Iranian (Iranica) Journal of Energy and Environment 12(3): 209-219, 2021

Iranian (Iranica) Journal of Energy & Environment
Journal Homepage: www.ijee.net
IJEE an official peer review journal of Babol Noshirvani University of Technology, ISSN:2079-2115

The Effect of Mixing Rate on Performance of Anaerobic Reactor in Methane Production

M. E. Kashfi[1], R. Kouhikamali[1], G. Khayati[2]*

[1] *Department of Mechanical Engineering, Faculty of Mechanical Engineering, University of Guilan, Rasht, Iran*
[2] *Department of Chemical Engineering, Faculty of Engineering, University of Guilan, Rasht, Iran*

P A P E R I N F O

Paper history:
Received 11 May 2021
Accepted in revised form 06 August 2021

Keywords:
Anaerobic digestion
Mathematical model
Methane production
Mixing rate
Wastewater treatment

A B S T R A C T

In this study, a mathematical model was used to predict the dynamic behaviour of the system under conditions of imperfect mixing in an Anaerobic Digestion (AD) process. To evaluate the system performance, the effect of mixing parameters by calculating the quantities of methane gas produced, system power, and effluent quality was investigated. Numerical results showed that with an increase in the mixing rate (α) by 20%, methane production rate, power production, and the effluent COD removal efficiency of the system increased by 19%, 19% and 12%, respectively. At an equal mixing rate, the amount of methane produced in influent with a concentration of 12.1% was 4.5 times higher than the influent with a concentration of 2.5%, while no significant change was observed in the effluent quality. Additionally, it was found that the mixing rate effect is more important than the mean cell retention time in the anaerobic reactor. The best fitted correlations for methane production rate and effluent COD removal efficiency using regression analogy at different organic loads of wastewater are presented.

***doi**: 10.5829/ijee.2021.12.03.05*

NOMENCLATURE

Latin letters			
A	Volatile acids concentration (g COD.dm^{-3})	K_s^A	Half-velocity coefficient for acidogenesis (g COD.dm^{-3})
b^A	Decay coefficient for acid-formers (day^{-1})	M	Methane concentration (g COD dm^{-3})
b^M	Decay coefficient for methanogens (day^{-1})	P	Degradable particulate COD concentration (g.dm^{-3})
COD	Chemical oxygen demand (g.dm^{-3})	Q	Volumetric flow rate (dm^3.day^{-1})
f_d	Net biodegradable fraction of active biomass (dimensionless)	R	Reaction rate (g.dm^{-3}.day^{-1})
K^A	Maximum specific substrate utilization rate for acid-formers (g COD utilized g^{-1} COD biomass day^{-1})	S	Soluble substrate COD concentration (g.dm^{-3})
K^M	Maximum specific substrate utilization rate for methanogens (g COD utilized g^{-1} COD biomass day^{-1})	t	Time (day)
K_c^M	Half-velocity coefficient for methanogens (g COD.dm^{-3})	V	Working volume of reactor (dm^3)
k_d	Activated-sludge cell death rate coefficient (day^{-1})	X	Microorganism concentration (g COD.dm^{-3})
$k_{Diffusion}$	Soluble BOD diffusion rate coefficient (day^{-1})	X_a^A	Active acidogenic microorganism concentration (g COD.dm^{-3})
k_h	Hydrolysis rate coefficient (day^{-1})	X_a^{AS}	Viable activated-sludge biomass COD concentration (g.dm^{-3})
$k_{E.H.}$	Extracellular hydrolysis rate coefficient (day^{-1})	X_v^M	Total methanogenic biomass (g.dm^{-3})
$k_{I.H.}$	Intracellular hydrolysis rate coefficient (day^{-1})	Y^A	Yield coefficient for acid-formers (g COD biomass g^{-1} COD utilized)
		Y^M	Yield coefficient for methanogens (g COD biomass g^{-1} COD utilized)
Greek symbols		**Subscripts**	
α	Ratio of the volume in the flow-through region to the total reactor volume (dimensionless)	$exch$	Exchange between zones

*Corresponding Author Email: *khayati@guilan.ac.ir* (G. Khayati)

Please cite this article as: M. E. Kashfi, R. Kouhikamali, G. Khayati, 2021. The Effect of Mixing Rate on Performance of Anaerobic Reactor in Methane Production, Iranian (Iranica) Journal of Energy and Environment, 12(3), pp. 209-219. Doi: 10.5829/ijee.2021.12.03.05

$(1-\alpha)$	Relative volume of the retention region (dimensionless)
γ	Cell soluble degradable COD immediately released (dimensionless)
Superscripts	
A	Acidogenic phase
AS	Activated sludge
M	Methanogenic phase
i	Initial conditions
0	Influent
1	Flow-through region
2	Retention region
Abbreviation	
FNU	Formazin Nephelometric Unit

INTRODUCTION

Today, most countries, especially the developing countries pay special attention to access to clean and cheap energy resources. The rapid growth of urban population with an increase in industrial activities has led to increase in energy consumption and also an increase in waste production. This can cause severe health and environmental problems, especially in metropolitan areas, which, if not properly managed, can lead to major crises in the region and the world. The development of renewable energy sources as an efficient solution to the energy crisis [1] is a way to achieve sustainable economic growth by keeping a clean environment and ensuring energy security. Applying renewable energy sources in addition to economic growth also keeps the environment clean and healthy for present and future generations [2].

There are a variety of methods for stabilizing and managing the organic waste and environmental contaminants. One of the most important and growing technologies is anaerobic digestion (AD) process. The AD is a biological process in which biogas is produced from biodegradation organic wastes and, the produced methane has the potential to be used as fuel. The AD technique is widely used in wastewater treatment plants to improve the quality of effluent and stabilization of the sludge produced from wastewater. The efficiency of this technique largely depends on the quality of the mixing process [3]. A good mixing will homogenize the wastewater, make effective use of the reactor volume and increase the transfer of material (substrate) to microbial end products. One of the most efficient and effective methods in the mixing process is the mechanical agitation and mixing for uniform mass transfer [4].

Bello-Mendoza and Sharratt [5] studied the modelling and simulation of anaerobic sludge reactors. They showed that mixing is an essential parameter in biogas production and, changing the mixing rate has a significant effect on the digestion process. Ong et al. [6] used a 10 litre anaerobic reactor containing concentrated cattle-manure slurry to the biogas production. The manure slurry has 8% total solids (TS). They studied the effect of two types of continuous and intermittent mixing. They showed that the biogas production rate in the continuous method is slightly higher than the intermittent method. Karim et al. [7] measured the methane production rate by changing the position of the stirrer in the tanks containing with low concentration slurry (TS=5%). They showed that the displacement of the stirrer in low-organic-load tanks did not have much effect on methane production rate and that the methane production rate was almost the same in all digesters. In an experimental study conducted by Karim et al. [8], which was performed using four laboratory-scale digesters having a working volume of 3.73 L, it was found that the mixing factor increased the biogas production rate compared to the approach without mixing. Syaichurrozi and Sumardiono [9] investigated the effects of different concentrations of Vinase on biogas production rate using anaerobic digestion. The anaerobic digester-laboratory scale is used in this study. The influence of substrate concentration content on the COD removal in the digester was also examined in this research. The results showed that the high level of COD concentration of substrates caused the more of COD removal at anaerobic condition in the digester. Rea [10] conducted an experimental and laboratory study of the process of the AD. In this research, an intermediate kinetic model based on the biogas production rate was proposed. Benali [11] investigated on effect of temperature for biogas production from cow dung in an anaerobic batch digester using mesophilic organism for the bioconversion. He used a batch of 18L bioreactor with 50% dilution for dialy biogas production of 340 mL for duration of 30 days. Prasad Lohani [12] used co-digestion of food wastes along with cow manure in an anaerobic digestion process. In this work more than 90% of waste content were digested and converted to biogas.

Ebrahimi and Najafpour [13] investigated the advantages or disadvantages of various systems of suspended and attached growth on the biochemical activities, while the process in different fabricated systems was provided. The study found that the combination of fluidized and fixed film were more efficient in treatment of industrial wastewater. Shanmugam et al. [14] employed CFD approach on different mixing modes to figure out biogas production yield. The results showed that the biogas production in the mixed digester was higher than the unmixed digester. Zhang et al. [15] examined the effect of different mixing strategies on the AD process of food waste and energy production. They showed that the semi-continuous mixing strategy is more efficient and stable than continuous mixing and without-mixing strategies in term of biogas production rate to provide a net positive heat and electricity output. Kolodynskij et al. [16] studied the efficiency of a semi-continuous three-stage bioreactor and, evaluated the quantitative (biogas yield) parameters of the produced biogas. In this work, homogeneous mixing of the substrate with a modified complex mixer causes to increase the yield of biogas by 42.3%, CH_4 concentration by 14.3% and reduces CO_2 and H_2S concentrations by 25.5% and 45.6%, respectively.

However, studies have shown that most of the reported results regarding the mixing effect on the anaerobic reactor performance are related to small-scale experimental experiments [6–8]; therefore, this study deals with the performance of real digesters in scale-up in terms of methane production, effluent quality, etc., which is considered a strength for the research work. Mathematical modelling has the potential to provide a logical explanation for the relationship between mixing parameters and anaerobic digestion kinetics. It should be noted that biological processes are inherently complex, so it is very difficult to develop mathematical models that indicate the behaviour of real systems [17]. It should also be noted that it is very difficult to achieve complete mixing in real reactors, and imperfect mixing pattern is more common than perfect mixing. In the present study, using the mathematical model presented by Bello-Mendoza and Sharratt [5], which is applicable to real digesters, methane gas production rate, power production and effluent COD removal efficiency were evaluated and analyzed. To achieve these aims, the biochemical nonlinear differential equations of the process and the mass balance equations are solved simultaneously and using numerical methods in different conditions, including; mixing rate (70%, 80% and 90%), wastewater concentration (TS = 2.5, 7.5 and 12.1%), and ($\frac{\tau}{\theta}$=1, 2 and 5) (where τ and θ denote the mean cell retention time and the hydraulic retention time, respectively) are performed by MATLAB software. Then, the values related to methane production rate, power production and effluent COD removal efficiency are calculated. By using linear regressions, the best fitted equations between the methane production and mixing rate and also between the effluent COD removal efficiency and mixing rate, together with the determination coefficients (R^2), at different wastewater concentrations are presented.

MATHEMATICAL MODEL

Considering the complexity of the AD process, its internal processes are simplified. Before describing the governing equations, the problem conditions and the simplifying assumptions are mentioned as follows.

- All variables except microorganism concentrations are expressed on a COD unit basis; in fact, they are expressed as degradable COD.
- The fluid is incompressible, and the system is at a mesophilic temperature of 35°C.
- In Equations (5-9) of Table 1, which refer to microbial growth and activity, the Monod model is used, but the first-order reaction is used for processes such as microbial decay and hydrolysis.
- The produced methane is assumed to be a gaseous single phase, and the interactions between the liquid-gas (bubble) phases, are also neglected.
- Each region of mixing model has a homogeneous situation, and also exchange between two regions is to be limited.

Biochemical reaction equations

In this study, a conceptual approach to the AD process presented by Pavlostathis and Gossett [18] was used in the steady state condition. They prepared and evaluated the comprehensive and developed kinetic model. Their study showed that this model could predict the AD process performance and the quality of the effluent. Figure 1 shows a conceptual model for AD of biological solids. Hence the kinetic equations of the AD process are defined in the form of five processes, including the processes of death and lysis of activated sludge biomass, hydrolysis of total suspended solids, growth and decay of acidogenic and methanogenic biomass, fermentation of soluble substrate, and consumption of volatile fatty acids

Table 1. Kinetic rate expressions of the anaerobic digestion process [5]

Biochemical reaction	Kinetic equation
1. Death and lysis of the viable activated-sludge biomass	$R(f_d X_a^{AS}) = f_d k_d X_a^{AS}$
2. Hydrolysis of death cell particulates	$R(P) = k_h P$
3. Decay of acidogenic biomass	$R(b^A) = b^A X_a^A$
4. Decay of methanogenic biomass	$R(b^M) = b^M X_v^M$
5. Fermentation of soluble substrates	$R(S^A) = \frac{k^A S^A X_a^A}{K_s^A + S^A}$
6. Volatile fatty acids utilisation	$R(A) = \frac{k^M A X_v^M}{K_c^M + A}$
7. Growth of acidogenic biomass	$R(X_a^A) = \frac{Y^A k^A S^A X_a^A}{K_s^A + S^A}$
8. Growth of methanogenic biomass	$R(X_v^M) = \frac{Y^M k^M A X_v^M}{K_c^M + A}$
9. Methane generation	$R(M) = \frac{k^M A X_v^M}{K_c^M + A} - \ldots$ $\ldots \frac{Y^M k^M A X_v^M}{K_c^M + A}$

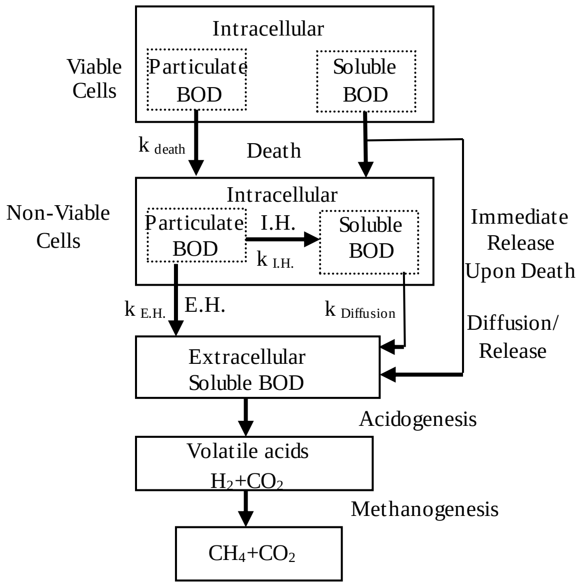


Figure 1. Conceptual model for anaerobic digestion of biological solids; BOD is biochemical oxygen demand (g.dm^{-3}), I.H. is intracellular hydrolysis, E.H. is extracellular hydrolysis [18].

in methane production. The relevant equations are summarized in Table 1. These equations are valid for biological sludge up to COD_{in}=14800 mg/L. The coefficients of the kinetic equations of the AD process are listed in Table 2.

Model of mixing and mass balancing

The mixing process is provided based on suspended-growth anaerobic digestion systems, and this is performed by a stirred anaerobic digester. The mixing model is considered as a two-region model. Figure 2 presents a conceptual representation of the model.

As observed, in this model, which is based on the imperfect mixing approach, the reactor volume is divided into two flow-through (region 1) and retention (region 2) regions. The details of the mass balance equations at the indicated boundaries are presented as follows.

Table 2. Coefficients of kinetic equations of anaerobic digestion process

Parameters	Values	Parameters	Values
Y^M	0.057	b^M	0.015
Y^A	0.2	b^A	0.1
K_c^M	0.045	k_h	0.15
k^M	6.2	k_d	2
K_s^A	0.045	f_d	0.73
k^A	8.0		

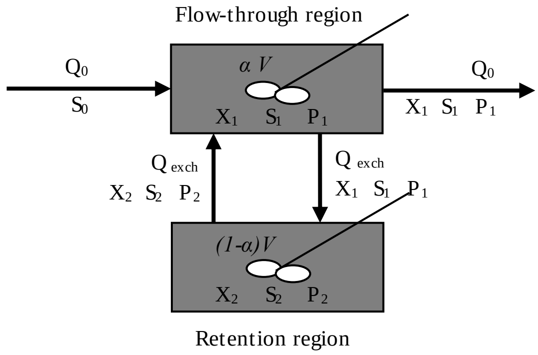


Figure 2. Conceptual representation of a two-region mixing model; α is the mixing rate.

- The mass balance on the degradable portion of viable activated-sludge microorganisms ($f_d X_a^{AS}$) gives:

$$\frac{df_d X_{a1}^{AS}}{dt} = \frac{f_d\left(X_{a0}^{AS}-X_{a1}^{AS}\right)}{\alpha\theta} + \frac{f_d\left(X_{a2}^{AS}-X_{a1}^{AS}\right)}{\alpha\tau} - R\left(f_d X_{a1}^{AS}\right) \quad (1)$$

$$\frac{df_d X_{a2}^{AS}}{dt} = \frac{f_d\left(X_{a1}^{AS}-X_{a2}^{AS}\right)}{(1-\alpha)\tau} - R\left(f_d X_{a2}^{AS}\right) \quad (2)$$

- The mass balance on particulate solids requiring hydrolysis (P) gives:

$$\frac{dP_1}{dt} = \frac{P_0-P_1}{\alpha\theta} + \frac{P_2-P_1}{\alpha\tau} + (1-\gamma)R\left(f_d X_{a1}^{AS}\right) - R\left(P_1\right) \quad (3)$$

$$\frac{dP_2}{dt} = \frac{P_1-P_2}{(1-\alpha)\tau} + (1-\gamma)R\left(f_d X_{a2}^{AS}\right) - R\left(P_2\right) \quad (4)$$

- The mass balance on the soluble substrate for acid-formers (S^A) gives:

$$\frac{dS_1^A}{dt} = \frac{S_0-S_1^A}{\alpha\theta} + \frac{S_2^A-S_1^A}{\alpha\tau} + R(P_1) + \gamma R\left(f_d X_{a1}^{AS}\right) - R\left(S_1^A\right) \quad (5)$$

$$\frac{dS_2^A}{dt} = \frac{S_1^A-S_2^A}{(1-\alpha)\tau} + R(P_2) + \gamma R\left(f_d X_{a2}^{AS}\right) - R\left(S_2^A\right) \quad (6)$$

- The mass balance on the degradable portion of acidogenic biomass (X_a^A) gives:

$$\frac{dX_{a1}^A}{dt} = \frac{X_{a0}^A-X_{a1}^A}{\alpha\theta} + \frac{X_{a2}^A-X_{a1}^A}{\alpha\tau} + R\left(X_{a1}^A\right) - R\left(b_1^A\right) \quad (7)$$

$$\frac{dX_{a2}^A}{dt} = \frac{X_{a1}^A-X_{a2}^A}{(1-\alpha)\tau} + R\left(X_{a2}^A\right) - R\left(b_2^A\right) \quad (8)$$

- The mass balance on volatile fatty acids for methanogens (A) gives:

$$\frac{dA_1}{dt}=\frac{A_0-A_1}{\alpha\theta}+\frac{A_2-A_1}{\alpha\tau}+R\left(S_1^A\right)-R\left(X_{a1}^A\right)+R\left(b_1^A\right)-R\left(A_1\right) \quad (9)$$

$$\frac{dA_2}{dt}=\frac{A_1-A_2}{(1-\alpha)\tau}+R\left(S_2^A\right)-R\left(X_{a2}^A\right)+R\left(b_2^A\right)-R\left(A_2\right) \quad (10)$$

- The mass balance on methanogenic biomass (X_v^M) gives:

$$\frac{dX_{v1}^M}{dt}=\frac{X_{v0}^M-X_{v1}^M}{\alpha\theta}+\frac{X_{v2}^M-X_{v1}^M}{\alpha\tau}+R\left(X_{v1}^M\right)-R\left(b_1^M\right) \quad (11)$$

$$\frac{dX_{v2}^M}{dt}=\frac{X_{v1}^M-X_{v2}^M}{(1-\alpha)\tau}+R\left(X_{v2}^M\right)-R\left(b_2^M\right) \quad (12)$$

- The mass balance on methane (M) gives:

$$\frac{dM_1}{dt}=\frac{M_0-M_1}{\alpha\theta}+\frac{M_2-M_1}{\alpha\tau}+R\left(A_1\right)-R\left(X_{v1}^M\right) \quad (13)$$

$$\frac{dM_2}{dt}=\frac{M_1-M_2}{(1-\alpha)\tau}+R\left(A_2\right)-R\left(X_{v2}^M\right) \quad (14)$$

where $\theta=\frac{V}{Q_0}$ (day) is the hydraulic retention time, $\tau=\frac{V}{Q_{exch}}$ (day) is the mean cell retention time, $\frac{\tau}{\theta}=\frac{Q_0}{Q_{exch}}$ (dimensionless) is the relative interchange rate, and mixing rate denoted by α (dimensionless), is defined as the ratio of the flow through-region volume to the total reactor volume [19].

Numerical solution

In this study, calculating related to the amount of methane gas production rate, power production and effluent COD removal efficiency and also, determining the best fitted equations with acceptable determination coefficients, R^2, between the methane production and mixing rate, and between the effluent quality and mixing rate are the two main objective functions.

To achieve the objectives of the research, numerical solution of the AD process kinetic equations is performed for a reactor with a volume of 1000 litres and a hydraulic retention time of 10 days. The equations show that the methane gas production rate, power production and also effluent COD removal efficiency depend on the factors such as; the mixing rate, the mean cell retention time in the reactor and the influent concentration. Obviously, the system with higher methane production and higher COD removal efficiency has a better performance. Since the relationship between the two parameters of wastewater COD and TS in the system helps to continuously monitor and control the quality of effluent, so it is always taken into account by the researchers; it can be referred to the studies conducted by Bersinger et al. [20] in this field.

Equations (15) and (16) are used to determine the COD value of the influent [21].

$$TSS=1.61\times turbidity-0.93 \quad (15)$$

$$COD_{in}=2.06\times turbidity+37.2 \quad (16)$$

where TSS (mg/L) is the total suspended solids, turbidity (FNU) is a measure of the amount of the TSS in the system.

Table 3 shows the characteristics of the studied wastewater. This table lists the COD_{in} of the wastewater at different TS. To determine the methane production rate in the AD process, the differential equations of Table 1 and the Equations (1–14) are solved simultaneously and numerically. The solution of differential equations is performed using the variable change method and the fourth-fifth order Runge-Kutta algorithm in MATLAB software (version 8.4). The initial conditions of the parameters for starting the calculations and executing the algorithm are presented in Table 4.

The initial concentration of activated sludge biomass is determined by the following equation [18].

$$X_{ai}^{AS}=\frac{DCOD_{in}}{f_d} \quad (17)$$

where D (fraction) = 0.558 is the ultimate digestibility.

The power production is obtained from the methane gas production rate multiplied by the methane calorific value. By using a linear regression, at the end of the hydraulic retention time, the $COD_{methane}$-α function can be obtained (at three TS and $\frac{\tau}{\theta}$=1):

$$COD_{methane}=A\times\alpha(\%)+B\Rightarrow \begin{Bmatrix} A=0.0148, B=0.5178 & R^2=0.9977 \\ for \quad TS=2.5\% & \\ A=0.0398, B=1.3973 & R^2=0.9973 \\ for \quad TS=7.5\% & \\ A=0.0686, B=2.3864 & R^2=0.9967 \\ for \quad TS=12.1\% & \end{Bmatrix} \quad (18)$$

Table 3. Characteristics of the studied wastewater

TS (%)	COD_{in} (mg/L)
2.5	3058
7.5	8426
12.1	14549

Table 4. Initial conditions of the parameters of the kinetic equations

Parameters	M_i	X_{vi}^M	X_{ai}^A	A_i	S_i^A	P_i	X_{ai}^{AS}
Values	0	0.12	0.1	0	0	0	Equation (17)

The effluent COD removal efficiency (or the effluent quality) in the system is defined by the following equation.

$$\eta = \frac{COD_{methane}}{COD_{in}} \times 100 \tag{19}$$

where η (%) is the percentage of the removal of influent COD value in the system.

Also in this case a linear regression between the effluent COD removal efficiency and mixing rate can be observed:

$$\eta = C \times \alpha(\%) + D \Rightarrow \begin{Bmatrix} C = 0.6344, D = 22.105 \quad R^2 = 0.9973 \\ for \quad TS = 2.5\% \\ C = 0.6182, D = 21.701 \quad R^2 = 0.9971 \\ for \quad TS = 7.5\% \\ C = 0.6172, D = 21.433 \quad R^2 = 0.9968 \\ for \quad TS = 12.1\% \end{Bmatrix} \tag{20}$$

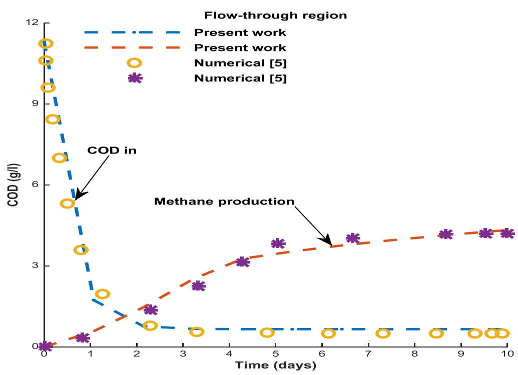
VALIDATION OF NUMERICAL SOLUTION

To validate the numerical solution method, which is performed in the current work, initially, the governing equations in the case which presented by Bello-Mendoza and Sharratt [5] are solved, and the results are compared. This comparison is shown in Figure 3. As observed, there is an acceptable agreement between the obtained results and the numerical data reported by Bello-Mendoza and Sharratt [5].

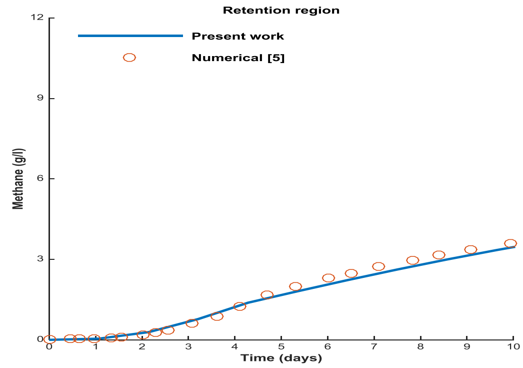
RESULTS AND DISCUSSION

The effect of mixing in the anaerobic digestion process

Mixing is one of the effective factors in the AD process. Given the positive effect of fluid motion on the quality and quantity of methane production in the AD process, mixing systems have higher efficiency than non-mixing systems [22]. According to the mixing model, there are two flow-through and retention regions in the system.



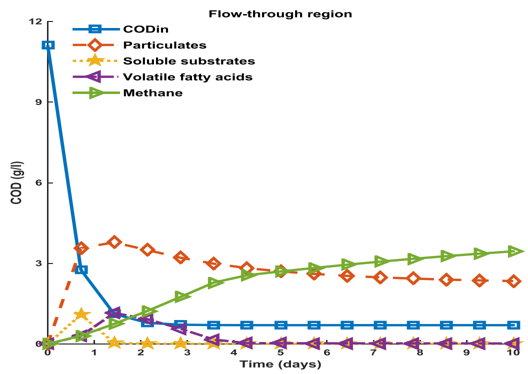
(a)



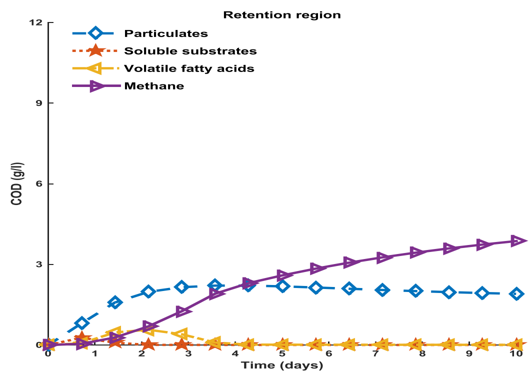
(b)

Figure 3. Validation of the present numerical solution for the (a) Flow-through region, and (b) Retention region

The biomass concentration and methane gas production rate in the flow-through region is higher than the retention region (see Figure 4). The reason for this can be attributed to the effect of mixing rate on fluid homogenization and the provision of favourable conditions for feed transfer to microorganisms. On the other hand, as it is known, the concentration of methane gas in the retention region in the last days of the mean cell retention time is slightly higher than the flow-through



(a)



(b)

Figure 4. The effect of mixing on the influent and biomass concentration of anaerobic digestion, TS = 12.1%, α = 70%, and $\frac{\tau}{\theta}=1$; (a) Flow-through region, and (b) Retention region

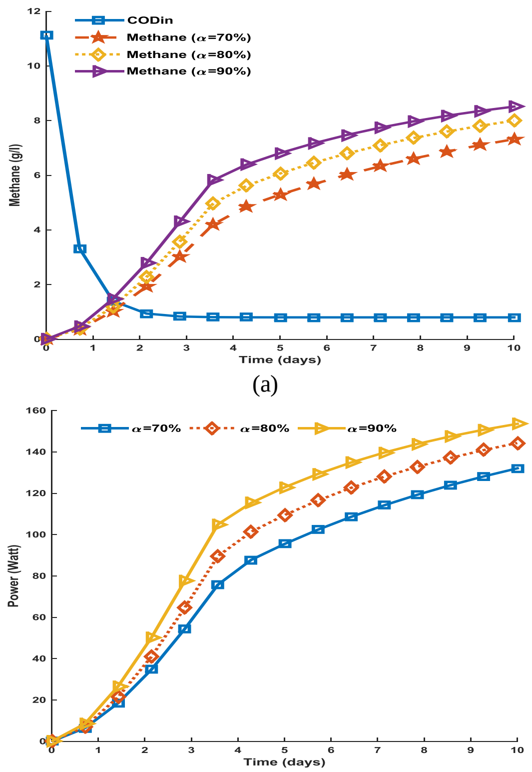
region. Due to the movement of fluid and more exchange of materials, feed consumption by microorganisms in the flow-through region is at a higher rate than the retention region a result, the concentration of methane gas in the first days of the mean cell retention time increases with a steeper slope. Since the feed concentration decreases more rapidly in the flow-through region than in the retention region in the system, therefore, it is predicted that in the last days of the mean cell retention time, the activity of methanogenic and as a result, the production of methane gas in it will be slightly reduced [5]. This trend can be obviously observed in Figure 4.

In the process of the AD, changes in biomass concentration consist of different growth phases, including lag phase, exponential growth phase, stationary phase, and death phase. Substrate concentration also has a decreasing trend [23, 24], which is consistent with the results obtained in Figure 4.

The effect of mixing rate on methane production, power production and effluent COD removal efficiency

The results show that increasing the mixing rate increases methane production and power production of the system (shown in Figure 5). The reasons for this can be attributed to the effect of mixing rate on increasing the contact surface between the suspended organic of the system and increasing the momentum diffusion in the lateral and upper layers of the fluid. Stronger mixing is one of the important factors in fluid homogenization and, causes more efficient use of reactor volume and provides more suitable conditions in biochemical processes [7, 8, 25]. According to the numerical results, increasing the mixing rate by 20% increases methane production and power production of the system by about 19%.

Also, increasing the mixing rate has increased the COD removal of the influent, in other words, has improved the quality of the system effluent (see Figure 6). Based on the obtained numerical results, it is expected that with increasing the mixing rate by 20%, the quality of the system effluent will improve by about 12%.



(b)

Figure 5. Effect of mixing rate on the methane production rate and power production, TS = 12.1%, and $\frac{\tau}{\theta}$=1; (a) Methane production rate, and (b) Power production

The effect of TS concentration in wastewater on methane production rate, power production and effluent COD removal efficiency

One of the effective factors in the mixing process is the TS concentration in the system. The initial biodegradable material concentration has a significant effect on the quality and quantity of the substrate, production of methane and bacterial population of the AD process [24]. There is a direct relationship between the TS concentration and the methane production rate [8]. Note that this result was also reported in literature in different approaches [26, 27].

The results show that the methane production rate and power production are higher in concentrated wastewaters (as shown in Figure 7). The reason for this can be attributed to the direct relationship between the concentration of organic matter in the wastewater and the methane production rate and power production. In other words, at equal mixing rates, the production capacity of methane with a concentration of 12.1% is about 4.5 times higher than the concentration of 2.5%. With increasing TS concentration in wastewater, no significant change in effluent quality was observed. This can be due to the negative effects of increasing osmotic pressure on the

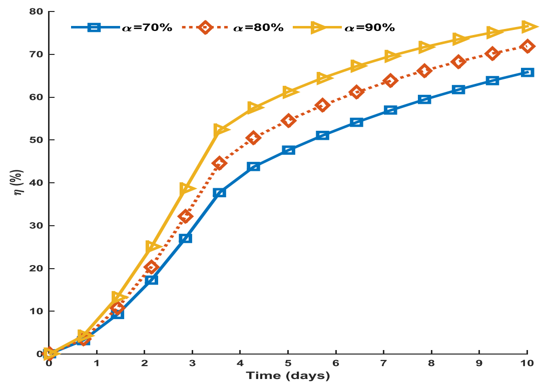


Figure 6. Effect of mixing rate on system effluent quality, TS = 12.1%, and $\frac{\tau}{\theta}$=1

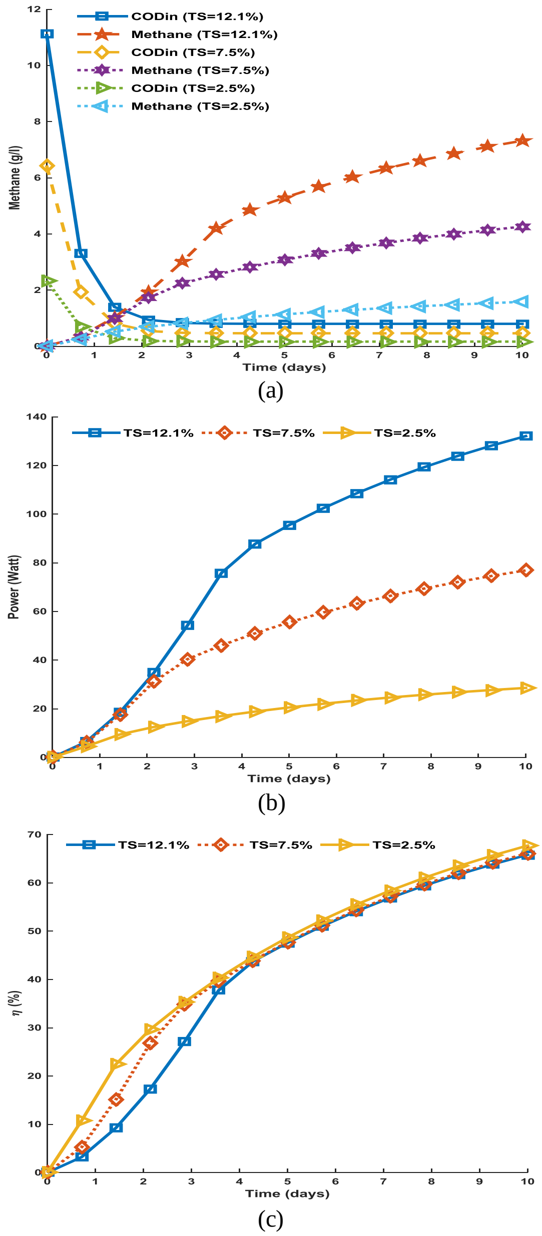


Figure 7. Effect of TS concentration on the methane production rate, power production and effluent quality, α =70%, and $\frac{\tau}{\theta}$=1; (a) Methane production rate, (b) Power production, and (c) Effluent quality

activity of microorganisms [28]. Also, at higher TS concentrations, the wastewater viscosity increases, which reduces the momentum diffusion into the lateral and upper layers of the system. The higher mixing rate is usually done by increasing the stirrer speed, impeller size or other effective factors in the system, but this may increase the stresses on the wastewater microorganisms and inactivates them. Therefore, at high mixing rates for concentrated wastewater, it is important to investigate the effects of stress on the microorganisms.

The effect of the mean cell retention time on methane production rate, power production and effluent COD removal efficiency in imperfect and perfect mixing systems

The methane production rate, power production and effluent quality of the imperfect mixing systems decrease with increasing the mean cell retention time (as shown in Figure 8). Based on the definition of the mean cell retention time in the mixing model, it is obvious that increasing the mean cell retention time reduces the volumetric flux of material exchange between flow-

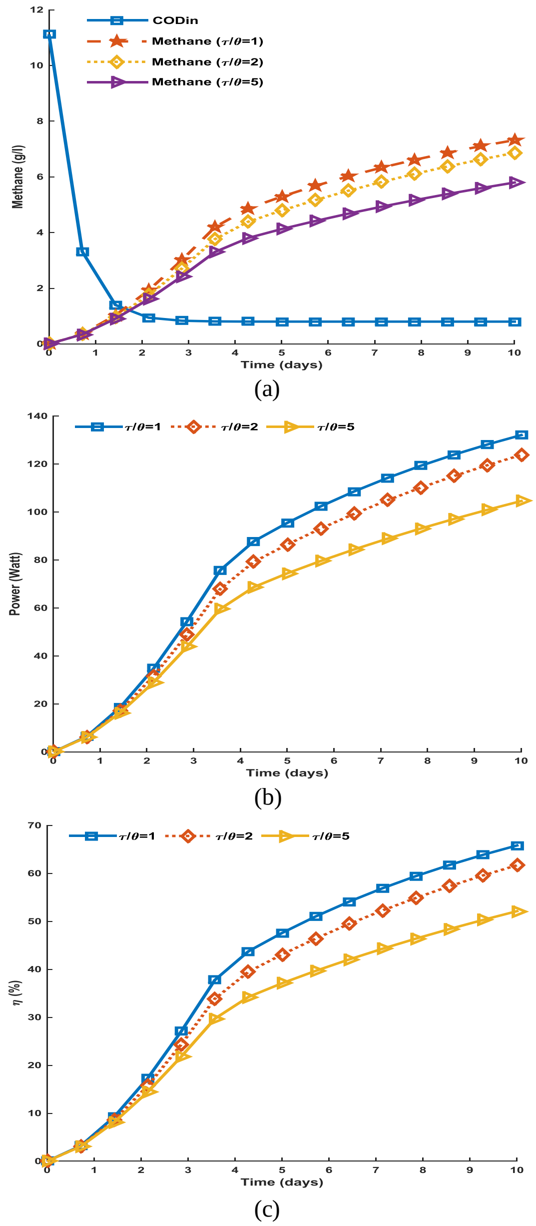


Figure 8. Effect of the mean cell retention time on the methane production rate, power production and effluent quality, TS = 12.1% and α = 70%; (a) Methane production rate, (b) Power production, and (c) Effluent quality

through and retention regions. However, increasing the mean cell retention time in perfect mixing systems (α≈1) has a favourable effect on methane production rate, power production and effluent quality. Perfect mixing reduces the volume of the retention region in the system and as a result, the material exchange rate between the two regions is significantly reduced. By keeping the wastewater in the system (or increasing the mean cell retention time), it is expected that the performance of the system will be improved slightly due to minor compensating the volume flux of material exchange between the two regions. This is also clear in Figure 9. In addition, according to the

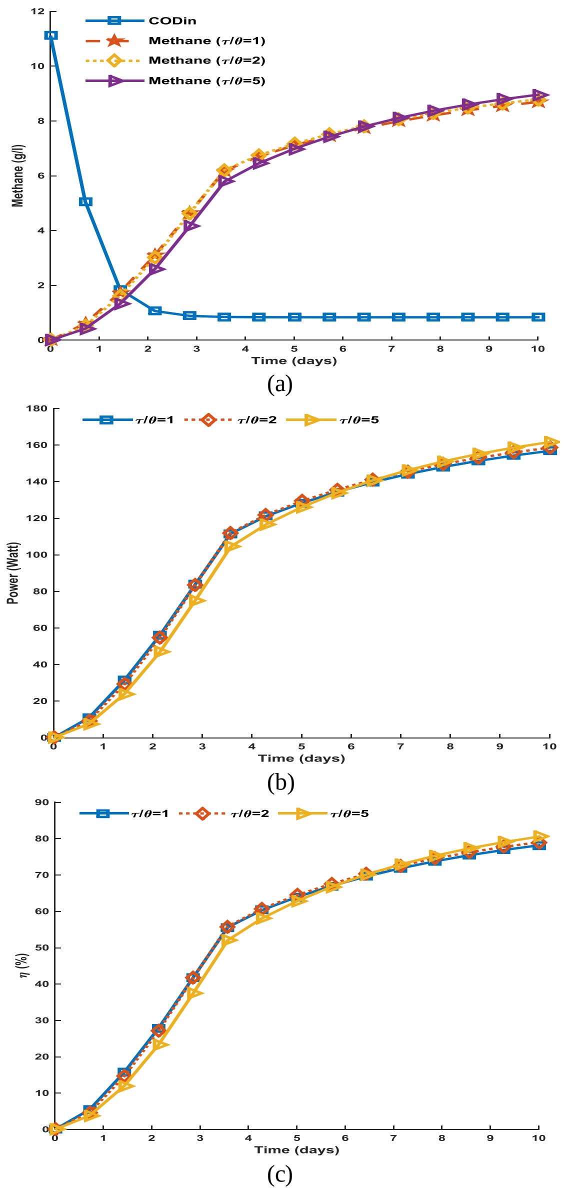


Figure 9. Effect of the mean cell retention time on the methane production rate, power production and system effluent quality, TS = 12.1% and α =96%; (a) Methane production rate, (b) Power production, and (c) System effluent quality

obtained results in imperfect mixing systems, it can be concluded that the most appropriate mean cell retention time is the hydraulic retention time. This has been confirmed in the results of Bello-Mendoza and Sharratt's research [5].

CONCLUSIONS

In this research, the kinetic model of AD process in the mixing system was investigated. One of the main objectives of the present study was to evaluate the performance of the system by calculating the quantities of methane production rate, power production and effluent COD removal efficiency, the most important results of which are as follows:

1) Mixing rate is one of the effective factors in methane production, power production and effluent quality. The results showed that increasing the mixing rate causes the performance of the system to increase. So that achieving the same efficiency in the perfect mixing system is done faster and in less time compared to the imperfect mixing system. Numerical results showed that with increasing the mixing rate by 20%, the methane production rate, power production and the effluent quality of the system increase by 19%, 19% and 12%, respectively. Furthermore, the future research work includes the evaluation of the mixing rate parameter in a CFD simulation of the mechanical mixing system in different operating conditions of the system.

2) Under similar operating conditions, the results showed that the system with more concentrated wastewater has better performance due to higher density of organic matter. So that at an equal mixing rate, the methane production capacity in the wastewater with a concentration of 12.1% is 4.5 times higher than the wastewater with a concentration of 2.5%. Of course, it should be noted that in denser wastewater, achieving a higher mixing rate may be limited by increasing the stresses on the microorganisms.

3) One of the effective parameters in the mixing system is the mean cell retention time. The results showed that in the imperfect mixing system, the most suitable mean cell retention time is the same hydraulic retention time. But in the perfect mixing system, with increasing the mean cell retention time, the performance efficiency of the system improved slightly. The study found that the mixing rate parameter is more important than the mean cell retention time parameter in the system and, it has a much more significant effect on the performance of the anaerobic digesters.

REFERENCES

1. Kumar Ghosh, S. and Mandal, S. 2018. "Evaluation of Biogas as an Alternative Driving Force of Electrically Operated Vehicles: A

Case Study." *International Journal of Engineering, Transaction B: Applications*, 31(5), pp.834–840. https://doi.org/10.5829/ije.2018.31.05b.20

2. Aceleanu, M. I., Șerban, A. C., Pociovălișteanu, D. M. and Dimian, G. C. 2017. "Renewable energy: A way for a sustainable development in Romania." *Energy Sources, Part B: Economics, Planning, and Policy*, 12(11), pp.958–963. https://doi.org/10.1080/15567249.2017.1328621
3. Lindmark, J., Thorin, E., Bel Fdhila, R. and Dahlquist, E. 2014. "Effects of mixing on the result of anaerobic digestion: Review." *Renewable and Sustainable Energy Reviews*, 40, pp.1030–1047. https://doi.org/10.1016/j.rser.2014.07.182
4. Colangiuli, S., Rodríguez, A., Sanromán, M. Á. and Deive, F. J. 2018. "Demonstrating the viability of halolipase production at a mechanically stirred tank biological reactor." *Bioresource Technology*, 263, pp.334–339. https://doi.org/10.1016/j.biortech.2018.05.017
5. Bello-Mendoza, R. and Sharratt, P. N. 1998. "Modelling the effects of imperfect mixing on the performance of anaerobic reactors for sewage sludge treatment." *Journal of Chemical Technology & Biotechnology*, 71(2), pp.121–130. https://doi.org/10.1002/(SICI)1097-4660(199802)71:2<121::AID-JCTB836>3.0.CO;2-7
6. Ong, H. K., Greenfield, P. F. and Pullammanappallil, P. C. 2002. "Effect of Mixing on Biomethanation of Cattle-Manure Slurry." *Environmental Technology*, 23(10), pp.1081–1090. https://doi.org/10.1080/09593332308618330
7. Karim, K., Thomasklasson, K., Hoffmann, R., Drescher, S., Depaoli, D. and Aldahhan, M. 2005. "Anaerobic digestion of animal waste: Effect of mixing." *Bioresource Technology*, 96(14), pp. 1607–1612. https://doi.org/10.1016/j.biortech.2004.12.021
8. Karim, K., Hoffmann, R., Thomas Klasson, K. and Al-Dahhan, M. H. 2005. "Anaerobic digestion of animal waste: Effect of mode of mixing." *Water Research*, 39(15), pp.3597–3606. https://doi.org/10.1016/j.watres.2005.06.019
9. Syaichurrozi, I. and Sumardiono, S. 2014. "Effect of Total Solid Content to Biogas Production Rate from Vinasse." *International Journal of Engineering, Transaction B: Applications*, 27(2), pp.177–184. https://doi.org/10.5829/idosi.ije.2014.27.02b.02
10. Rea, J. 2014. "Kinetic Modelling and Experimentation of Anaerobic Digestion". Bachelor Degree Thesis, U.S.A, MIT University, Massachusetts.
11. Benali, M. 2019. "Experimental Investigation of Biogas Production from Cow Dung in an Anaerobic Batch Digester at Mesophilic Conditions." *Iranian (Iranica) Journal of Energy and Environment*, 10(2), pp.121–125. https://doi.org/10.5829/IJEE.2019.10.02.09
12. Prasad Lohani, S. 2020. "Anaerobic Co-digestion of Food Waste with Cow Manure." *Iranian (Iranica) Journal of Energy and Environment*, 11(1), pp.57–60. https://doi.org/10.5829/IJEE.2020.11.01.09
13. Ebrahimi, A. and Najafpour, G. D. 2016. "Biological Treatment Processes: Suspended Growth vs. Attached Growth." *Iranian (Iranica) Journal of Energy and Environment*, 7(2), pp.114–123. https://doi.org/10.5829/idosi.ijee.2016.07.02.05
14. Shanmugam, L., Ramalingam, V., Palaniyandi, S. and Subramanian, S. 2019. "Comparison of different mixing phenomena in anaerobic digestion using food waste and sewage treatment plant for green biofuel through simulations of velocity contours." *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 41(18), pp.2233–2245. https://doi.org/10.1080/15567036.2018.1555627
15. Zhang, J., Mao, L., Nithya, K., Loh, K.-C., Dai, Y., He, Y. and Wah Tong, Y. 2019. "Optimizing mixing strategy to improve the performance of an anaerobic digestion waste-to-energy system for energy recovery from food waste." *Applied Energy*, 249, pp.28–36. https://doi.org/10.1016/j.apenergy.2019.04.142
16. Kolodynskij, V., Baltrėnas, P. and Dobele, G. 2020. "Experimental research of biogas production by using a three-stage semi-continuous bioreactor with modified mixer." *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, pp.1–15. https://doi.org/10.1080/15567036.2020.1772909
17. Ghovvati, M., Khayati, G., Attar, H. and Vaziri, A. 2016. "Kinetic parameters estimation of protease production using penalty function method with hybrid genetic algorithm and particle swarm optimization." *Biotechnology & Biotechnological Equipment*, 30(2), pp.404–410. https://doi.org/10.1080/13102818.2015.1134279
18. Pavlostathis, S. G. and Gossett, J. M. 1986. "A kinetic model for anaerobic digestion of biological sludge." *Biotechnology and Bioengineering*, 28(10), pp.1519–1530. https://doi.org/10.1002/bit.260281010
19. Vesvikar, M. S. and Al-Dahhan, M. 2005. "Flow pattern visualization in a mimic anaerobic digester using CFD." *Biotechnology and Bioengineering*, 89(6), pp.719–732. https://doi.org/10.1002/bit.20388
20. Bersinger, T., Le Hécho, I., Bareille, G., Pigot, T. and Lecomte, A. 2015. "Continuous Monitoring of Turbidity and Conductivity in Wastewater Networks." *Revue des sciences de l'eau*, 28(1), pp.9–17. https://doi.org/10.7202/1030002ar
21. Mucha, Z. and Kułakowski, P. 2016. "Turbidity measurements as a tool of monitoring and control of the SBR effluent at the small wastewater treatment plant – preliminary study." *Archives of Environmental Protection*, 42(3), pp.33–36. https://doi.org/10.1515/aep-2016-0030
22. Stafford, D. A. 1982. "The effects of mixing and volatile fatty acid concentrations on anaerobic digester performance." *Biomass*, 2(1), pp.43–55. https://doi.org/10.1016/0144-4565(82)90006-3
23. Tchobanoglous, G., F. L. Burton and H. D. Stensel, 2003. "Wastewater Engineering; Treatment and Reuse". New York: McGraw Hill Inc.
24. Fedailaine, M., Moussi, K., Khitous, M., Abada, S., Saber, M. and Tirichine, N. 2015. "Modeling of the Anaerobic Digestion of Organic Waste for Biogas Production." *Procedia Computer Science*, 52, pp.730–737. https://doi.org/10.1016/j.procs.2015.05.086
25. Monteith, H. D. and Stephenson, J. P. 1981. "Mixing efficiencies in full-scale anaerobic digesters by tracer methods." *Journal (Water Pollution Control Federation)*, 53(1), pp.78–84. Retrieved from https://www.jstor.org/stable/25041020
26. Jijai, S., Srisuwan, G., O-Thong, S., Norli, I. and Siripatana, C. 2016. "Effect of Substrate and Granules/Inocula Sizes on Biochemical Methane Potential and Methane Kinetics." *Iranian (Iranica) Journal of Energy and Environment*, 7(2), pp.94–101. https://doi.org/10.5829/idosi.ijee.2016.07.02.02
27. Ubaidah, M. A., Hilmi, S. M. H. S., Yunus, M. F. M. and Tahiruddin, S. 2016. "A Comparative Study on Biogas Production between Day and Night at Sime Darby's Palm Oil Mill." *Iranian (Iranica) Journal of Energy and Environment*, 7(2), pp.102–108. https://doi.org/10.5829/idosi.ijee.2016.07.02.03
28. Khayati, G. and Barati, M. 2017. "Bioremediation of Petroleum Hydrocarbon Contaminated Soil: Optimization Strategy Using Taguchi Design of Experimental (DOE) Methodology." *Environmental Processes*, 4(2), pp.451–461. https://doi.org/10.1007/s40710-017-0244-9

Persian Abstract

چکیده

در این مطالعه، از یک مدل ریاضی برای پیش‌بینی رفتار دینامیکی سامانه در شرایط اختلاط ناقص در فرآیند هضم بی‌هوازی استفاده شد. به منظور ارزیابی عملکرد سامانه، اثر پارامترهای اختلاط از طریق محاسبه مقادیر گاز متان تولیدی، توان سامانه و کیفیت پساب بررسی شد. نتایج عددی نشان داد که با افزایش ۲۰ درصدی میزان اختلاط، میزان تولید متان، توان تولیدی و راندمان حذف COD پساب در سامانه به ترتیب ۱۹، ۱۹ و ۱۲ درصد افزایش یافت. در میزان اختلاط مساوی، مقدار گاز متان تولیدی در فاضلاب با غلظت ۱۲/۱ درصد، ۴/۵ برابر بیشتر از فاضلاب با غلظت ۲/۵ درصد است، در حالی که تغییر قابل ملاحظه ای در کیفیت پساب مشاهده نشد. علاوه بر این، مشخص شد که تاثیر میزان اختلاط مهمتر از تاثیر پارامتر میانگین زمان ماند سلولی در راکتور بی‌هوازی (سامانه اختلاط) است. با استفاده از تکنیک‌های رگرسیون، مناسب‌ترین رابطه برای میزان تولید متان و راندمان حذف COD پساب در غلظت‌های مختلف فاضلاب ارائه می‌شود.