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Research Article

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Dynamic Simulation of Methane Production from Food Waste

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Abstract This research has been carried out to study the dynamics simulation of methane production from anaerobic digestion of food waste with the aid of MATLAB/Simulink. The models used were obtained from literature and converted to a Simulink model of the process. The Simulink model was simulated with the aid of MATLAB *mfile* program. The dynamic responses were obtained by varying the retention time, specific death rate of methane-forming bacteria and influent biodegradable volatile solid concentration. It was revealed from the results obtained that methane can be produced from food waste because its amount was found to increase within the time of 7 days considered. Also, the amount of methane obtained from the process was found to be affected by the retention time and the specific death rate of methane-forming bacteria whereas the effect of concentration of influent biodegradable volatile solid was negligible.

Keywords Methane, anaerobic digestion, bio-digester, dynamics, MATLAB, Simulink

Nomenclature

AD	Anaerobic Digestion
BVS	Biodegradable Volatile Solids
VFA	Volatile Fatty Acid
VS	Volatile Solids
S_0	Concentration of influent biodegradable volatile solid
θ	Retention time
k_{dc}	Specific death rate of methane-forming bacteria

1. Introduction

Anaerobic digestion is the process of molecular breakdown of biodegradable material using microorganisms under a controlled environment to generate biogas in form of an energy source from organic matter. This technique of generating energy was noted in the 17th century. Furthermore, in the 19th century, the consistency of the produced biogas as a renewable energy was explored. Most recently in the 20th century, anaerobic bacteria for commercial digestion have been discovered [1].

Anaerobic digestion (AD) was practiced in the 10th century for heating baths in Assyria by biogas (gas produced by the breakdown of organic matters). In the 17th century, Jan Baptita Van Helmont of Belgium discovered that decaying organic matters produce flammable gas. In 1808, the British Chemist, Sir Humphry Davy, discovered that methane gas was present in cow manure [2].

This process conserves nutrients and reduces pathogens in organic matter. According to Wellinger *et al.* [3], 1000 lbs of human waste can produce 0.6 cubic meters of biogas.

Anaerobic digestion involves breaking down of organic material by bacteria in four major processes: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Hydrolysis is the process in which carbohydrates, proteins, fats are converted to sugars, fatty acids, and amino acids. Acidogenesis is the process in which the sugars, fatty acids, and amino acids are converted to carbon dioxide, ammonia, and carbonic acids. Acetogenesis is the process that creates acetic acid and carbon dioxide. The final process, methanogenesis, is the one that gives rise to the formation of biogas, which is a mixture methane and carbon dioxide gases. The extracted methane from this process can serve as a fuel for heat and electricity [4].

There are two common types of digesters used for anaerobic treatment: batch and continuous. Batch digesters are the simpler of the two because the material is loaded in the digester and then allowed to digest. Once the digestion is complete, the effluent is removed, and the process is repeated [5]. Continuous digesters can be used for large commercial purposes. Either in a batch or a continuous mode, anaerobic digestion occurs as a controlled biological degradation process and allows for efficient capturing and utilization of biogas (approximately 60% methane and 40% carbon dioxide) for energy generation. The digestate from anaerobic digesters contains many nutrients and can be used as plant fertilizer and soil amendment [2].

Researches have been carried out on the production of methane from food waste by anaerobic digestion, but few are in the area of modelling and simulation. Bala and Satter [6] presented a dynamic model of biogas production. The model, which was solved using DYNAMO, had four coupled nonlinear first-order differential equations, two microbial growth equations and the resulting equation for biogas production. The predictive ability of the model was determined by comparing the model output with the observed values reported. The sensitivity analysis carried out in the work showed that gas production was sensitive to influent concentration and retention time. Adak *et al* [7] developed a simplistic mathematical model for anaerobic digestion of municipal solid waste in a continuous flow reactor unit under homogeneous steady-state condition by assuming that the kinetics of biomass growth and substrate utilization rate followed first order reaction kinetics. In the work, design table and charts were able to be prepared for ready use in actual plant operations. Masebinu *et al* [8] simulated a biogas upgrading plant operation that was using gas permeation technique for methane enrichment of biogas by studying the effect of recycling permeate stream on methane recovery, and it was discovered that recycling of the permeate stream improved the methane recovery of the simulated process. Contreras-Andrade *et al* [9] proposed a model, in form of differential equations, of a digester to study the dynamic simulations of biogas generation using Vensim software by taking the main factors of the biogas production to be the retention time and the methanogen mortality ratio. It was discovered in the work that the best yield of biogas could be obtained when the mortality ratio in methanogen and acidogenic bacteria were lower than 0.2 and the retention time was 30 h. Manjusha and Beevi [10] used the Anaerobic Digestion Model 1 (ADM1), which gives complete information about the physicochemical reactions in the anaerobic process, that was solved with the aid of MATLAB, to model and simulate anaerobic digestion of solid waste in order to investigate how biogas production was affected by different parameters such as pH and volatile fatty acid (VFA).

This work has been carried out to contribute to biogas development by simulating the anaerobic digestion of food waste for the production of methane with the aid of MATLAB/Simulink using the dynamic models obtained from the literature.

2. Methodology

The version of MATLAB used in this work was R2018a [11], and the system used to carry out the simulation was Core(TM) -i5 6200U CPU @ 2.30 GHz. The models used for the simulation of the anaerobic digestion of food waste for methane production in this work were obtained from the works of Balaand Satter [6] and Contreras-Andrade *et al* [9]. The steps involved in the production of methane by solid waste decomposition were analysed using differential equations. Thus, to model the quantity of solid waste flow in the system, an equation relating the solid material feed and its quantity in the reactor was used, and it was expressed as the biodegradable volatile solids (BVS) in the digester as in Equation (1),

$$\frac{dS}{dt}=\frac{S_0-S}{\theta}-\frac{\mu M}{Y} \tag{1}$$

where S_0 is the concentration of influent biodegradable volatile solids (g VS/liter), S is the concentration of biodegradable volatile solids in the digester (g VS/liter), M is the concentration of acid-forming bacteria (g organism/liter), θ is the retention time (day), μ is the specific growth rate of acid-forming bacteria (day^{-1}), Y is the yield coefficient of acid-forming bacteria (g organism/g BVS) and t is the process time (day).

Also, an expression for describing the quantity of fatty acids available for methanogen bacteria was obtained in form of volatile fatty acids (VFA) in the digester to be as expressed in Equation (2),

$$\frac{dAC}{dt} = \frac{AC_0 - AC}{\theta} + \mu M Y_a - \frac{\mu_c M_c}{Y_c} \tag{2}$$

where AC_0 is the concentration of influent volatile fatty acids (g VFA/liter), AC is the concentration of volatile fatty acids in the digester (g VFA/liter), Y_a is the yield of volatile fatty acids from acid-forming metabolism (g VFA/g organism), $\mu_c$is the specific growth rate of methane-forming bacteria (day^{-1}), M_c is the concentration of methane-forming bacteria (g organism/liter), Y_c is the yield coefficient of methane-forming bacteria (g bacteria/g VFA).

The expression for the dynamics of concentration of acid forming bacteria (acidogen) and methane forming bacteria (methanogen) were given as in Equations (3) and (4) respectively,

$$\frac{dM}{dt} = \left(\mu - k_d - \frac{1}{\theta}\right) M \tag{3}$$

$$\frac{dM_c}{dt} = \left(\mu_c - k_{dc} - \frac{1}{\theta}\right) M_c \tag{4}$$

where $k_d$is the specific death rate of acid-forming bacteria (day^{-1}) and k_dc is the specific death rate of methane-forming bacteria (day^{-1}).

Since the quantity of biogas produced is a direct function of the quantity of methanogen in the bio-digester, it was deemed necessary to add a proportionality constant to this factor in order to obtain a correlation for the dynamics of the biogas production. The rate of biogas production, which was considered to be dependent on the concentration of methane-forming bacteria, was expressed as given in Equation (5),

$$\frac{dm}{dt} = \beta \mu_c M_c \tag{5}$$

where m is the amount of methane produced (liter/liter digester volume) and β is the proportionality constant.

The model set was setup with the aid of MATLAB/Simulink version R2018a as shown in Figure 1 and simulated by running an *mfile* containing codes written in MATLAB using some parameters (Table 1) obtained from the work of Balaand Satter (1991) [6]. Other parameters (Table 2) used were selected until acceptable output values, which were non-negative, were obtained.

Table 1: Parameter values of the model obtained from the work of Bala and Satter [6]

Parameter	**Values**	**Unit**
μ	0.40	day^{-1}
μ_c	0.40	day^{-1}
k_d	0.04	day^{-1}
Y	0.10	g organism/g BVS
Y_c	0.05	g organism/g VFA
Y_a	9.00	g VFA/g organism

Table 2: Other chosen parameters used for the simulation

Parameter	**Values**	**Unit**
θ	1	day
β	0.5	-
S_0	40	g VS/litre
M_0	4	g organism/litre
MC_0	2	g organism/litre
AC_0	3	g VFA/litre
P_0	1.5	litre/litre digester volume

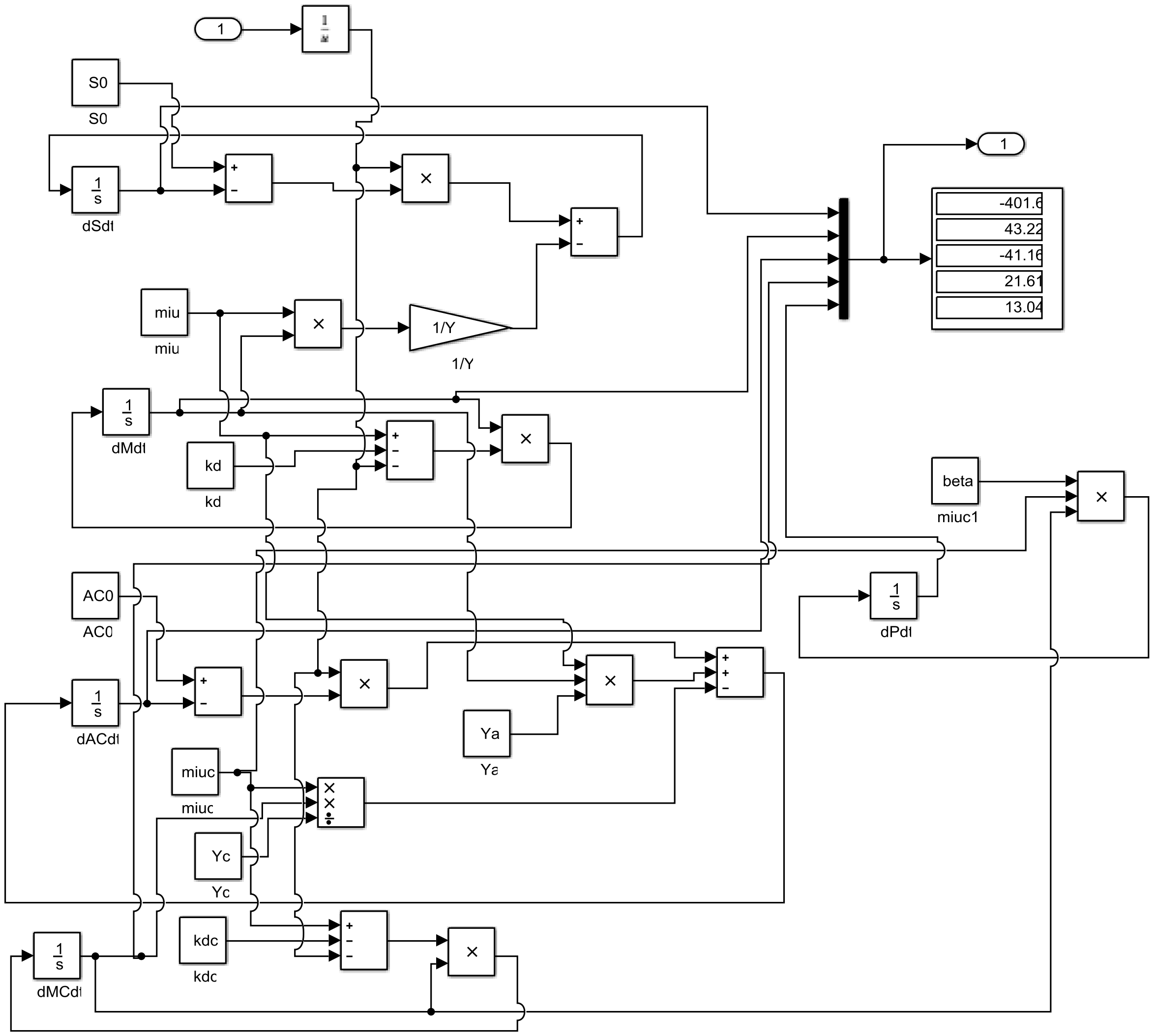

Figure 1: Simulink model for anaerobic digestion of food waste for methane production

Finally, the dynamic responses of the model were obtained while varying the retention time (θ), the specific death rate of methane-forming bacteria (k_{dc}), and the concentration of influent biodegradable volatile solids (S_0). The value of θ were varied arbitrarily between 10 and 50 days with a step size of 10 days that of k_{dc} were between 0.25 and 0.75 day^{-1} with a step size of 0.25 day^{-1} while that of S_0 were from 40 to 120 (g VS/litre) with a step size of 20 (g VS/litre).

3. Results and Discussion

The results obtained from the dynamic simulation of the model developed for the production of methane from food waste are as outlined and discussed thus.

Figure 2 shows the dynamic responses of influent volatile fatty acid concentration when the retention time was varied. According to the results shown in Figure 2, the change in the retention time of the process gave rise to changes in the concentration of the influent volatile fatty acid, and it was noticed that the higher the retention time the higher the final concentration of the influent volatile fatty acid. Also noticed from the results shown in Figure 2 was that as the retention time was increasing from 10 to 50 days, the difference between the final concentration of the influent fatty acid for the different retention times was decreasing from about 23 to about 24.5 gVFA/liter.

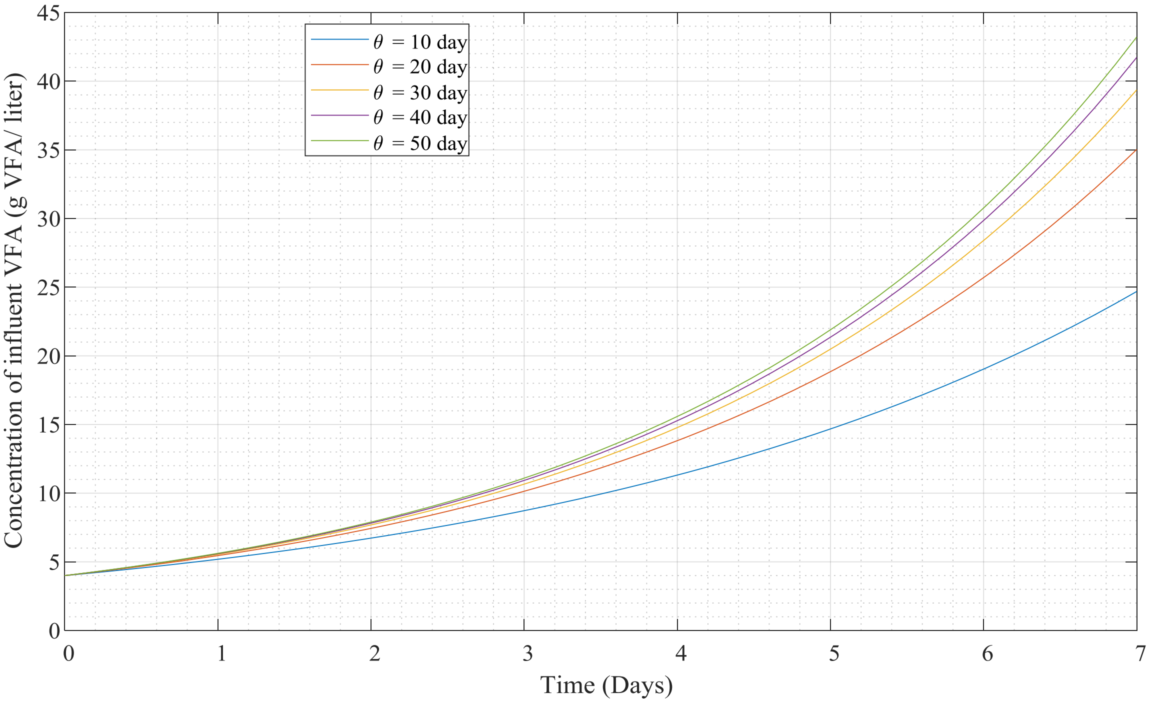

Figure 2: Dynamic concentration of influent volatile fatty acid (g VFA/ liter) at different retention times

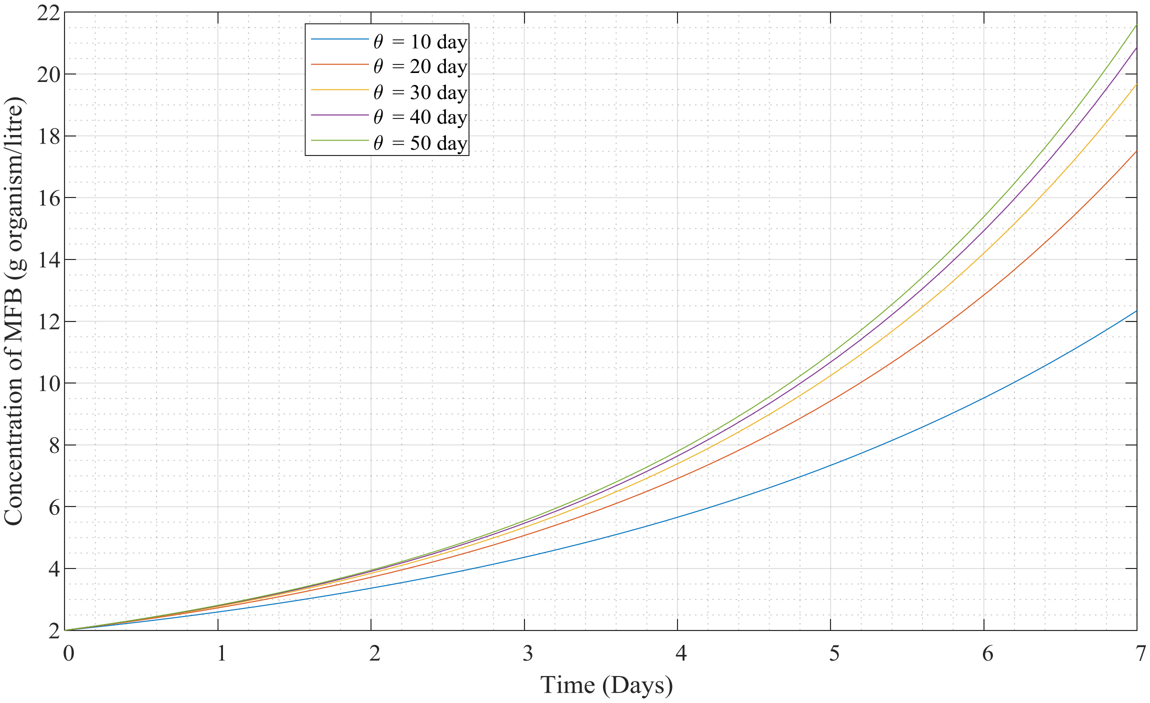

Figure 3: Dynamic concentration of methane-forming bacteria (g organism/litre) at different retention times

Similar observations to those of the results given in Figure 2 were made in the case of Figure 3 in which the dynamic responses of the concentration of methane-forming bacteria were shown at different retention times. However, the final values of the concentration of methane-forming bacteria were found to be different from those of the concentration of influent volatile fatty acid.

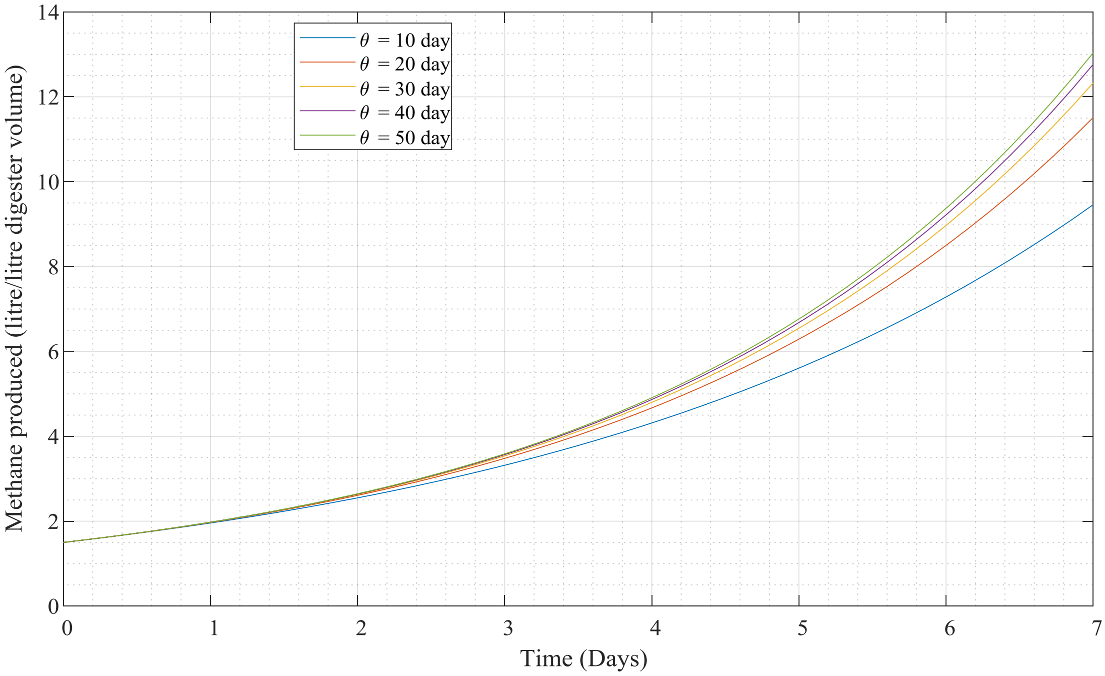

Figure 4: Dynamic response of methane produced (litre/litre digester volume) at different retention times

The dynamic responses of the amount of methane produced from the process is given in Figure 4. It can be seen from the figure that the amount of the methane was observed to vary as the process retention time was being varied. Also noticed from the results shown in the figure was that,despite the fact that the initial values of the simulation at the different retention times used were the same, the final values of the amount of methane produced were different, although the difference was becoming lesser as the retention time was increasing.

Furthermore, the effects of different specific death rates of methane-forming bacteria on the dynamic responses of some variables of this process were also investigated, and the results obtained were as given in Figures 5-7.

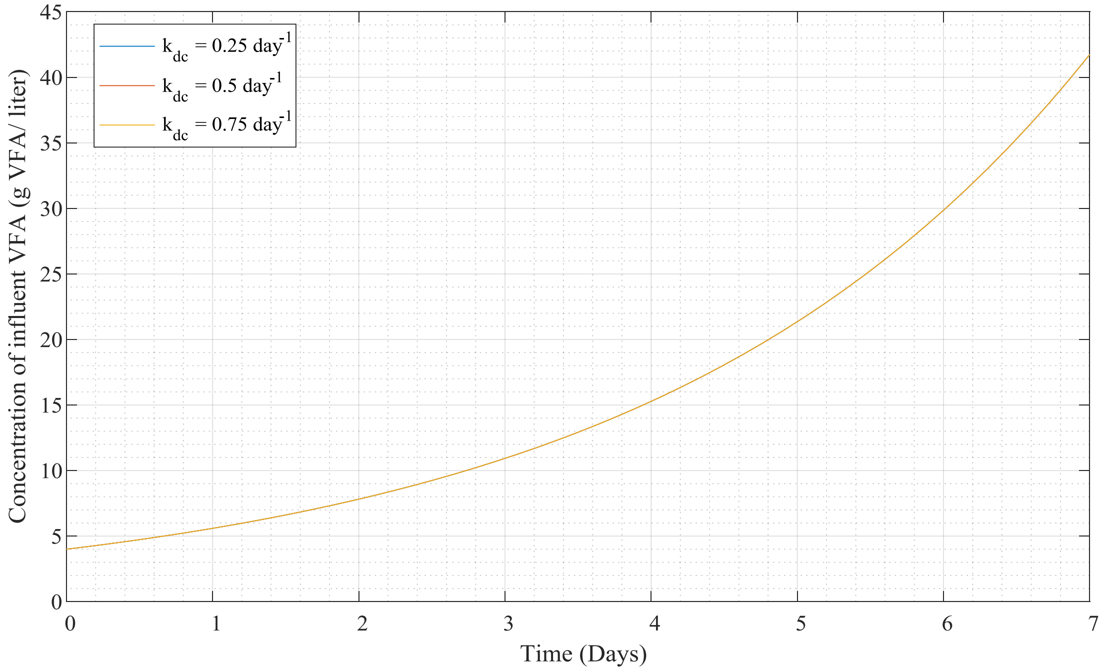

Figure 5: Dynamic concentration of influent volatile fatty acid (g VFA/ liter) at different specific death rate of methane-forming bacteria

Figure 5 shows the dynamic concentration of influent volatile fatty acid at different specific death rates (0.25, 0.50 and 0.75 per day) of methane-forming bacteria. It was observed from the results shown in the figure that the three responses obtained were found to overlap, and that was the reason for the appearance of a single curve on the figure. The implication of this is that the values of the specific death rate of the methane-forming bacteria at this instance has not any effect on the concentration of influent volatile fatty acid of the process.

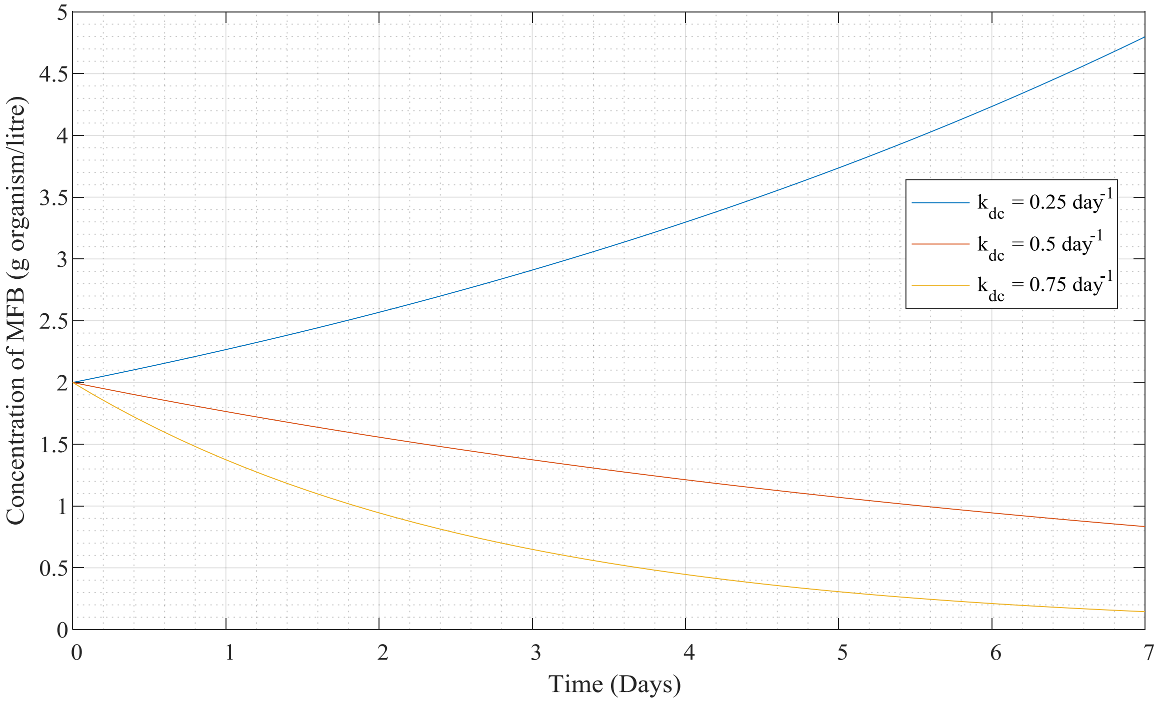

Figure 6: Dynamic concentration of methane-forming bacteria (g organism/litre) at different specific death rate of methane-forming bacteria

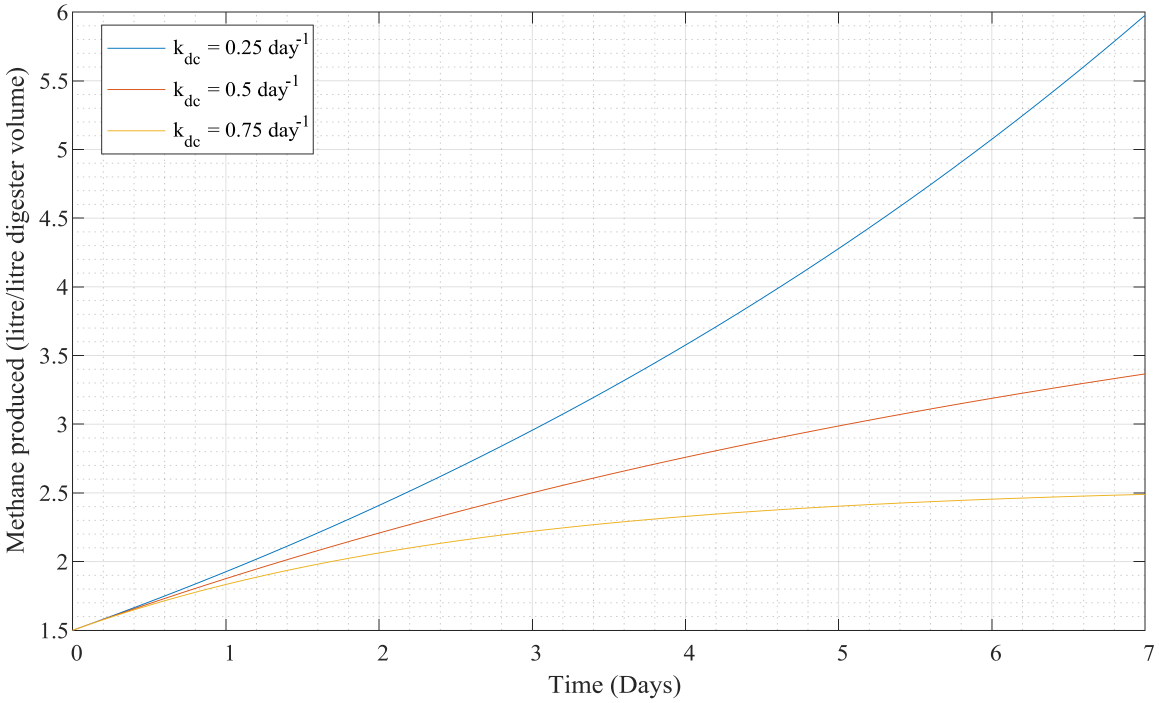

Figure 7: Dynamic concentration of produced methane (litre/litre digester volume) at different specific death rate of methane-forming bacteria

The results obtained as the dynamic response of the concentration of methane-forming bacteria with variation in the specific death rate of the bacteria are shown in Figure 6. As can be observed from the results, the concentration of the methane-forming bacteria was found to increase with days when the specific death rate was 0.25 per day because the death rate was not high enough to hinder the formation of the bacteria for methane production. When the death rates were 0.5 and 0.75 per day, the concentrations of methane-forming bacteria were observed to decrease owing to the fact the rates were high enough then for the hindrance of the formation of the bacteria.

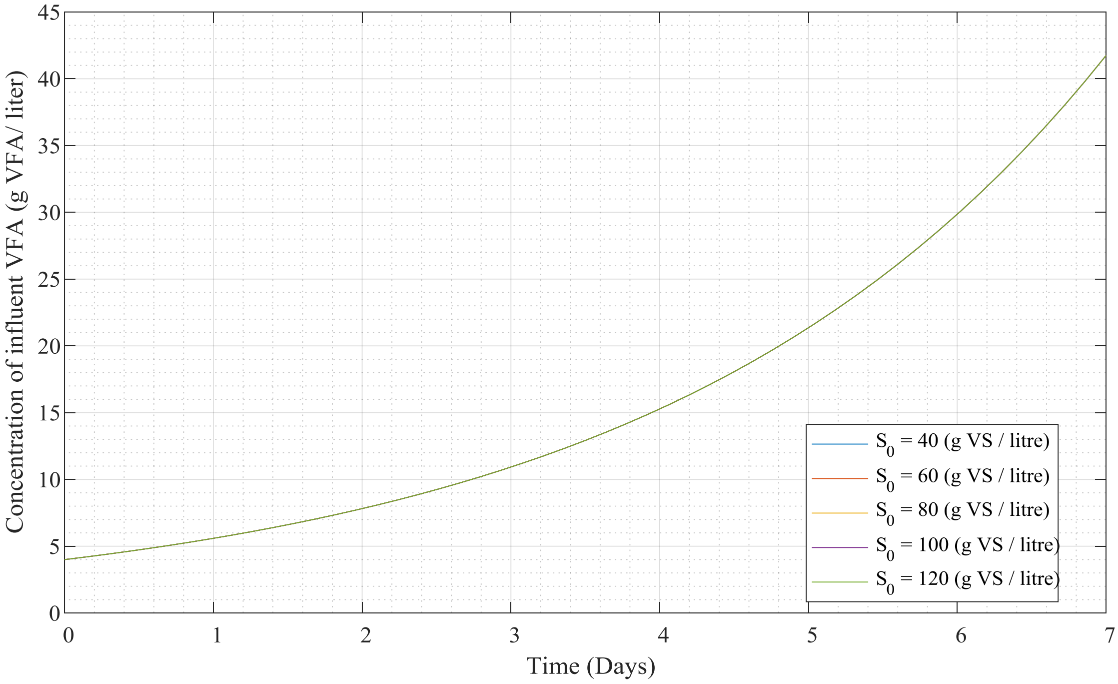

Figure 8: Dynamic concentration of influent volatile fatty acid (g VFA/ liter) at different concentration of influent biodegradable volatile solid

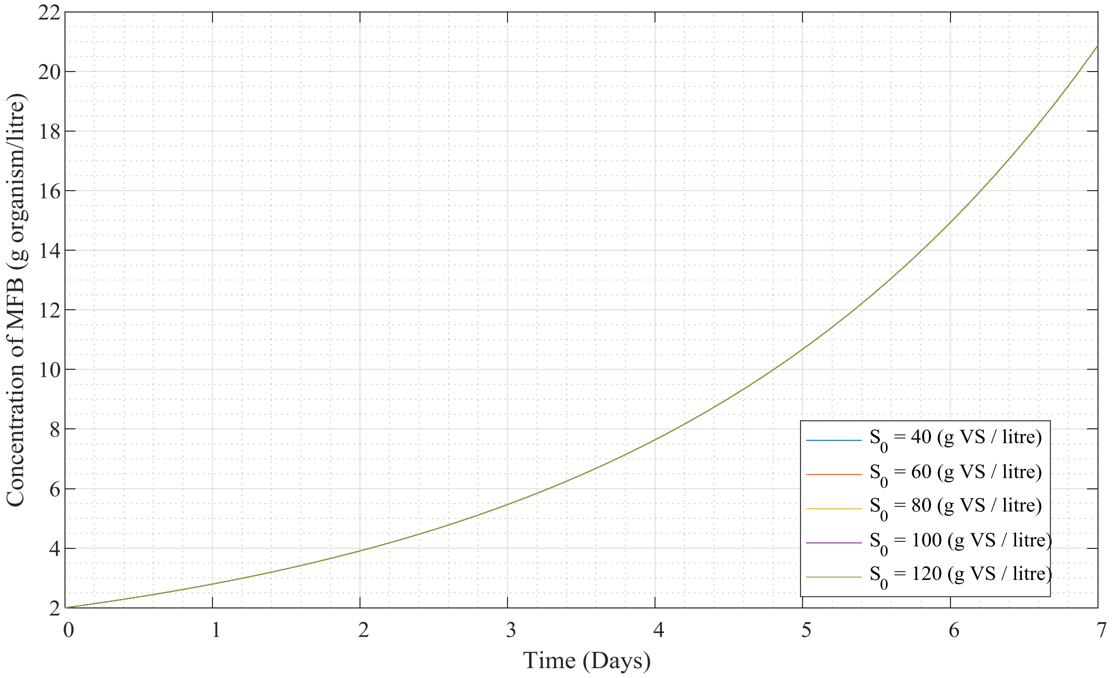

Figure 9: Dynamic concentration of methane-forming bacteria (g organism/litre) at different concentration of influent biodegradable volatile solid

Figure 7 shows the dynamic responses of the methane produced at different specific death rates of methane-forming bacteria. Using a simulation time of 7 days, the highest amount of methane was observed to be obtained when the death rate was 0.25 followed by that of 0.5 and the least value was given by the death rate of 0.75. Also, within the simulation time considered, the three responses were found to be increasing. However, the amount of methane produced from the process was found to decrease as the specific death rate of the bacteria was increasing because the higher the death rate the less the bacteria that would be available for methane formation.

The dynamic responses of the influent volatile fatty acid concentration, methane-forming bacteria concentration and amount of methane produced obtained from the simulation of the process was carried out with variation in the concentration of influent biodegradable volatile solid were as shown in Figures 8, 9 and 10 respectively.

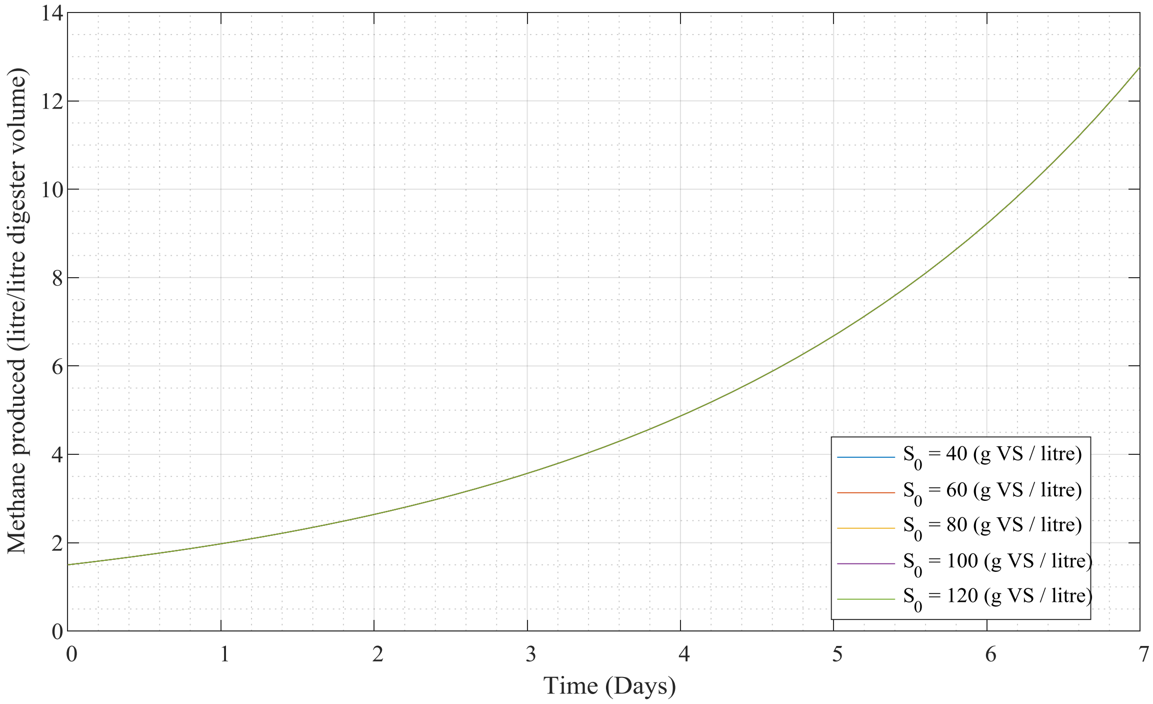

Figure 10: Dynamic concentration of produced methane (litre/litre digester volume) at different concentration of influent biodegradable volatile solid

According to the results (Figures 8-10), the concentration of influent biodegradable volatile solid was discovered not to have any effect on the selected process variables (influent volatile fatty acid concentration, methane-forming bacteria concentration and amount of methane produced) because the same dynamic responses were given for each of them, and this made the response curves to overlap one another.

The results obtained in this work were found to compare well with those obtained in the researches of Bala and Satter [6] and Contreras-Andrade *et al* [9].

4. Conclusion

The results obtained from the simulation carried out in this work for the process producing methane from food waste with the aid of MATLAB/Simulink revealed that methane can be produced successfully from food waste because, with all the input parameters, the amount of methane in the digester was found to increase within the simulation time of 7 days considered. The retention time and the specific death rate of methane-forming bacteria were found to have effects on the amount of methane produced from the process. For instance, as the retention time was varied from 10 to 50 days, the concentration of methane-forming bacteria was found to vary from about 12.5 to 21.5 at the end of the simulation period of 7 days. It is recommended that experiments should be carried out to validate the simulation responses obtained in this work. Also, the process can be investigated using process simulators such as Aspen HYSYS and Aspen Plus as those simulators have been applied to successfully investigate reactive distillation, which is a complex process that allows the occurrence of reaction and separation in a single piece of equipment [12-36].

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