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Kinetics Modelling of Batch Anaerobic Co-digestion of Domestic Primary Sewage Sludge and Food Waste in a Stirred Reactor

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Abstract. Anaerobic digestion was conventionally applied for treating sewage sludge. However, the accumulation of solid waste particularly food waste has reach the critical levels worldwide. In practice, the food waste was dumped into the landfill for ultimate disposal. However, the greenhouse gases produced in the landfill makes this is no longer a preferable option. Anaerobic digestion was seen as an alternative for managing the food waste in a sustainable way. Methane, a renewable energy is potentially in replacing fossil fuel. However, the methane yield from the digestion of food waste inefficient. Therefore, a study of the co-digestion of sewage sludge and food waste was conducted to investigate the improvement of the methane yield. This study was conducted by using a mixture of domestic primary sewage sludge and food waste as a co-substrate for the anaerobic digester. The kinetics modified Gompertz modelling was applied to describe the anaerobic digestion process. A series of batch biochemical methane potential (BMP) assay was prepared using Automatic Methane Potential Test System (AMPTS II) to investigate the anaerobic digestibility of the mixture of domestic primary sewage sludge and food waste. The BMP assay showed that the co-digestion improved the ultimate methane yield by 32.6% higher than domestic primary sewage sludge alone, indicated that the co-substrate characteristics influencing the methane yield. Besides that, the greater VS/TS ratio of the substrate also resulted in the greater methane yield. The kinetics parameter from the modelling analysis were slightly lower as compared to the laboratory data.

1. Introduction

Rapid development has leads to a significant environmental problem with the increasing of waste [1]. In Malaysia, Solid Waste Corporation of Malaysia (SWCorp) established under the Solid Waste Management and Public Cleansing Corporation Act 2007 (Act 673) to ensure solid waste and public management become more effective. Malaysia authority face great challenges in handling waste and treatment due to lack of expertise and fund [2]. Generally, organic waste is the highest amount of waste generated, with 50% by weight dominated by food waste (FW). Numerous of waste including food waste and sewage sludge were burned or disposed into landfill [3]. Once disposed into landfill, the waste will naturally biodegrade and release environmental harmful element such as leachate and gases [4].

Anaerobic digestion mainly applied for sewage sludge stabilization. Nevertheless, this treatment also actively developed for other waste such as FW [5]. According to [6] FW is suitable used as substrate for anaerobic digestion since its characteristics of high organic content and easily biodegradable. However, anaerobic digestion of FW as sole substrate is inefficient [7]. Anaerobic digestion of FW conducted by

[8] obtained ultimate methane yield of 201.5±11 mL CH_4/g VS. As alternative, co-digestion of sewage sludge and FW was conducted. Previous study conducted by [9] shows a significant improvement of methane yield of 393 mL CH_4/g VS with addition of FW as compared to sewage sludge alone (310 mL CH_4/g VS). On other study, co-digestion of sewage sludge and organic fraction municipal solid waste (OFMSW) consisted of restaurant and canteen waste obtained higher ultimate methane yield of 365.49 mL CH_4/g VS compared to sewage sludge as mono-digestion [10]. This difference possible due to the different mixture of co-substrate used and inoculum to substrate (I/S) ratio. Two mixing ratio of sewage sludge and food waste was used to investigate the effect of co-substrate mixture of sewage sludge and food waste on the methane yield conducted by [11]. The observation of 4:1 mixing ratio of sewage sludge and FW produced higher methane yield 355 mL CH_4 g/ VS compared to 2.4:1 (239 mL CH_4 g/ VS). Other study with similar mixing ratio of 4:1 of sewage sludge and FW conducted by [12] produced methane yield of 215 mL CH_4 g/ VS which almost 85.3% higher than mono-digestion.

Biochemical methane potential test (BMP) could be conducted in continuous, semi-continuous or in batch study to evaluate the methane production from anaerobic digestion [8], [13]. Recently, studies on batch BMP assay using Automatic Methane Potential Test System (AMPTS II) was used as its precise predictability [5]. As the BMP assay took long duration, the kinetics modelling applied to describe the anaerobic digestion process. Modified Gompertz applied to verified the validity of model by comparing the laboratory and predicting data [8]. Batch BMP assay on co-digestion of sewage sludge and OFMSW (consist of food waste) conducted by [8] showed that the modified Gompertz estimated the ultimate methane yield of 211.76 mL CH_4/g VS which is well fitted to the methane yield from the laboratory assay.

Due to the fact of less study of co-digestion of domestic sewage sludge and FW in Malaysia, this study was carried out to investigate the anaerobic digestibility of this mixture and the methane production kinetics.

2. Material and methods

2.1. Substrate and inoculum

This study used primary domestic sewage sludge (PSS) for mono-digestion. Meanwhile, 4:1 mixing ratio with wet mass ratio of PSS and FW was prepared adapting the ratio describe by [11]. PSS was collected from sewage treatment plant in Universiti Tun Hussein Onn Malaysia (UTHM). While the FW consist of leftover consists of rice, vegetables and meats collected from UTHM cafeteria. The FW was manually screened for non-biodegradable contaminants before roughly chopped and blended around two to three minutes using household blender into a thick consistency. Then, the substrate was frozen until use in the digestion experiment [14]. Inoculum is the anaerobically digested sludge was collected from existing full-scale anaerobic digester treating palm oil mill effluent (POME). The samples and inoculum was stored at 4°C until the anaerobic digestion assay [15].

2.2. BMP assay

AMPTS II was used for the batch BMP assay. Duran bottles of 500mL (reactor) were used and filled with substrate and inoculum [5] and illustrated in Figure 1. The BMP assay conducted with inoculum to substrate (I/S) ratio of 2:1 based on VS basis [9]. Duplicate blank and triplicate sample reactor were prepared each for mono-digestion (PSS) and co-digestion (PSS and FW). The pure nitrogen gas (N_2) was flushed for 2 minutes to create anaerobic environment in the headspace [9]. To avoid early reaction, the reactor was prepared one after another. The reactor was incubated in water bath at mesophilic temperature (37°C) and mixing speed at 100rpm [6]. The mass of inoculum and substrate filled into the reactor were calculated based on the manual of AMPTS II [16].

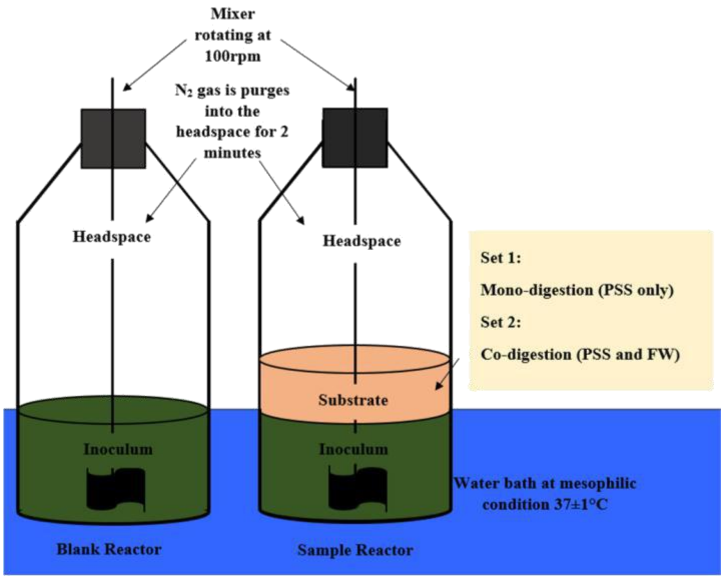

Figure 1. The reactor used in this study

2.3. Analytical method

Table 1 summarized the analytical method for determining the characteristics of PSS and mixture of PSS and FW.

Table 1. Analytical method used in this study

Parameter	Analytical method	Reference
COD (mg/L)	HACH 8000 method	[17]
TS (mg/L)	APHA Standard method (2540B)	[18]
VS (mg/L)	APHA Standard method (2540E)	[18]
Protein (mg/L)	Lowry method	[19]
Carbohydrate (mg/L)	Dubois method	[10]
Alkalinity (g/L as $CaCO_3$)	APHA Standard method: method 2320B	[10]

2.4. Kinetic modelling

Modified Gompertz modelling is a common equation used to describe the kinetic methane production for co-digestion of sewage sludge and FW [5], [8]. Modified Gompertz are well described as Equation 1.

$$M = M_0.\exp\left\{-\exp\left[\frac{R_m.e}{M_0}(\lambda - t) + 1\right]\right\} \quad (1)$$

Where y(t) is the specific methane yield (mL/g Vs) at anaerobic digestion time t (d), f_d is the maximum methane potential (mL/g VS), R_m is the maximum methane production rate (mL/g VS day), e is Euler's constant (2.7183), and λ is the lag phase time (days).

3. Result and discussion

3.1. Substrate characteristics

Table 2 summarized the characteristics of substrates in this study. Due to the mixing of PSS and FW, the TS, VS, COD, protein and carbohydrate were increased. This is possible to the additional of organic from the FW. From observation, the VS/TS ratio increase to 0.92 from 0.55 with additional of FW. [20] also observed VS/TS ratio of 0.82 from the mixture of sewage sludge and FW. High VS/TS indicated high organic transformation potential of substrate in anaerobic digestion process [10]. This study also showed increasing of COD. The similar result of COD also observed by [8]. Improvement of COD for co-digestion indicates adequate organic substrate to produce methane [21]. Additional of FW into the mixture relatively increase of protein and carbohydrates. From observation, the mixture was dominated by carbohydrate similar to mixture of FW and sewage sludge observed by [10].

Table 2: Characteristics analysed in this study (N=3)

Parameter	PSS	PSS+FW
Total solid, TS (mg/l)	7.33	43.33
Volatile solid, VS (mg/l)	4.00	39.67
VS/TS	0.55	0.92
COD (mg/l)	111.50±0.63	2246.50±0.91
Protein (mg/l)	72.75±6.02	711.43±11.93
Carbohydrate (mg/l)	79.83±8.57	1561.10±60.35

3.2. Methane accumulation

Figure 2 and Figure 3 showed the methane accumulation from the BMP assay for mono-digestion and co-digestion which ends on 25th days and 12th days respectively. The blank data was the average of duplicate blank reactor while sample reactor was the average of triplicate reactors. The net methane accumulation was obtained after subtracting the blank from each substrate. From the BMP assay, the net accumulated methane was 620.3mL and 183.5mL for co-digestion and mono-digestion respectively. As expected, higher net methane accumulation of co-digestion was observed compared to mono-digestion. The other study of co-digestion of sewage sludge and FW, the maximum methane production was observed at 8th day of BMP assay [22]. [23] focused on co-digestion study of FW and waste activated sludge, observed that the biogas production range from 170 to 443mL/g TS.

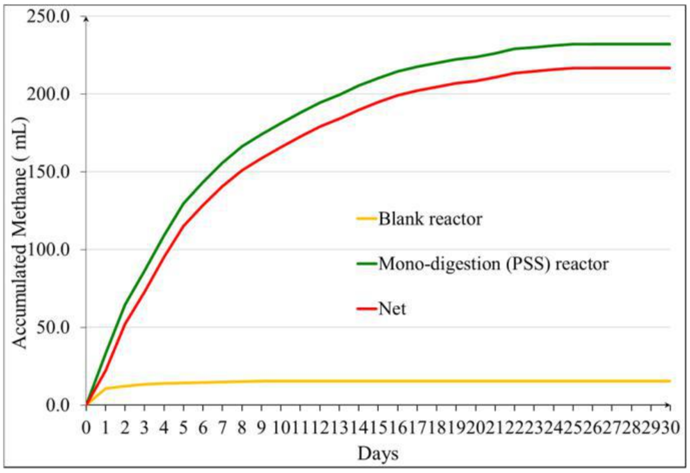

Figure 2: The accumulated methane for mono-digestion

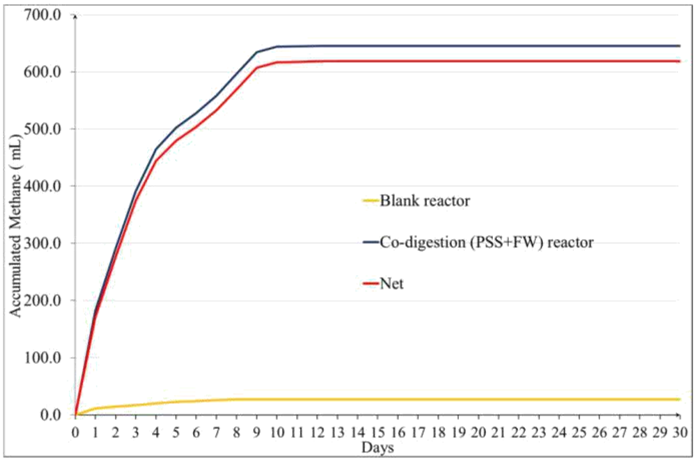

Figure 3. The accumulated methane for co-digestion

3.3. Methane potential

The ultimate methane yields were presented in Figure 4. Mono-digestion yields at 833.21 mL CH_4/g VS and the ultimate methane yield of the co-digestion was 1236.43 mL CH_4/g VS. The ultimate methane yield obtained slightly higher compared to previous studies. [10] observed ultimate methane yield of 365.49 mL CH_4/g VS of co-digestion of OFMSW consisting canteen and restaurant waste with sewage sludge. Similar co-digestion conducted by [8] observed the ultimate methane yield of 200.2 mL CH_4/g VS which higher than was observed from mono-digestion of secondary sludge (164.5 mL CH_4/g VS). This different most probably due to the fact of difference in the organic content, chemical composition or inoculum to substrate (I/S) ratio between each of BMP assay conducted [21].

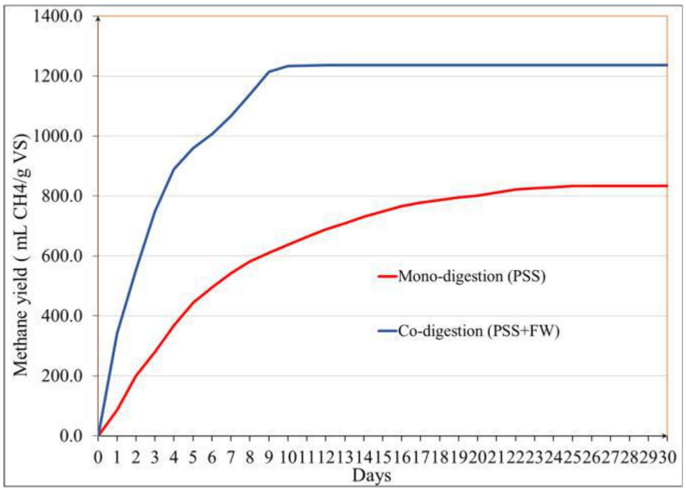

Figure 4. Methane yield for mono-digestion and co-digestion

According to [24], methane production rate can be determined using the steepest slope from the methane yield. In this study, the methane production rate of co-digestion is higher as compared to mono-digestion, at 342.27 mL CH_4 VS/day and 114.87 mL CH_4 VS/day respectively. Methane production rate was important as it is used to reflects the biodegradability and amount of degradable matter in assay [11]. [25] concluded that higher methane production rate could be achieved with higher carbohydrate content. In this study, the co-digestion mixture have high carbohydrate concentration (Table 2). Other study on co-digestion of FW and sewage sludge, [22] observed almost 37% of degradation rate and with minimum of 18% increase in methane yield production rate.

3.4. Kinetic modelling

Methane production for all parameter were modelled based on Equation 1. The kinetic constants of M_o, R_m, and λ of the model were determined using the least squares fitting method (non-linear regression approach) with the aid of solver function in MS Excel ToolPak [23]. Table 4 summarized the results of fitting the kinetic modelling to the BMP assay. By plotting laboratory and analysis of modified Gompertz data, Figure 5 and Figure 6 were prepared. Each figure was showing the methane yield curve from mono-digestion and co-digestion respectively.

Table 3 showed the ultimate methane yield, maximum methane production rate and lag phase from both laboratory and kinetics data. The modelling analysis showing slightly lower kinetics as compared to the laboratory observation. Study of mono-digestion and co-digestion by [8] observed the similar trends of lower kinetic modelling compared to laboratory data in which the ultimate methane yield observed from the laboratory data were twofold from the Gompertz modelling for both mono-digestion and co-digestion.

Lag phase of 0.04 day of mono-digestion and co-digestion was observed from the assay. However, the lag phase was neglected as it is low. The kinetic modified Gompertz observed no lag phase. Budiyono et al. [26] stated that short lag phase indicated no acclimation period and short time to produce methane. If the substrate used is not lack of nutrient, the degradation activity and methane production will generated immediately. Seswoya et al. [5] also observed the lag phase in the assay but no lag phase from analysis of kinetic modelling. The lag phase could be minimize by co-digestion with higher carbohydrates and lower protein [27].

Table 3. Summary of laboratory data with kinetic modelling

Parameter	Mono-digestion		Co-digestion	
	(L)	(MG)	(L)	(MG)
Ultimate methane yield, f_d (mL CH_4/g VS)	833.21	795.04	1236.43	1218.48
Maximum methane production rate, Rm (mL CH_4/g VS d)	114.87	88.12	342.27	267.35
Lag phase, λ (d)	0.04	0.00	0.04	0.00

*L- Laboratory data, MG- Modified Gompertz

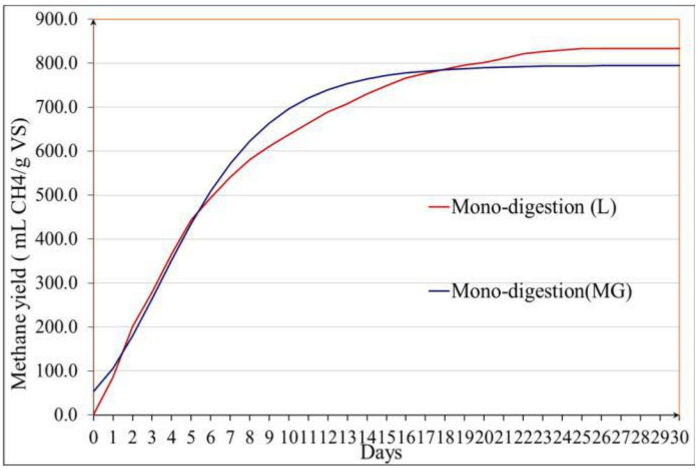

Figure 5. The laboratory data and modified Gompertz for mono-digestion

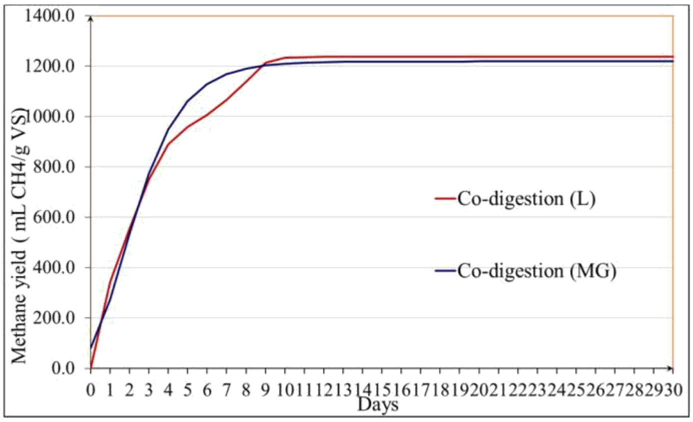

Figure 6. The laboratory data and modified Gompertz for co-digestion

4. Conclusion

Additional of FW as co-substrate not only enhance to the improvement of ultimate methane yield but also improve the characteristics of the co-substrate. With FW in anaerobic co-digestion, significant difference of ultimate methane yield was observed. This study showed the ultimate methane yield increased 32.6% higher than PSS alone. Although the kinetic Gompertz modelling used was slightly lower than laboratory data, about 90% of ultimate methane yield estimated within seven days of the BMP assay. Also, no lag phase was observed in the kinetic modelling. In future, various series of mixture of co-substrate and I/S ratio will be applied to estimate the methane yield. Besides, more kinetics modelling will be used to describe the anaerobic co-digestion of PSS and FW.

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