

Modeling Lab-sized Anaerobic Fluidized Bed Reactor (AFBR) for Palm Oil Mill Effluent (POME) treatment: from Batch to Continuous Reactors

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Abstract. Indonesia is aiming to produce 30 million tones/year of crude palm oil (CPO) by 2020. As a result, 90 million tones/year of POME will be produced. POME is highly polluting wastewater which may cause severe environmental problem due to its high chemical oxygen demand (COD) and biochemical oxygen demand (BOD). Due to the limitation of open pond treatment, the use of AFBR has been considered as a potential technology to treat POME. This study aims to develop mathematical models of lab-sized Anaerobic Fluidized Bed Reactor (AFBR) in batch and continuous processes. In addition, the AFBR also utilized natural zeolite as an immobilized media for microbes. To initiate the biomass growth, biodiesel waste has been used as an inoculum. In the first part of this study, a batch AFBR was operated to evaluate the COD, VFA, and CH₄ concentrations. By comparing the batch results with and without zeolite, it showed that the addition of 17 g/gSCOD zeolite gave larger COD decrease within 20 days of operation. In order to elucidate the mechanism, parameter estimations of 12 kinetic parameters were proposed to describe the batch reactor performance. The model in general could describe the batch experimental data well. In the second part of this study, the kinetic parameters obtained from batch reactor were used to simulate the performance of double column AFBR where the acidogenic and methanogenic biomass were separated. The simulation showed that a relatively long residence time (Hydraulic Residence Time, HRT) was required to treat POME using the proposed double column AFBR. Sensitivity analyses was conducted and revealed that μ_{m1} appeared to be the most sensitive parameter to reduce the HRT of double column AFBR.

Keywords: POME; AFBR; natural zeolite; modeling; batch reactor; continuous reactor; COD; VFA; CH₄

1. Introduction

Indonesia is aiming to produce 30 million tons of bulk palm oil (crude palm oil / CPO) per year by 2020. As a result, it is estimated that the amount of liquid waste namely palm oil mill effluent (POME) from all palm oil mills in Indonesia is expected to be as much as 90 million tons of POME per year. By utilizing appropriate technology, there is a huge potential energy from that amount of POME which may generate 900,000 tons of methane, which is equivalent to 1.3 million kilo liters of diesel oil, equivalent to 5 million MWh of electricity, and the power plant capacity (gas engine) 660 MW [1].

The current conventional practice of POME treatment is conducted using open pond system (lagoon). The pond system is simple and inexpensive, however it requires a large area and the amount of methane release could be enormous which resulted on large greenhouse gas



emissions from the lagoons. According to Hanum [2], anaerobic treatment requires approximately 7 hectares of land for typical palm oil mill with a capacity of 30 tons of fresh fruit bunches (FFB)/hour. In addition, the lagoon treatment requires a long residence time, i.e. about 120 to 140 days. Although the current price of land in the surrounding area of palm oil mills and palm oil plantations is still considerably affordable, several palm oil mills are located near the outskirts of cities and far from plantations with high land price. Apparently, this would be the future trend in palm oil business. As a result, there is a need to develop new technology to process POME with low residence time.

Bioreactor process design requires at least three essential factors, namely: thermodynamics, kinetics of microbial growth, and transfer phenomena [3]. The process of acquiring parameters for kinetic growth is typically conducted on a small scale batch reactor. The kinetic parameters obtained from batch experiments will be very useful if one would like to increase the production capacity from batch to continuous operation.

In the bioprocess, the shift of operating conditions from batch to continuous operation certainly presents different characteristics. In terms of the availability of the substrate, batch process gives substrate concentrations change over the time and this allows the batch reactor to reach the lowest substrate concentration. As a result, the growing rate of microorganisms decelerates along with the reduced substrate or can even reach dead phase. Unlike batch reactor, continuous reactors maintain the availability of substrate concentration within the range of certain values that tends to be stable because there is always inlet feed substrate within the range of certain COD and VFA concentrations. Thus, the growth of microorganisms are more stable and more productive in terms of biogas production. However, various technical problems are often encountered during continuous operation such as infections and unwanted mutations of microorganisms [3].

The use of Anaerobic Fluidized Bed Reactors to treat POME has been investigated intensively in our group [4, 5, 6, 7]. The conversion of POME to methane follows two reaction steps as illustrated in Figure 1.

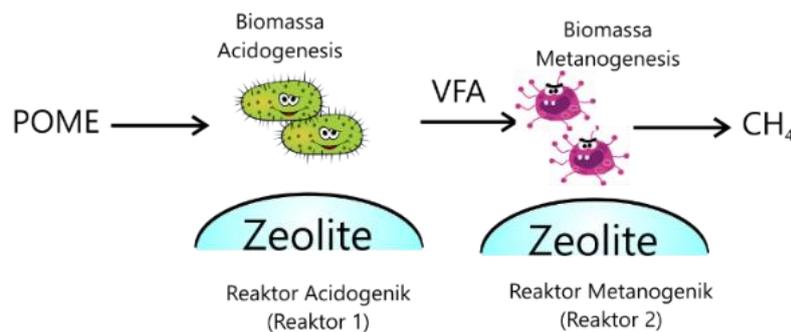


Figure 1 A simplified mechanism of POME conversion into methane

In batch operation, acidogenic and methanogenic microorganisms are present in the same reactor. During continuous operation, we proposed the use of double-stage AFBR to separate acidogenic and methanogenic microorganisms. In addition, the reactor utilizes natural zeolite from Lampung as an immobilized media for microbes. Zeolite is expected to allow microbes to grow and cover the surface of the zeolite so that the bioreactor may work well to break down POME with certain residence time. The experimental results from batch reactors of POME treatment have been presented in [5] using biodiesel waste as the inoculum (starter).

The aim of this study was to simulate the batch reactor to obtain a number of kinetic parameters which describes the microbial growth. Further, the kinetic parameters which is obtained from the batch reactor were used to assess the performance of double stage AFBR.

2. Experimental and Modeling Methods

2.1. Experimental Methods

The detail of experimental method for batch reactor has been described in [5]. Briefly explained here, batch reactor (2.8 L) was used to process 2 L of POME with an initial value of soluble COD of 8220 mg/L. The amount of COD, VFA, and CH₄ were monitored periodically. The amount of zeolite loading was varied and the experiment results used in the present study was 17 g zeolite/g sCOD. The values of soluble Chemical Oxygen Demand (sCOD) and Volatile Fatty Acid (VFA) concentration were measured according to the Standard Methods for Examination of Water and Wastewater. The pH was measured using a Lutron PH-208 pH meter. The analysis method of the gas volume was performed using gasometer and the amount of methane concentration was analyzed using Gas Chromatography (GC).

2.2. Simulation and parameter estimation of kinetic coefficients for batch reactor

The kinetic microbial growth was predicted using Contois equation in accordance with [7]. The mass balance of biomass and substrate are presented [8]:

$$\frac{dX_1}{dt} = \frac{\mu_{m1} \cdot C_{sCOD} \cdot X_1}{K_{SX1} \cdot X_1 + C_{sCOD}} - k_{d1} \cdot X_1 \quad (1)$$

$$\frac{dX_2}{dt} = \frac{\mu_{m2} \cdot C_{VFA} \cdot X_2}{K_{SX1} \cdot X_2 + C_{VFA}} - k_{d2} \cdot X_2 \quad (2)$$

$$\frac{dC_{sCOD}}{dt} = -\frac{1}{Y_{X1/sCOD}} \cdot \frac{dX_1}{dt} - m_{s,X1} \cdot X_1 \quad (3)$$

$$\frac{dC_{VFA}}{dt} = Y_{VFA/X1} \cdot \frac{dX_1}{dt} - \frac{1}{Y_{X2/VFA}} \cdot \frac{dX_2}{dt} - m_{s,X2} \cdot X_2 \quad (4)$$

$$\frac{dC_{CH_4}}{dt} = Y_{CH_4/X2} \cdot \frac{dX_2}{dt} \quad (5)$$

Simulations of batch reactor were conducted by solving equation (1) to (5) using an ODE15s function in a MATLAB commercial software. For parameter estimation, there were 12 parameters to estimate in equation (1) to (5). These parameters were estimated using a gradient search method in lsqnonlin function in MATLAB. The aim of the optimization process was to minimize the SSE and for this purpose “weighting factors” were introduced to obtain larger sensitivity for a certain parameter. The SSE as well as weighting factor are described in equation (6) and (7).

$$SSE = \sum (w_{C,i} \cdot \sum ([C_i]_{exp} - [C_i]_{calc}))^2 \quad (6)$$

$$w_{C,i} = \frac{1}{[C_i]_{exp, max}} \quad (7)$$

2.3. Simulation of Double-Stage AFBR

Simulation of Double-Stage AFBR was conducted by steady state simulation of well-mixed reactors.

a. For acidogenic reactor, the equations used to conduct simulations are:

$$0 = \frac{X_{1,in} - X_{1,out}}{\theta_1} + \frac{\mu_{m1} \cdot C_{sCOD} \cdot X_1}{K_{SX1} \cdot X_1 + C_{sCOD}} - k_{d1} \cdot X_1 \quad (8)$$

$$0 = \frac{C_{sCOD1,in} - C_{sCOD1,out}}{\theta_1} - \frac{1}{Y_{X1/sCOD}} \cdot \frac{\mu_{m1} \cdot C_{sCOD} \cdot X_1}{K_{SX1} \cdot X_1 + C_{sCOD}} - m_{s,X1} \cdot X_1 \quad (9)$$

$$0 = \frac{C_{VFA1,in} - C_{VFA1,out}}{\theta_1} + Y_{VFA/X1} \cdot \frac{\mu_{m1} \cdot C_{sCOD} \cdot X_1}{K_{SX1} \cdot X_1 + C_{sCOD}} \quad (10)$$

b. Similarly, for methanogenic reactor, the following equations are used:

$$0 = \frac{X_{2,in} - X_{2,out}}{\theta_2} + \frac{\mu_{m2} \cdot C_{VFA} \cdot X_2}{K_{SX1} \cdot X_2 + C_{VFA}} - k_{d2} \cdot X_2 \quad (11)$$

$$0 = \frac{C_{VFA1,out} - C_{VFA2,out}}{\theta_2} - \frac{1}{Y_{X2/VFA}} \cdot \frac{\mu_{m2} \cdot C_{VFA} \cdot X_2}{K_{SX1} \cdot X_2 + C_{VFA}} - m_{s,X2} \cdot X_2 \quad (12)$$

$$0 = \frac{0 - C_{CH_4,out}}{\theta_2} + Y_{CH_4/X2} \cdot \frac{\mu_{m2} \cdot C_{VFA} \cdot X_2}{K_{SX1} \cdot X_2 + C_{VFA}} \quad (13)$$

Simulations of equation (8) to (13) were conducted using fsolve function in MATLAB. Sensitivity analyses were conducted by substituting each parameter while keeping other parameters constant.

3. Results and Discussion

3.1. Simulation of Batch AFBR

Figure 2 shows the results of experiments and simulations of batch reactor in the presence and absence of zeolite. As time increases, it can be seen that generally the value of soluble COD decreases. In addition, the value of VFA (indicator of intermediate products) tends to decrease rather slowly as a function of time. Observation of methane accumulation, as an indicator of biogas formation, indicates that biogas production increased rapidly during the first 20 days before reaching a relatively stable values until the end of the experiment.

The results from experiments without zeolite (control) showed that after 21 days, a decrease of COD from 8220 to 995 mg/L can be observed or equivalent to the value of 88% COD removal. To study the effect of zeolite, addition of 17 g zeolite/g sCOD has been conducted. It could be seen that by adding 17 g zeolite/g sCOD, a larger drop of COD could be observed after 21 days where the value of COD dropped from 8220 to 615 mg/L, which is equivalent to 92% COD removal. Thus, the effect of adding zeolite is generally positive with respect to COD reduction over a span of 21 days.

Formation of VFA as a result of COD conversion into biogas is also presented in Figure 2. It appears that the dynamics of VFA is similar between the control condition and the 17 g/g sCOD. There was an increase during the first 10 days which was followed by a constant decline until the end of the experiment.

With the aid of methanogenic microorganisms, the conversion of organic matters in POME resulted in the production of methane gas. As seen in the third panel of Figure 2, methane production appeared to show the same characteristics with the presence and absence of zeolite. During the first 40 days, the concentration of methane increased steadily until it reached values ranging between 400-500 ml/gSCOD.

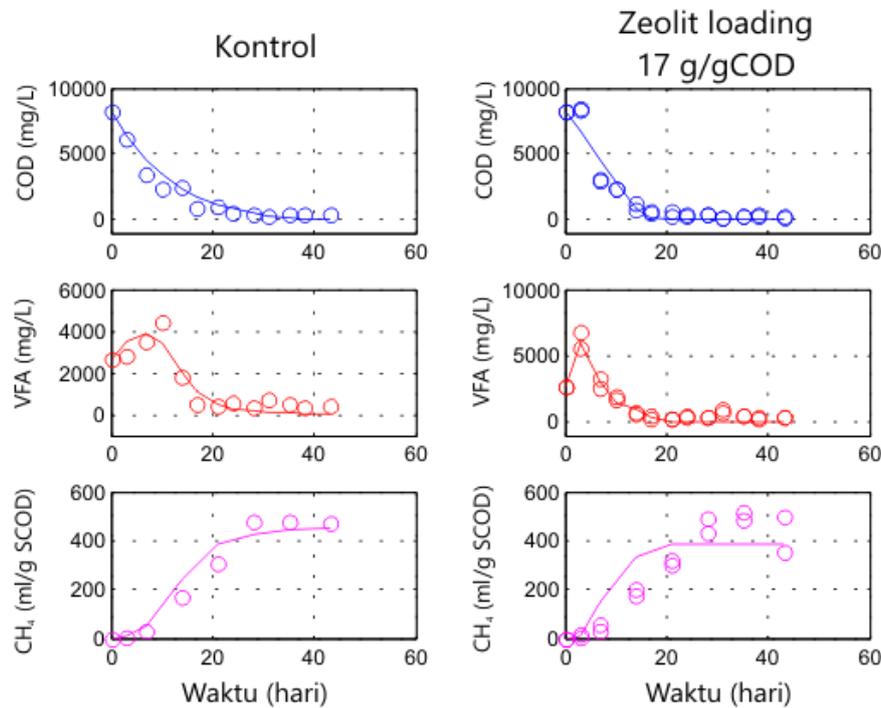


Figure 2. Simulation of batch reactor (sCOD, VFA, and CH_4 concentrations) as a function of *zeolite loading* with inoculum of biodiesel waste. Experimental data is denoted as (o) and simulation (—).

The results of parameter estimations from batch reactor with biodiesel waste inoculum are presented in Table 1. The simulation results (Figure 1) generally show that the proposed model can explain the experiment results quite well. Based on the fitted parameters, the trend of parameters which are consistent with the decrease of COD along with increasing zeolite loading is μ_{m1} , μ_{m2} and $Y_{\text{VFA}/X1}$, $Y_{X2/\text{VFA}}$, and k_{d1} . Thus, these parameters can be used as indicators to enhance batch reactor performance although it is not trivial to understand their complex and simultaneous effects together.

Table 1 Result of parameter estimations from batch reactor with biodiesel waste as inoculum

Kinetic Parameters	control	17 g/gCOD
μ_{m1}	0.96867	1.3004
K_{SX1}	5.5449	4.6403
K_{SX2}	2.7683	1.3495
μ_{m2}	0.9614	1.0644
$Y_{CH4/X2}$	0.11728	0.02523
$Y_{VFA/X1}$	9.6437	23.464
$Y_{X1/sCOD}$	0.086438	0.16664
$Y_{X2/VFA}$	0.56066	0.64129
k_{d1}	1.0207	1.224
k_{d2}	0.59802	0.000296
$m_{s.X1}$	6.2736	3.7196
$m_{s.X2}$	0.009475	3.31E-11

3.2. Simulation of Double-Stage AFBR

Simulation of double-column AFBR is conducted by solving equation (8) to (13). Figure 3 gives the results of steady-state COD, VFA and CH₄ as a function of residence time in reactor 1 and reactor 2 of Double-Column AFBR. Figure (3) shows the simulation results obtained from kinetic parameters using biodiesel waste as inoculum and zeolite loading of 17 g/ g sCOD.

The main target of double-stage AFBR simulation is to obtain high COD removal rate with short residence time. The simulations showed that in order to achieve COD removal as much as 75%, the required residence time is still relatively high, i.e ca. 28 days.

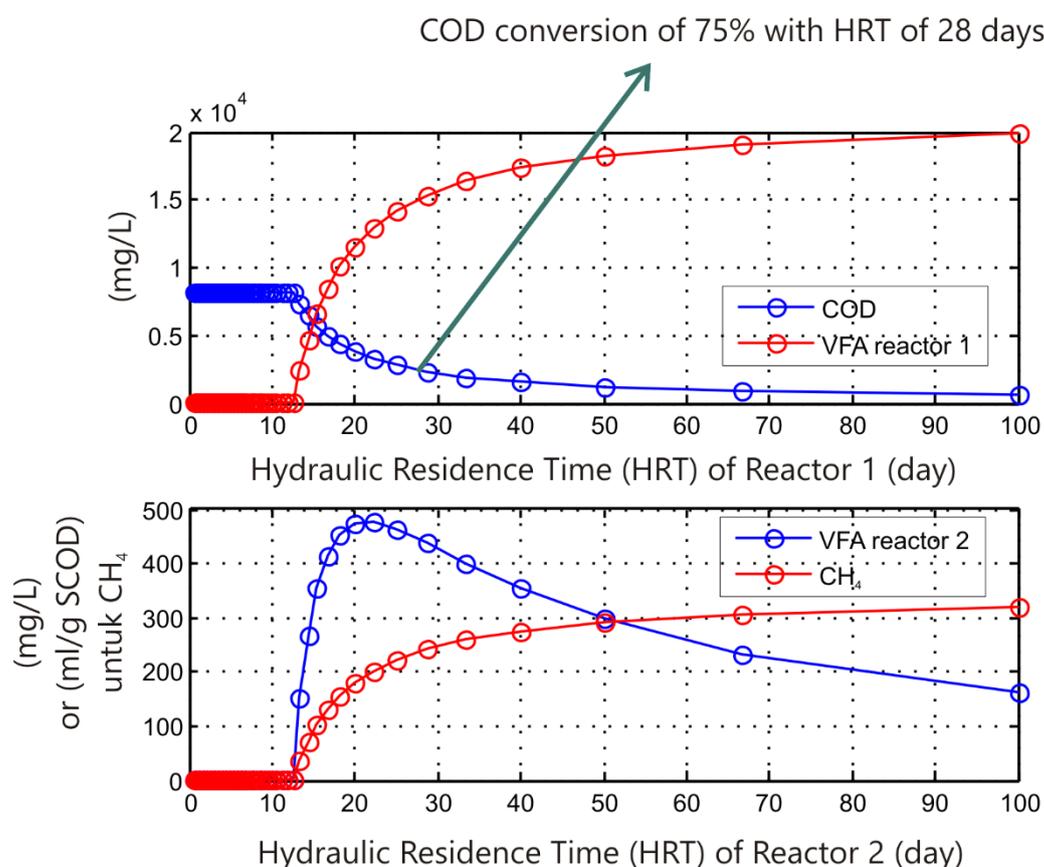


Figure 3. Simulation of Double-Stage AFBR. Operating conditions: biodiesel waste as inoculum and zeolite loading of 17 g zeolite/g sCOD.

3.3 Sensitivity Analyses of Double Stage AFBR simulations

Based on the results that we obtained from Figure 3, further analysis such as sensitivity analyses of kinetic parameters on the performance of Double-Column AFBR have been conducted. The sensitivity analysis was performed by changing one parameter value by keeping the values of other parameters constant in base case. The result showed that μ_{m1} appears to be the most sensitive parameter. By changing the value of μ_{m1} to 3 times greater ($3 \cdot \mu_{m1, \text{base case}}$), 75% conversion of COD removal could be obtained with a residence time \approx 1 day. Other parameters appear to be less sensitive and give more or less similar results as displayed in Figure 3.

4. Conclusions

Mathematical models to simulate batch and double-stage AFBR have been proposed in the present study. Several conclusions can be withdrawn from the present work:

- The experiment results from batch reactor using biodiesel waste as the inoculum showed that the addition of zeolite gave a positive impact i.e. higher COD removal than the control condition (without addition of zeolite).
- The modeling of batch reactor with 12 kinetic parameters appears to be sufficiently well to explain the experiment data. Parameters μ_{m1} , μ_{m2} and $Y_{VFA/X1}$, $Y_{X2/VFA}$ and k_{d1} appears to increase with higher zeolite loading, in which h resulted in higher COD removal rate. Thus, these parameters can be used as indicators to enhance batch reactor performance although it is not trivial to understand their complex and simultaneous effects together.
- The result from the simulation of Double-Stage AFBR showed that the required residence time for high COD removal remains high (ca. 28 days). Sensitivity analysis showed that the increase of μ_{m1} to 3 times greater than the reference value gave a dramatic impact where 75% of COD removal could be obtained in ≈ 1 day.

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List of symbols:

sCOD	soluble chemical oxygen demand (mg/L)
VFA	volatile fatty acid (as acetic acid) concentration (mg/L)
CH ₄	methane concentration in the liquid (mg/L)
X ₁	acidogenic cell concentration (mg/L)
X ₂	methanogenic cell concentration (mg/L)
μ_{m1}	maximum specific growth rate of acidogenic cell (day ⁻¹)
μ_{m2}	maximum specific growth rate of methanogenic cell (day ⁻¹)
KSX ₁	half-saturation constant associated with sCOD (mg sCOD/mg acidogenic cell)
KSX ₂	half-saturation constant associated with VFA (mg VFA/mg methanogenic cell)
Y _{X1/COD}	yield of cell formation per mg sCOD reduction (mg acidogenic cell/mg sCOD)
Y _{X2/VFA}	yield of cell formation per mg VFA reduction (mg methanogenic cell/mg VFA)
Y _{CH₄/X₂}	yield of CH ₄ formation per mg methanogenic cell/L increase (mg CH ₄ /L)/[mg methanogenic cell/L]
Y _{VFA/X1}	yield of VFA formation per mg acidogenic cell (mg VFA/mg acidogenic cell)
kd ₁	death rate constant of acidogenic cell
kd ₂	death rate constant of methanogenic cell
θ	hydraulic retention time (HRT)

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