# INVESTIGATION OF STABILITY OF ANAEROBIC DIGESTION OF FOOD WASTE IN A PLUG FLOW REACTOR USING MATHEMATICAL MODELING AND SIMULATION

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## ABSTRACT

Anaerobic treatment has gained wide acceptance as a sustainable technology for treatment of solid wastes and waste water. Recently, novel plug flow reactor system has been installed at few local institutions to treat semi solid wastes with improved efficiency. However lack of understanding of operational parameters and functional units of this reactor system has led to suboptimal operation and thereby low gas production and methane yield. In this study, plug flow anaerobic reactor is modeled using two modeling scenarios. For this task, Anaerobic Digestion Model No.1 (ADM1) implemented in the simulation software package called AQUASIM 2.1f is used. Under first scenario, advective diffusive reactor compartment followed by two continuous stirred tank reactors for collection of slurry and gas was used to model the plug flow reactor. Under second scenario, series of CSTR reactors were used to model plug flow reactor and biogas was collected into a common head space via diffusive link. Simulation was performed for the different hydraulic retention times and feed flow rates for the substrate of food waste. Simulation results from advective-diffusive reactor model revealed that accumulation of gasses in the slurry causes an inhibition in methane production. In series of CSTR model, when the food waste alone was used at low hydraulic retention times, pH decreases drastically and causes to process inhibition in the first reactor. This inhibition propagates towards the other connected CSTR reactors and after a certain periods of time total methane production ceases.

***Keywords***: Anaerobic digestion, ADM No.1, Mathematical modeling, food waste

## 1. INTRODUCTION

Anaerobic treatment has gained wide acceptance as a sustainable technology in treatment of solid wastes and wastewater [1]. Anaerobic digestion (AD) provides an ultimate solution for the disposal of biodegradable solid wastes while producing a valuable renewable energy source of biogas. Due to its determinate energy value and ease of storage, biogas is arguably a more versatile renewable energy source [2]. It can be used directly for heating and electricity generation, and as substitute for fossil fuel applications, e.g. transport fuel [3].

The digester performance is highly depends on the reactor configuration. Currently different reactor configurations are used to treat solid waste anaerobically. Small scale PFR has received greater attention due to high efficient over biogas production and good stability [4]. The evolution of plug flow reactors used in AD has several aspects. According to studies by Cuzin et.al [5], Cassava peel can be digested in a tubular digester in which the piston flow shows a progressive elimination of intermediate acid compounds during substrate transit and prevent drastic acidification. The Taiwanese - Model digester is simple and has an ability to withstand fluctuation in influent wastewater quality. The reactor has been built using tubular polyethylene bag, PVC piping and plastic housing to transport the biogas generated from the digester [4]. An inclined plug flow reactor was tested for the semi-solids of fruit and vegetables. With the objective of energy recovery the reactor can be operated with shorter retention times [6]. ABR is an Anaerobic Baffle Reactor in which baffles had been placed inside in order to make separate chambers within the reactor [7].

This study mainly focuses on dynamic mathematical modeling of anaerobic digestion of food waste in plug flow reactor. Previous studies had shown that anaerobic digestion of food waste is vulnerable to inhibition due to the accumulation of volatile fatty acids (VFA) and irreversible decrease of pH [8]. Major objective of this study is to study the stability of plug flow anaerobic reactor by varying hydraulic retention time (HRT). Stability is evaluated in terms of bulk liquid pH, volatile fatty acids (VFA) and total biogas production rate. Mathematical modeling is carried out considering two basic plug flow reactor configurations. Under first reactor configuration, an advective diffusive reactor was considered to model the plug flow reactor and in the other reactor configuration, series of CSTRs were approximated as a plug flow reactor. The Anaerobic digestion model No. 1 (ADM No.1) [9] was implemented in reactor compartments of AQUASIM 2.1f.

## 2. METHODOLOGY

In this study, the modeling of plug flow reactor is carried out according to two scenarios. In each scenario the effluent is fed continuously in to the reactor systems.

### 2.1. Advective- Diffusive Reactor Model

In the first method, modeling and simulation were carried out by considering the plug flow reactor as an advective diffusive reactor. A schematic of reactor arrangement is shown in Figure 1.

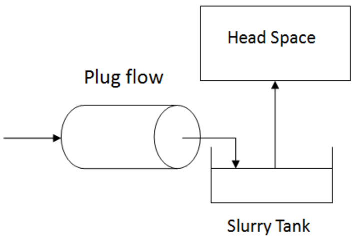


**Figure 1: Schematic model of advective diffusive reactor with slurry collection tank and gas collection tank**

Slurry that is coming out from the plug flow reactor is collected in to a slurry tank. Reason is that advective diffusive reactor compartment in the Aquasim 2.1f simulator does not allow lateral gas transfer along the length of the reactor. The slurry tank itself is a CSTR type reactor and no anaerobic digestion take place in it. A head space was defined in order to collect gas which is released from the slurry tank and these two compartments are connected via a diffusive link. All the gasses formed inside the plug flow reactor is in a dissolved form in slurry.

**Table 1: Input characteristics of the feed**

| Particulate Substrate | Concentration ($kgCOD/m^3$) |
|---|---|
| Carbohydrates | 5.78 |
| Proteins | 2.29 |
| Lipids | 1.10 |

In this model the reactor volume is 40 $m^3$. Volume of slurry tank is 40 $m^3$ while head space volume is 10 $m^3$. The input concentrations of the substrates shown in the Table 1 are used in model. Simulation was performed under five scenarios in which the input flow rate was varied as shown in the Table 2.

**Table 2: Input flow rates and hydraulic retention times**

| Scenario | Feed Rate($m^3$/d) | Retention time (days) |
|---|---|---|
| 1 | 0.67 | 60 |
| 2 | 0.33 | 120 |
| 3 | 0.17 | 240 |
| 4 | 0.11 | 360 |
| 5 | 0.08 | 480 |

### 2.2. CSTRs in Series Model

In this model, ten CSTRs were connected (Figure 2) in series to represent the plug flow reactor.

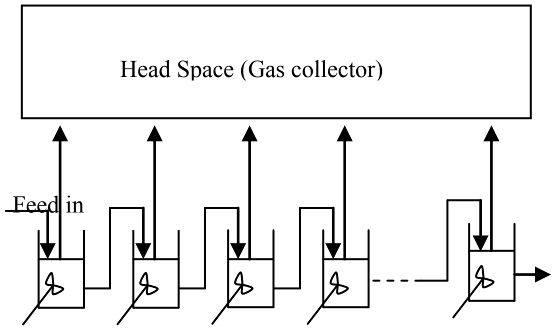


**Figure 2: Schematic model of CSTR in series reactor arrangement (n=10)**

Model consists of one common headspace that all reactors are connected with diffusive links to transfer biogas. The bulk liquid volume of each CSTR is 4 $m^3$ and the headspace is volume of 10 $m^3$. Same input conditions (Table 1) and feed rates (Table 2) were used for the simulation.

### 2.3 Model Parameters

For the model development, estimated optimum hydrolysis parameters for carbohydrates, lipids and proteins were obtained from previous study [10].

## 3. RESULTS AND DISCUSSION

### 3.1. Simulation Results from Advective – Diffusive Reactor Model

#### 3.1.1. Biogas production

Biogas production rate was determined by varying the substrate feed rates in to the reactor system. As shown in Figure 3, high biogas production rate can be observed under 60 days of reactor HRT. Rate of biogas production reduced with the increase of reactor HRT and minimum at 480 days.

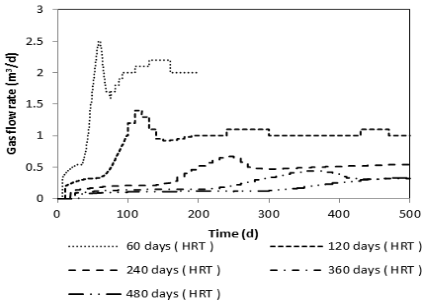


**Figure 3: Variation of biogas production rate in PFR under varying feed rates**

With the increase of input flow rates, more slurry enters to slurry tank with dissolve gases which enhanced the rate of biogas transfer into the headspace. Biogas production rate continued to decrease with reduction of feed rate.

#### 3.1.2. Biogas Composition

Biogas composition was investigated at the headspace under different feed conditions. Methane composition decreases from the beginning of the reactor operation and it rapidly decreases after time reach the reactor retention time (HRT) of the reactor. At the same time compositions of both carbon dioxide and hydrogen start to increase.

#### 3.1.3. Variation of TVFA and pH along the Advective – Diffusive Reactor Model

Variation of TVFA and pH were studied under different feed conditions. Figure 4 shows the variation of TVFA at the reactor front. Accordingly, a high rate of formation observed at 60 days of HRT. Due to high feed rate at the reactor front, time was not adequate to reach TVFA into a higher concentration. Low feed rates have high rate of formation of TVFA and given enough time to form TVFA at reactor front. Consequently maximum TVFA concentration observed at reactor retention time of 480 days

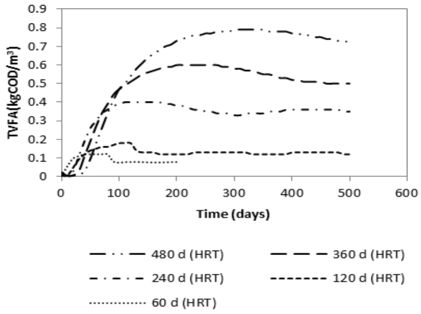


**Figure 4: Total VFA variation at the front of the reactor**

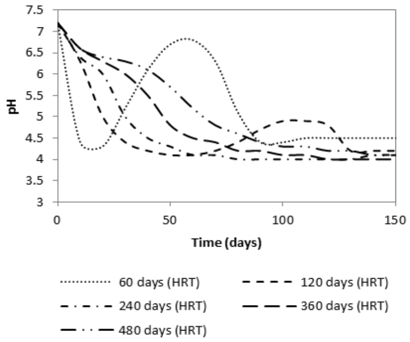


**Figure 5: pH variation of the plug flow reactor at front**

Figure 5 shows the variation of pH at the reactor front under different HRTs. At lower HRT, a rapid reduction of pH is observed at the reactor front owing to high production rate of TVFA. The reason is high organic loading rates and high rate of fermentation process. According to different conversion steps of AD process, fermentation rate is faster than methenogenesis rate. The pH variation gradually decreased with increase of reactor HRT and became steady state. At higher HRT, OLR is lower and amount of VFA produced is lower. This is reflected in pH variation under different HRTs.

Simulated results of biogas composition under different feed conditions show a gradual reduction of methane while increasing the carbon dioxide composition of biogas in headspace. This observation reveals a fact that the anaerobic digestion process gets inhibited within the plug flow reactor under each simulated conditions in Advective – Diffusive reactor model.

### 3.2. Simulation Results of CSTRs in Series Reactor Model

#### 3.2.1. Biogas Production and pH Variation

The rates of biogas production increase with the increase of retention times in reactors. Variation of pH was investigated at the 1st reactor of the CSTR series. pH reduction was very high under low reactor retention time.

#### 3.2.3. Biogas Composition

Biogas composition was investigated at the headspace under different feed conditions. Variation of methane and carbon dioxide compositions were not very high throughout the reactor operations. Reactor series with 480 days of HRT, the $CH_4$ percentage drops rapidly until it comes to a value of 60 %. Meanwhile the $CO_2$ percentage increases until 35 % and this continues for 25 days. After 25 days the mole percentage of $CH_4$ starts to increase gradually and subsequently $CO_2$ percentage decreases.

## 4. CONCLUSIONS

Advective – Diffusive model shows some deviation from the behavior of actual plug flow reactor. In actual plug flow anaerobic digesters, the liquid and gas get separated within the reactor and there is a continuous transfer of gases form liquid phase to gas phase with reactor length. This characteristic doesn't exist in an advective diffusive reactor compartment in AQUASIM 2.1f. As a result, produced methane in a dissolve state in reactor slurry and doesn't transfer to a gaseous phase until it leaves the PFR. Consequently this led an accumulation of VFA. In scenario 1, Due to the accumulation of Volatile fatty acids and reactor pH dropped. Drop of pH resulted in inhibition of the anaerobic digestion process and inhibition observed in all retention times of the reactor simulations. Immense decrease of pH reported at the reactor front at low HRT values. In second scenario, methane production increases with increase of reactor HRT and maximum rate was at 480 days of HRT. pH drop observed at first reactor under all feed conditions. It resulted in inhibition of the anaerobic digestion process. Sudden pH drop observed at first CSTR reactor under low reactor HRT. Compared with the Advective – Diffusive reactor model, CSTR model gave acceptable results equivalent to an actual PFR. Accordingly CSTR in series model is an acceptable approximation of representing the behavior of actual plug flow reactor.

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