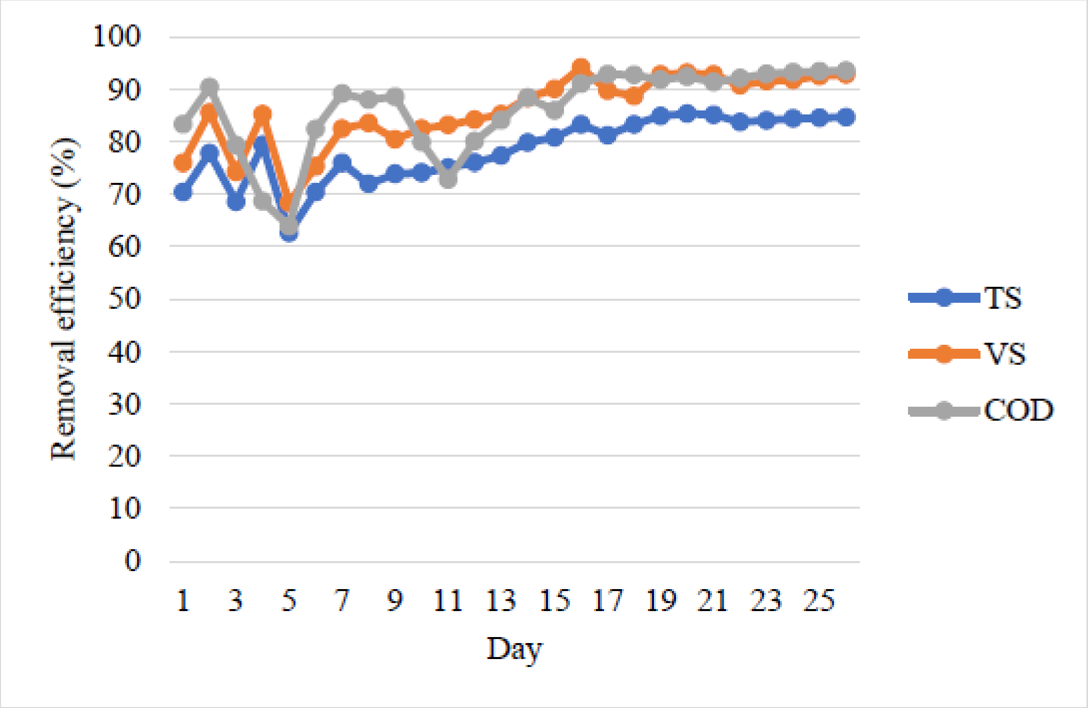

Figure 3

The removal efficiency throughout the anaerobic digestion process

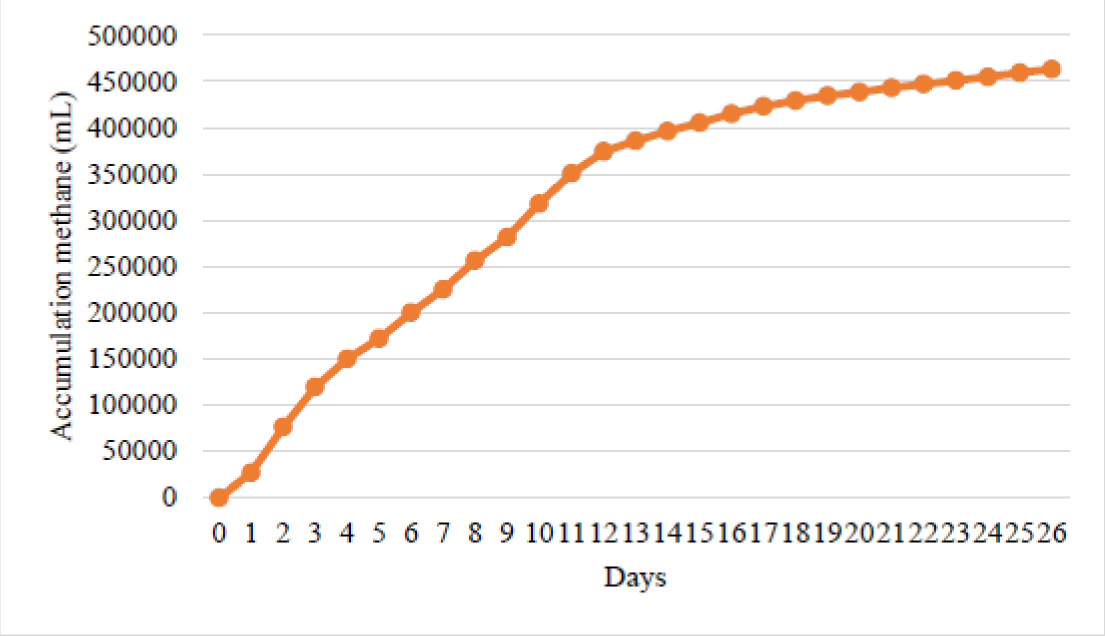

Figure 4

The methane accumulation of anaerobic digestion of food waste for 26 days

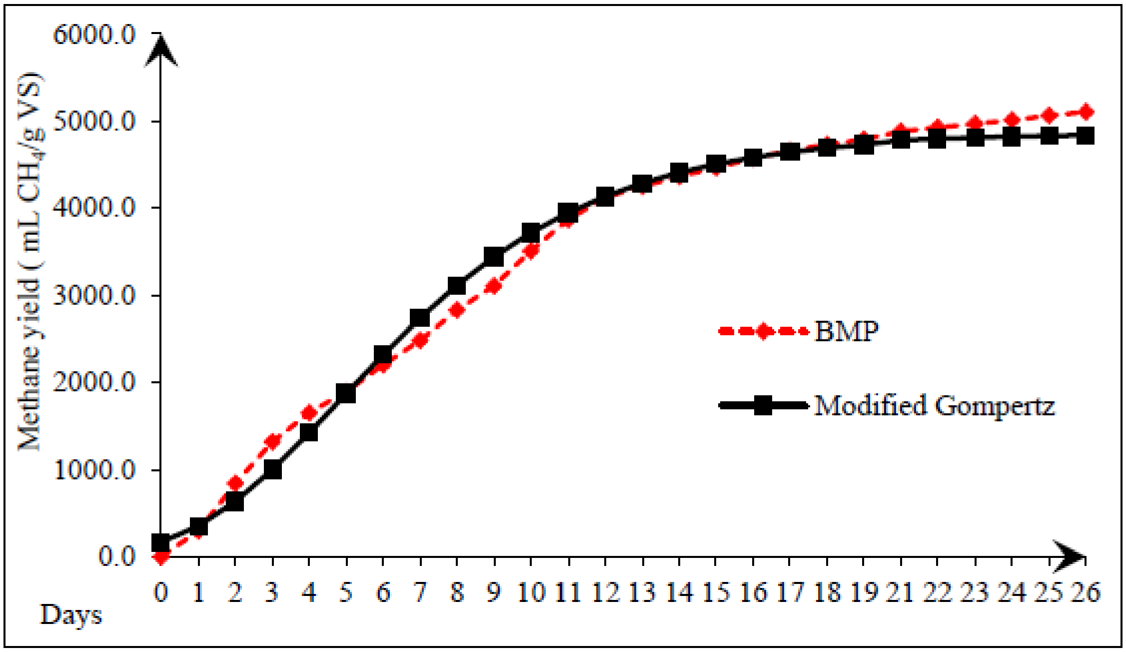

Figure 5

The methane yield for the Modified Gompertz modelling for 26 days

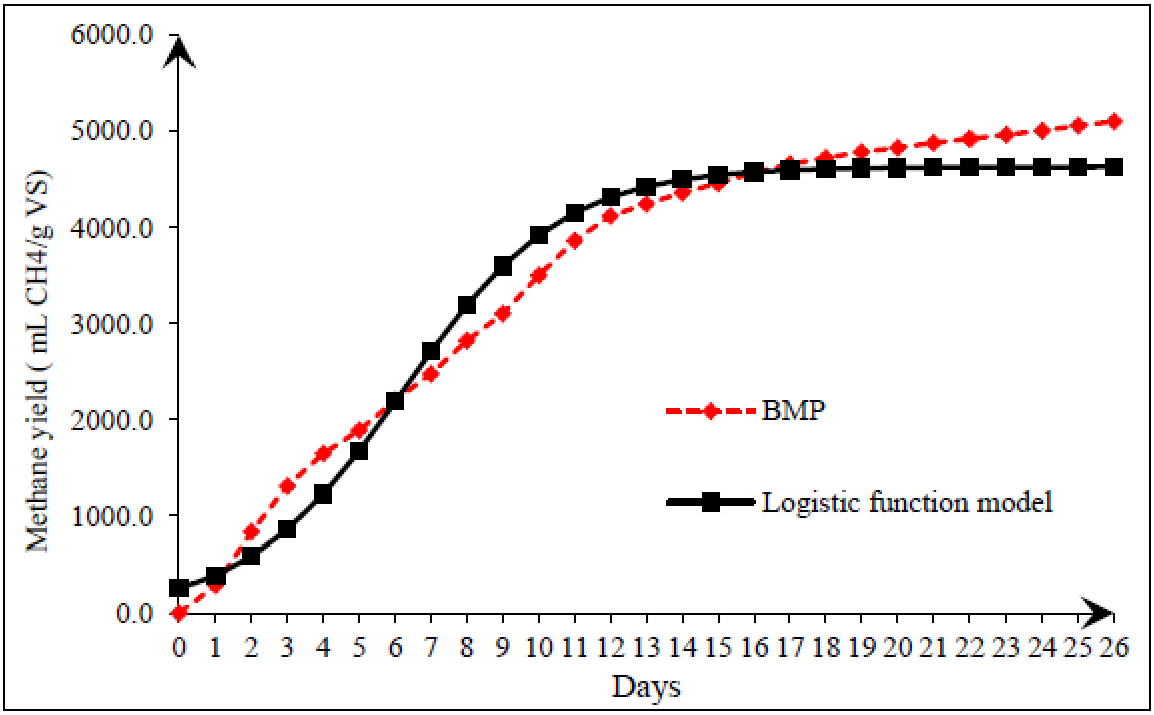

Figure 6

The methane yield for logistic function model for 26 days