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MODELING OF BATCH AND CONTINUOUS ANAEROBIC DIGESTION OF PALM OIL MILL EFFLUENT: THE EFFECT OF WASTEWATER-SLUDGE RATIO

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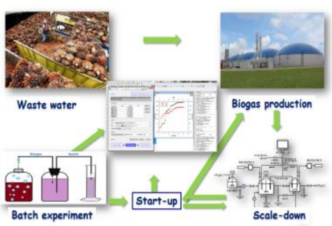
Graphical abstract



Abstract

In this work, both models for batch and continuous anaerobic digestion of palm oil mill effluent were developed based on Monod's kinetics. Then the authors attempt to understand the effect of wastewater-sludge (WW:S) ratio on the biogas production efficiency in batch digesters. The experiments were carried out at a controlled temperature of 35±0.5 °C. Two series of the experiment were conducted. In the first series, the wastewater-sludge ratios covered 1:1 (add sodium bi-carbonate), 1:1, 1:2 and 2:1. It was found that the ratio of 1:2 gave the highest biogas producing efficiency followed by the ratio 1:1 (add sodium bi-carbonate). At 1:1 ratio, sodium bi-carbonate addition was required to start anaerobic digestion at a workable pH range whereas at 1:2 ratio the initial pH is in the workable range without the need of its addition. However, at the ratio of 2:1 the starting pH was too low to adjust pH economically by adding sodium bi-carbonate. The second series was to confine experiments to a narrower ratio range, namely: 1:1 (add sodium bi-carbonate), 1:1.5, 1:2, 1:2.5. In both sets of experiment, the ratio 1:2 gave the best biogas production potential of 76.62 and 78.52 ml of biogas/g COD removed respectively. In all treatments, the process was able to remove more than 80% of wastewater initial COD. The modified Gompertz equation was used to estimate the maximum specific biogas production rate (MBPR or R_m/S_0). It was also found that the ratio of 1:2 gave the best MBPR in both experimental series (26.87 ml biogas/g COD-day). A modified Monod-type Model was also developed to describe the microbial growth, substrate consumption and biogas production in continuous operation. In general, sludge recycle provided active biomass which can use the substrate in the wastewater instantly without significant lag phase or delay. Furthermore, continuous-flow model developed, with parameters estimated from batch experiments, predicted the experimental kinetics of the actual continuous experiments satisfactory.

Keywords: POME, biogas production, biogas modeling, wastewater-sludge ratio

1.0 INTRODUCTION

Palm oil industry is a major industry in Thailand, particularly in the southern region. It is estimated that the wastewater discharged from each oil palm mill 300-700 m^3/day on average (50,000-150,000 mg COD/l). Currently there are more than 80 plants around the country, thus the total amount of wastewater to be treated is more than 40,000 m^3/day or 14,600,000 m^3 annually.

Currently, most of medium to large oil-palm mills are on the move to build plants which produce electricity from wastewater through biogas generated in anaerobic digestion process. Various designs exist which are operated with satisfactory efficiency in term of COD reduction but most of them are not yet welloptimized for biogas production. However to study the dynamics of biogas generation in an actual commercial-scale plant is not practical and risky. Thus a more practical approach is to scale down the commercial plants to much smaller scales while retaining equivalent operating states.

In start-up mode of biogas plants we need to build-up biomass (microbial cells) such that enough cells to consume organic matters in palm oil mill effluent (POME) to prevent pH reduction down to the lower limit for methanogens to grow normally.

This work focuses on the start-up period of the plant. However, instead of using the scaled-down plant in this step, we will use a series of batch experiments to understand how the wastewater-to-sludge ratio in the start-up step affects the performance of biogas plant. In addition, we attempt to obtain more insight regarding the mechanisms behind the experimental result using both semi-empirical model (Gompertz model) [1, 2] and mechanistic model (Monod-type kinetics) in both batch and continuous modes.

2.0 MATERIALS AND METHODOLOGY

2.1 Wastewater and Sludge

The wastewater samples were collected from an oil palm mill where an existing biogas plant is located. Its characteristics are shown in Table 1. Figure 1 shows the experimental set-up.

Table 1 The characteristics of wastewater and sludge

Ratio/Parameter (wastewater : sludge)	COD g/L	Initial pH	MLVSS g/L	Alkalinity mg/l as $CaCO_3$	VFA mg/l as $CaCO_3$
1 : 1+ $NaHCO_3$	12,350	7.0	11,955	12,665	3,900
1:1.5	20,150	6.5	11,955	7,916	2,643
1:2	18,450	6.4	11,955	5,100	1,218
1:2.5	13,750	7.0	11,955	6,975	1,933

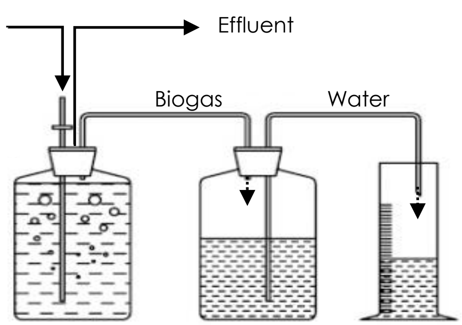


Figure 1 Schematic view of the experimental set-up

2.2 Experimental Design

In batch mode, the anaerobic digesters having a total volume of 1,100 ml. and a working volume of 1,000 ml. were used in all experiments. There was no initial pH adjustment except for the wastewater: sludge 1:1 which was adjusted to pH 7. The temperature was controlled at the 35°C by temperature-controlled water circulator. Biogas production was measured daily by water displacement method as used by other authors [3, 6-8]. The methane content was measured using Gas Chromatograph (GC-8A Shimadzu) and the average value was 56 % methane. For continuous mode, the three identical laboratory–scale UASB reactors were used in this study. They have cylindrical shape with 100 cm high, 5.4 cm internal diameter and 2.06 L working volumes. The feed was pump by peristaltic pump (Longer pump, Model BT 100-1F, DG-4 channel pump head) at the rate defined by HRT. Three reactors were operated continuously at seven hydraulic retention times (HRTs) of 5, 4, 3, 2, 1, 0.5 and 0.25 day. The corresponding organic loading rates (OLR) were 0.84, 1.05, 1.4, 2.1, 4.2, 8.4, and 16.8 kg COD/m^3d^{-1} respectively.

2.3 Chemical Analysis

All analytical procedures are performed in accordance with standard methods for examination of water and wastewater[9].

2.4 Kinetic Model of Biogas Production

2.4.1 Semi-empirical Model (Gompertz Model)

It is customary to use some form of kinetic or empirical models to describe the data and estimate the BMP from model's parameters. Recently, Gompertz equation has been used very often which has the following forms [4, 5, 10].

Modified;

$$P = (P_\infty + P_0)\left[\exp\left(-\exp\left(\frac{R_m \times e}{P_\infty}(\lambda - t) + 1\right)\right)\right] \quad (1)$$

Where P, P_∞ are accumulated methane at time t and its long time values respectively. R_m is maximum specific methane production rate (ml/d), λ is lag

phase period and e is 2.178282. Of course this is equivalent to its original form.
Original form:

$$P = P_{\infty}\left[\exp\left(-\frac{r_0}{\alpha}\exp(-\alpha t)\right)\right] \quad (2)$$

Where r_0 and α are parameters in Gompertz equation which directly related to R_m and λ in (1) [11]
Corrected form:L

$$P' = (P_{\infty} + P_0)\left[\exp\left(-\frac{r_0}{\alpha}\exp(-\alpha t)\right) - \exp\left(-\frac{r_0}{\alpha}\right)\right] \quad (3)$$

2.4.2 Monod Model for Batch Anaerobic Digestion

A classical way of describing growth and product formation kinetics is due to Monod [12] and it's various modified forms.

$$\frac{dX'}{dt} = \mu X = \frac{\mu_m S}{K_S + S}X \quad (4)$$

$$\frac{dX}{dt} = (\mu_m - k_d)X = \left(\frac{\mu_m S}{K_S + S} - k_d\right)X \quad (5)$$

Using the definitions $Y_{PS} = \frac{\Delta P}{\Delta S}$, $Y_{XS} = \frac{\Delta X}{\Delta S}$, $Y_{PX} = \frac{\Delta P}{\Delta X} = \frac{Y_{PS}}{Y_{XS}}$ and noting that $\frac{P_0}{Y_{PS}} = \frac{X_0}{Y_{XS}}$ equation (5) can be written as following

$$\frac{dS}{dt} = \mu\left(S - S_0 - \frac{X_0}{Y_{XS}}\right), \ \frac{dP}{dt} = Y_{PS}\mu\left(\frac{P}{Y_{PS}} - \frac{P_0}{Y_{PS}} - \frac{X_0}{Y_{XS}}\right) = \mu P \quad (6)$$

Here X, X_0, X', S, S_0, Y_{XS}, Y_{PS}, μ, μ_m, K_S and k_d are biomass and initial biomass concentration, accumulative biomass concentration assumed no death, substrate and initial substrate concentration, substrate-to-biomass and methane-to-biomass yield coefficients, specific and maximum specific growth rate, saturation constant, and specific death rate respectively. Assuming $k_d = 0$ the solutions of (4), (5), (6) are

$$t = \frac{(K_S Y_{PS}) + P_{\infty} + P_0}{(P_{\infty} + P_0)\mu_m}\ln\left(\frac{P}{P_0} + 1\right) - \frac{(K_S Y_{PS})}{(P_{\infty} + P_0)\mu_m}\ln\left(1 - \left(\frac{P}{P_{\infty}}\right)\right) \quad (7)$$

If, however, k_d not = 0, the full solution is

$$t = \frac{X_0 + (Y_{XS}(K_S + S_0))}{\left((\mu_m - k_d)\left((S_0 Y_{XS}) + X_0\right)\right) - (K_S Y_{XS} k_d)}\ln\left(\frac{X}{X_0}\right) - \frac{(K_S Y_{XS}\mu_m)}{\left(X_0(k_d - \mu_m)^2\right) + Y_{XS}\left((K_S k_d(k_d - \mu_m)) + \left(S_0(k_d - \mu_m)^2\right)\right)} \times \ln\frac{(X - S_0 Y_{XS} - X_0)(k_d - \mu_m) - (K_S Y_{XS} k_d)}{S_0 Y_{XS}(\mu_m - k_d) - (K_S Y_{XS} k_d)} \quad (8)$$

Monod model for continuous anaerobic digestion

$$\frac{dX}{dt} = \frac{\mu_m S}{K_S S + S}X - k_d X + \frac{Q}{V}(X_i - X) \quad (9)$$

$$\frac{dS}{dt} = -\frac{1}{Y_{XS}}\frac{\mu_m S}{K_S S + S}X + \frac{Q}{V}(S_i - S) \quad (10)$$

Assuming the biogas generated is growth-associated, we have

$$\frac{dP}{dt} = -\frac{Y_{PS}}{Y_{XS}}\frac{\mu_m S}{K_S + S}X \quad (11)$$

In the following simulation we first started simulating the batch mode for WW:S ratio 1:2 until 5 days then switched to continuous mode with different inlet CODs and HRTs.

3.0 RESULTS AND DISCUSSION

In general the experimental data fitted both Gompertz and Monod model very well (Table 2) although it was evident that the actual biogas produced slightly lagged behind the model prediction. This suggested that there was a significant portion of slowly degradable substrate in palm oil mill effluent (approximately 10-20 % total COD).

In normal batch experiments, the most easily measurable state variables are accumulative biogas, solution and total COD. However, the biomass concentration can be observed using the model prediction (Figure 4, 5, 6, 7) as long as the yield coefficient (Y_{XS}) is approximately constant. This was quite reasonable particularly for the batches which exhibited balance growth (Figure 2).

Table 2 Summarized description of the models, parameters and the best-fit parameter (R^2)

Model	Parameters	Wastewater : Sludge Ratio			
		1:1NaHCO$_3$	1:1.5	1:2	1:2.5
Corrected Gompertz equation	r_0 (d^{-1})	2.2246	3.5808	3.9330	5.3839
$P' = (P_{\infty} + P_0)\left[\exp\left(-\frac{r_0}{\alpha}\exp(-\alpha t)\right) - \exp\left(-\frac{r_0}{\alpha}\right)\right]$	α (d^{-1})	0.6196	0.9702	0.9301	1.1436
	P_0 (ml)	0.6	0.5	0.3	0.05

Model	Parameters	Wastewater : Sludge Ratio			
		1:1NaHCO$_3$	1:1.5	1:2	1:2.5
	Fitted P_∞ (ml)	1,459	1,320	1,449	1,306
	R_m (ml/d)	332.33	471.13	495.80	549.44
	R^2	**0.9949**	**0.9984**	**0.998**	**0.9960**
Monod of product model	K_S (mg/l)	29,480	27,415	55,552	11,387
$t=\frac{(K_SY_{PS})+P_\infty+P_0}{(P_\infty+P_0)\mu_m}\ln\left(\frac{P}{P_0}+1\right)-\frac{(K_SY_{PS})}{(P_\infty+P_0)\mu_m}\ln\left(1-\left(\frac{P}{P_\infty}\right)\right)$	Y_{PS}	0.1416	0.0878	0.0907	0.2087
	P_∞ (ml)	1,459	1,320	1,449	1,306
	μ_m (d^{-1})	0.2065	0.35	0.25	0.25
	R^2	**0.9859**	**0.6919**	**0.944**	**0.9189**
Monod of biomass model	X_0 (mg/l)	11,955	11,955	11,955	11,955
$t=\frac{X_0+(Y_{XS}(K_S+S_0))}{((\mu_m-k_d)((S_0Y_{XS})+X_0))-(K_SY_{XS}k_d)}\ln\left(\frac{X}{X_0}\right)$	Y_{XS}	0.4602	0.06522	0.1523	0.6282
$-\frac{(K_SY_{XS}\mu_m)}{\left(X_0(k_d-\mu_m)^2\right)+Y_{XS}\left((K_Sk_d(k_d-\mu_m))+\left(S_0(k_d-\mu_m)^2\right)\right)}$	K_S (mg/l)	46,551	336,625	13,586	66,832
$\times\ln\frac{(X-S_0Y_{XS}-X_0)(k_d-\mu_m)-(K_SY_{XS}k_d)}{S_0Y_{XS}(\mu_m-k_d)-(K_SY_{XS}k_d)}$	S_0 (mg/l)	12,350	20,150	18,450	13,750
	μ_m (d^{-1})	0.6012	0.9042	0.2553	1.5539
	k_d (d^{-1})	0.02517	0.01355	0.0429	0.1564
	R^2	**0.9820**	**0.7109**	**0.955**	**0.8904**

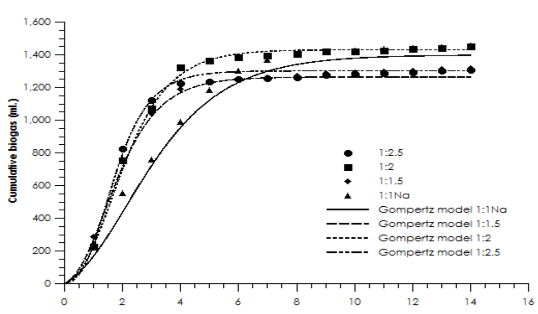


Figure 2 Accumulative biogas versus time

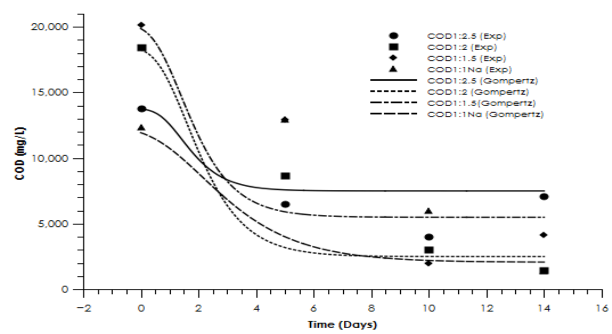


Figure 3 Substrate (gCOD/l) concentration versus time and best fitted Gompertz equation

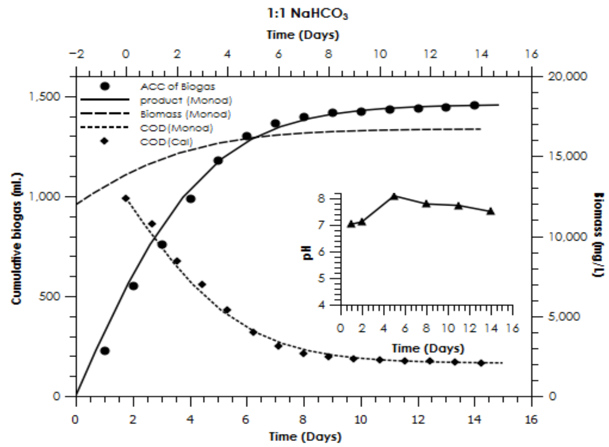


Figure 4 Monod model prediction versus experimental data (wastewater-sludge: 1:1NaHCO$_3$)

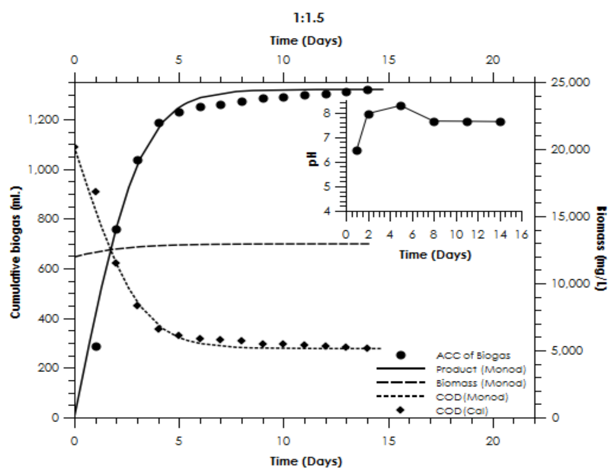


Figure 5 Monod model prediction versus experimental data (wastewater-sludge: 1:1.5)

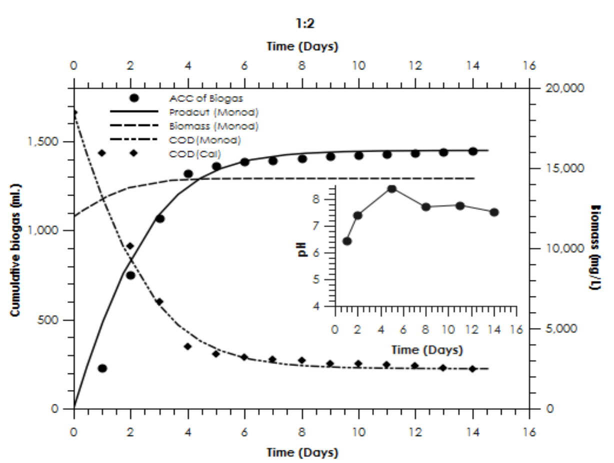


Figure 6 Monod model prediction versus experimental data (wastewater-sludge: 1:2)

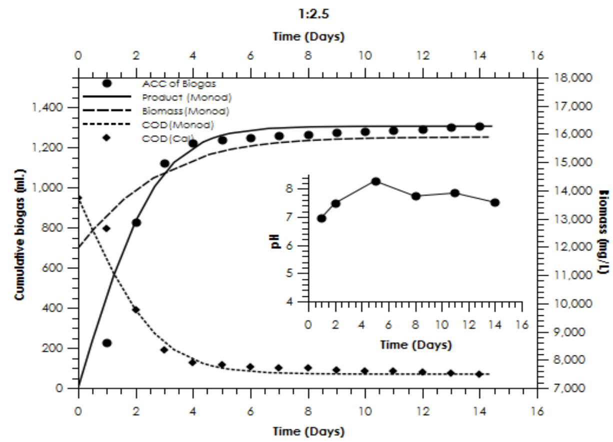


Figure 7 Monod model prediction versus experimental data (wastewater-sludge: 1:2.5)

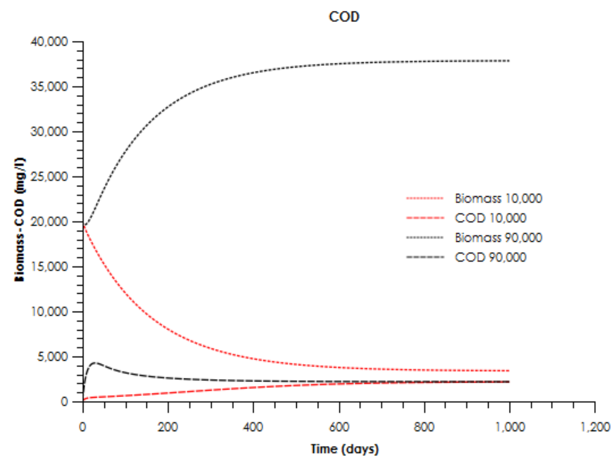


Figure 8 Start-up simulation showing the effect of inlet substrate concentration on the dynamic responses of the plant.(10,000 < Si < 90,000)

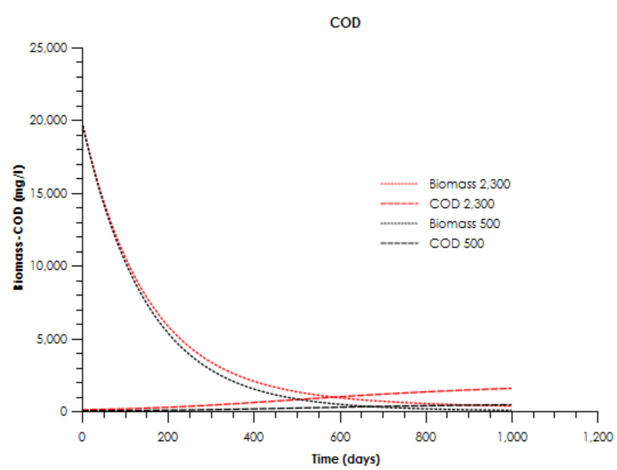


Figure 9 Start-up simulation showing the effect of inlet Substrate concentration on the dynamic responses of the plant. (500 < Si < 2,300)

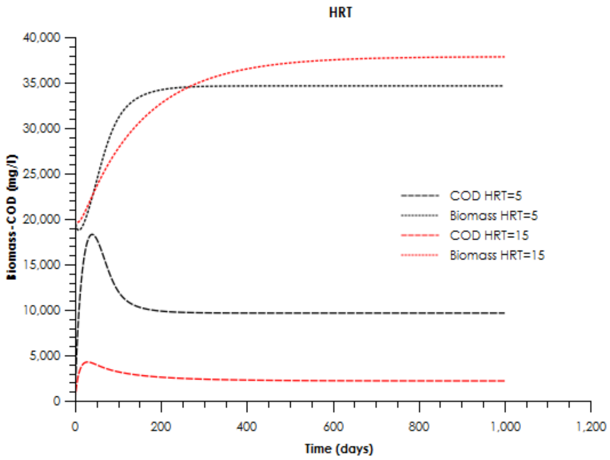


Figure 10 Start-up simulation showing the effect of HRT on the dynamic responses of the plant.(5< HRT < 15)

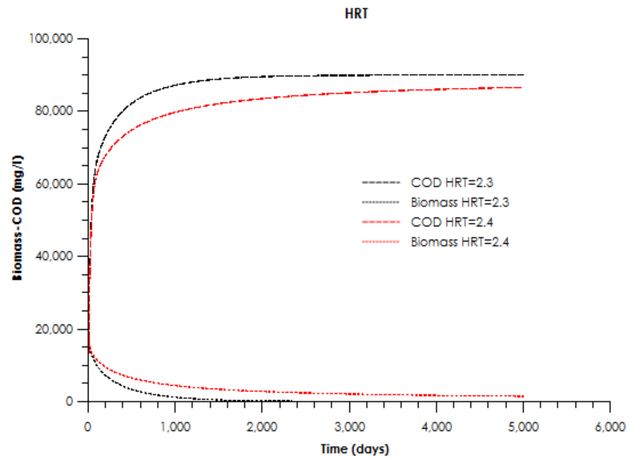


Figure 11 Start-up simulation showing the effect of HRT on the dynamic responses of the plant.(2.3 <HRT <2.4)

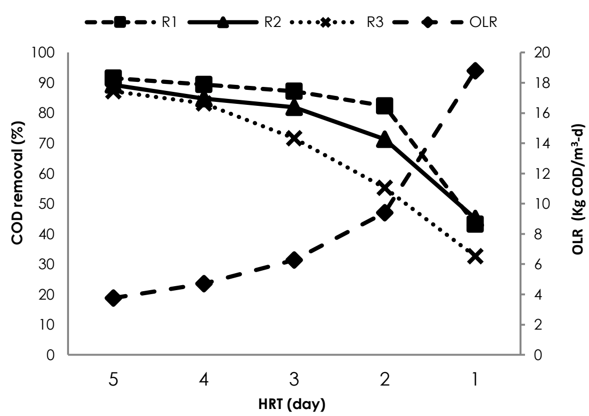


Figure 12 actual experimental continuous operation

In our batch experiments, the anaerobic process failed if the initial cell biomass was too low (wastewater : sludge 2:1 and 1:1) because the initial pH was fallen out of the suitable range (6.8-7.2). This can be mitigated by adding alkaline solution ($NaHCO_3$) to increase the pH and provide sufficient time for methangens to grow, producing methane and keep pH within the optimal range. This can be costly and it is better to use higher ratio (>1:2) since it allowed us to avoid any addition of chemicals.

3.1 Start-up Simulation

In our start-up process, we began with batch digestion to activate the microbes and build the biomass level to ensure smooth continuous operation. In this step, there are few questions to be answered at least qualitatively. Firstly, how does the influent COD affect the dynamics of the anaerobic processes?. Secondly, what is the HRT range that ensures stable operation?. Here we answer these questions by continuous mode simulation for the ratio 1:2. Note that in the model formulation for this purpose, we assume Monod kinetics without substrate and product inhibition.

The results in Figure 8 and 9 are worth special remarks. Firstly, the system seems to be robust, being capable to adjust itself to face high influent COD without losing ability to keep the COD at a low/constant level. Secondly, as long as the influent COD is higher than 2,000 mg/l, the system can cope with sudden change in influent COD, establishing a new steady state. As for HRT, similar characteristics also apply. With the ratio 1:2, the system is stable down to HRT of 2.4 (Figure 10, 11). This simulation result was in agreement with actual experimental continuous operation as shown in Figure12. It is clear that the system failed at the neighborhood of HRT of 2.0-2.5.

4.0 CONCLUSION

Batch experiments with Gompertz and Monod models are powerful tools in study the startup period in biogas production for palm oil mill effluent. If saved time and gave a corrected prediction of steady state performance of the biogas plant both qualitatively and quantitatively although this will need more elaborated verification.

Acknowledgement

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