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Effect of Hydraulic Retention Time on Anaerobic Digestion of Xiao Jiahe Municipal Sludge

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Abstract

In this study, the research protocol was designed to examine the effect of hydraulic retention time (HRT) on the efficiency of the production of biogas from sewage concentrates recovered from coagulation and adsorption process from Xiao Jiahe municipal wastewater treatment plant and to report on its overall performance. Three complete-mix, continuous stirred tank reactor (CSTR) with working volume of 900 mL were used. The digesters were operated at different HRT of 10 d, 20 d and 30 d. Biogas produced had methane composition of 60-70% and biogas production rates of 18 mL/d in reactor 1, 169 mL/d in reactor 2 and 114 mL/d in reactor 3. Reactor 3 showed stable performance with the highest methane yield of 166 mL/gCOD. Reactor 1 recorded lowest methane yield of 10 mL/gCOD. Due to high organic loading rate (OLR) and shorter HRT, the VS degradation and biogas yield in reactor 1 decreased. Based on the data from this study, 30 d HRT and OLR of 0.6 gCOD/(L.d) was suggested as the designed criteria for ideal methane production from CSTR anaerobic digestion AD of sewage sludge recovered from coagulation and adsorption process.

Keywords: Continuous stirred tank reactor; Anaerobic digestion; Sewage concentrates; Hydraulic retention time; Coagulation/adsorption process; Biogas; Methane

Introduction

Dealing with sewage sludge is closely linked to the protection of the natural environment [1-3]. Where sludge cannot be prevented during wastewater treatment process, there is considerable emphasis on recovering energy and available nutrients [4]. In addition, using sludge as a resourceful material for renewable energy production could avoid land filling of the waste which creates environmental problems [5,6].

Sewage sludge only as substrates for anaerobic digestion (AD) for energy recovery requires relatively straightforward process and the treated sludge bio-solids can be directly used for agriculture purpose. It is a widely-used method of sludge treatment because of its good performance in waste reduction and energy recovery in the form of methane [7]. Currently, AD process for biogas production is receiving attention globally because of the economic advantage in bioenergy production and as a cost effective sludge stabilization technique [8,9]. Also, methane production via anaerobic digestion of energy wastes could replace fossil fuel derived energy and reduce environmental problems [10].

Anaerobic sludge digester is designed to enhance the growth of anaerobic bacteria in the digester system to break down organic materials, most especially the methane producing bacteria that reduce organic solids by breaking them into soluble substance [11]. However, the process is difficult to maintain stable condition because a balance favorable to several microbial populations is necessary. Inhibition during AD process including by-products and the intermediates are the main causes of failure in digester performance [12]. As such, process performance optimization is required for effective biogas recovery. Previous studies documented the importance of optimization in process performance and data analysis [13-15]. HRT, on the other hand, is an important parameter because it determines the amount of organic matter and volatile solids to be fed into the digester. Currently, most methanogenic reactors in wastewater treatment plant are operated with HRT of 15 to 30 days under mesophilic temperature conditions of 30-35°C. Shorter HRT leads to washout of methanogens and the decline in p^H [16]. Several studies have documented the influence of HRT on energy recovery from sewage concentrate. For example, Anbalagan et al. [17] investigated the influence of HRT on nutrient removal, settleability and biogas production from the integration of microalgae from freshwater and activated sludge. They demonstrated that 6 and 4 days HRT are optimal for TN removal for microalgae and a rapid biogas production was observed within 9 days of incubation.

However, much research has not been done on biogas recovery from sewage sludge recovered from coagulation and adsorption process of membrane-based sewage pre-concentration and the role of HRT condition has not been considered in other studies about energy recovery from sewage sludge recovered from sewage treatment using Polyaluminum chloride (PACl) and powder activated carbon (PAC) as coagulants and absorbents [18,19]. In this study, a lab-scale anaerobic CSTR digester was fed with sludge recovered from Xiao Jiahe municipal wastewater treatment plant in Beijing P.R China with the average COD value of 8815 mg/L over a selected HRT condition of 10, 20 and 30 days, aimed at maximizing the volumetric rate of methane production and demonstrate optimum condition suitable for effective digestion process in CSTR.

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Materials and Method

Experimental setup

The digester experiment was carried out in three CSTRs fitted with a bottom plate, which supported the mixer and the mixer's rotation. The experiment was carried out in a continuous mode with daily feeding. Anaerobic digestion of sewage concentrate was investigated in mesophilic temperature condition of 35°C with three different HRT of 10, 20 and 30 days for reactor 1, 2 and 3 respectively and with OLR of 1.8, 0.9 and 0.6 gCOD/(L.d). The reactors had one outlet at the bottom for digested effluent removal and sampling. Each of the reactors had the total volume of 1,000 mL. The reactors were initially fed with the concentrated sewage to a working volume of 900 mL, allowing the top space of 100 mL for biogas accumulation. A tube was connected from each of the reactors to a gas bag for biogas collection. The three HRT were maintained by removing 90 mL of effluent from reactor 1 and feeding 90 mL of substrate, 45 mL in reactor 2 and 30 mL in reactor 3 as shown in Table 1. The process was maintained daily throughout the period of 112 days. Figure 1 illustrates the experimental setup.

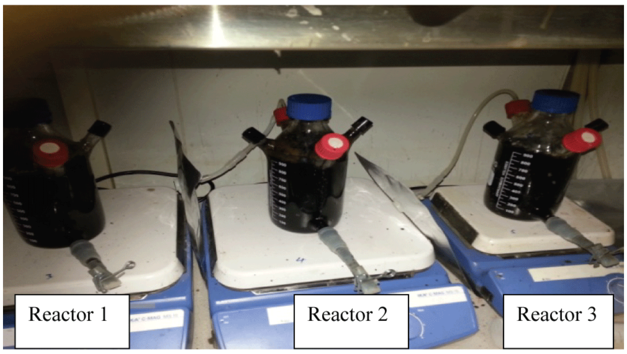

Figure 1: The experimental setup for reactors 1, 2 and 3.

The p^H of the three reactors was adjusted to 6.8-7.0 by adding NaOH. Inoculums sludge was initially used to run the reactor for four days to emit available biogas present in the system before proper experiment.

Reactors	Temperature (°C)	HRT=SRT (d)	Working Volume (L)	Discharge rate (mL/d)
Reactor 1	35	10	0.9	90
Reactor 2	35	20	0.9	45
Reactor 3	35	30	0.9	30

Table 1: CSTRs feeding and discharge rate.

Sewage concentrates sources and characteristics

Sewage concentrates used as feed for this experiment was collected regularly from pilot-scale reactor located at Xiao Jiahe municipal wastewater treatment plant in Beijing. The reactor treats sewage with the addition of Polyaluminum chloride (PACl) as coagulants and powder activated carbon (PAC) as adsorbents to reduce membrane fouling and enhance concentration efficiency. The average total solid (TS) was 8.9 g/L, volatile solid (VS) of 4.5 g/L and average COD value of 8815 mg/L. The sample for AD experiment was collected during 2 d SRT condition of membrane filtration process as shown in Table 2. Daily collected sample was mixed thoroughly and stored in a 4°C refrigerator prior to use. The seeding sludge for inoculation of anaerobic digestion process was collected from a mesophilic anaerobic digester in Xiao Jiahe Wastewater treatment plant.

	COD(mg/L)	TS(g/L)	VS(g)	pH
No Discharge	12081 ± 345	12.5 ± 06	6.5 ± 0.2	7.78
SRT 0.5 d	6508 ± 117	6.3 ± 0.2	3.5 ± 0.1	7.82
SRT 2 d	8815 ± 136	8.9 ± 0.3	4.5 ± 0.2	7.79

Table 2: Characteristics of the sewage concentrate.

Analytical methods

Volume of biogas production was measured using a gas meter and gas composition was frequently tested by Agilent technology 7890A gas chromatography system with a thermal conductivity detector (TCD) and a 2.0 mm stainless column. Ammonia and soluble chemical oxygen demand (sCOD) were also determined by using membrane filter to filter samples and later tested according to the standard methods. Other parameters such as p^H, COD, and VS were all tested according to the standard method [20].

Results and Discussion

Biogas and methane production

One of the main objectives of this research study was to determine the performance of CSTR anaerobic digestion process operated at different HRT and OLR. Thus, it is important to evaluate process performance base on biogas production and methane gas composition. Daily biogas production obtained in reactor 1 was approximately 18 mL/d, 169 mL/d in reactor 2 while average daily biogas production in reactor 3 was 114 mL/d. From the result, it was observed that low biogas production experienced in reactor 1 was as a result of the shorter HRT and higher OLR. Shorter HRT results in accumulation of

VFA, whereas at HRT longer than 15 d, the digester components will be fully utilized and biogas will be produced in a more efficient way [21]. Acidification is the first stage of AD process for producing biogas. Complex organic matter was converted into simple form of soluble chemical oxygen demand and then as volatile fatty acids (VFA) in acidogenic phase. Then the VFAs was converted to biogas by methanogenic phase. The effects of HRT conditions on the methanogenesis were studied in order to enhance the law of using different HRT conditions for the control of feeding and discharging of substrates, leading to the improvement in AD methane gas production and digestion rate.

Recovered biogas proportion composed average methane gas of 63.5% in reactor 1, 57.7% in reactor 2 and 61.4% in reactor 3 as shown in Table 3. The low methane content observed in reactor 2 was attributed to the slight exposure of the reactor to air during substrate feeding. However, methane composition in reactor 2 increased during the later stage of the experiment. Methane is the final product in the digestion process, and its production is a measure of how well the digester is working. The amount of methane produced during the digestion process is directly linked to the amount of organic matter destroyed. More importantly, the more methane is produced, the more energy that can be generated.

Biogas composition	**Average % (Reactor 1)**	**Average % (Reactor 2)**	**Average % (Reactor 3)**
Methane	63.5%	57.7%	61.4%
Carbon dioxide	13.1%	18.4%	17.8%

Table 3: Biogas composition during the stable period of the AD process.

Methane production rate per day

Figure 2 shows methane production rate per day in the reactors. Methane production rate per day represents the rate at which organic matter is converted to methane per day. Daily production increased in the reactors from the stable period from day 40; the rate of methane production depends on organic loading and the HRT conditions. High production was observed daily from reactor 2 and 3 with the producing rate of 100 mL/(L.d) of biogas daily. Reactor 1 has methane producing rate of 19 mL/(L.d). It is important to note that the higher biogas produced daily, the higher the rate of methane production.

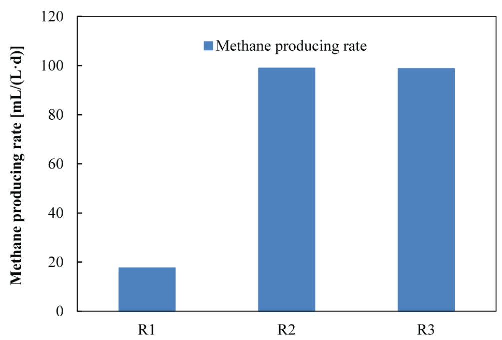

Figure 2: Methane production rate per day.

Methane yield and accumulated methane yield

For further illustration, methane yield and accumulated methane yield were analyzed and presented in Figure 3a and b. Reactor 3 recorded highest methane yield of 166 mL/gCOD. With Longer HRT, more methane was produced and Methanogenesis have longer culture doubling time. The average energy production from the CSTR reactors every day is 60% of methane which is equivalent to 6.0 kWh per normal cubic meter daily. A decreased in methane yield of 10 mL/gCOD was observed in reactor 1 as a result of excess loading. The overloading in reactor 1 was marked by decline in pH and methane yield. Methane yield in reactor 2 was 111 mL/gCOD. According to the literature, every gram of COD yields 0.35 L of methane at suitable temperature where the produced biogas constitute about 65 to 75% of methane [22]. In this study, suitable methane yield was obtained with HRT condition of 30 d. Methane yield obtained in this optimum HRT was found to be satisfactorily successful as compared to data in the literature obtained using vegetable and fruit waste. It should be cautioned here that optimal HRT depends on the reactor set up and other operational conditions.

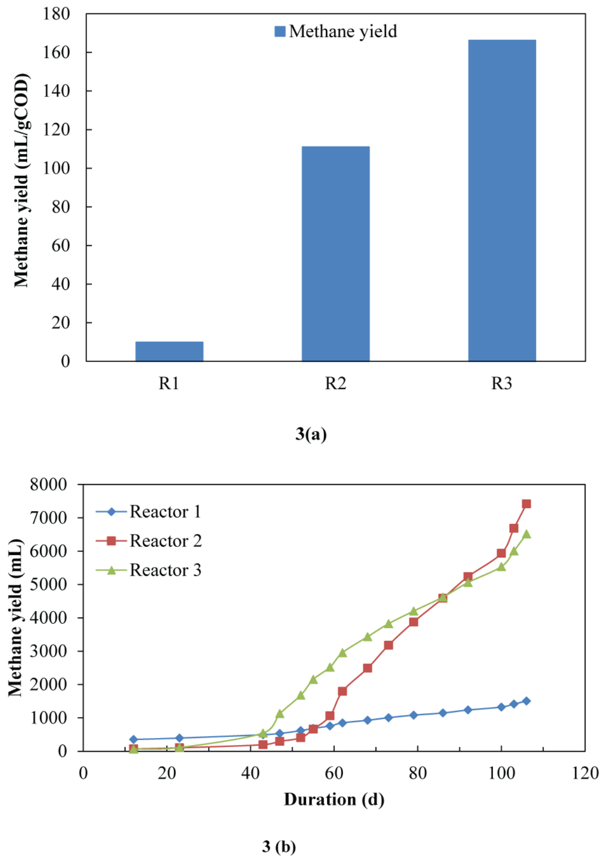

Figure 3: (a) Methane yield from three CSTR (b) Accumulated methane yield.

Accumulated methane yield was used to analyze the total methane produced in each of the reactors from the beginning of the experiment to the final period. Figure 3b depicts accumulated methane yield from the reactors. Reactor 1 had accumulated methane yield of 1.505.31 mL

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out of the total biogas yield of 2.645 mL with the remaining 1.139.7 mL containing carbon dioxide and traces of other gasses. In reactor 2 the accumulated methane yield was 7.416.55 mL out of the total biogas yield of 12693 ml with the remaining biogas yield of 5276.45 mL consist of other gasses present in the digestion system.

Figure 4 shows the accumulated biogas yield from each reactor, the total accumulated yield in reactor 2 was higher than reactor 1 and 3. This was due to slight inhibition observed in reactor 1 and 3 as a result of excess feeding. COD values of feed substrates fluctuated at some points and subsequently lead to slight inhibition. In principle, microbes in digestion process break down organic matter to produce methane. Several components of feed substrates undergo anaerobic biodegradation to produce gas living components that are readily biodegradable. Fluctuation in substrates COD affects microbial activity in the digestion process and hence reduces biogas production. The systems picked up again after feeding was suspended for two days. From the result, reactor 2 and 3 that were operated with 20 days and 30 days HRT produced the highest methane throughout the period of the experiment this is because both organic matter that are easily degradable and those that take a longer time to degrade were methanized during the longer days HRT.

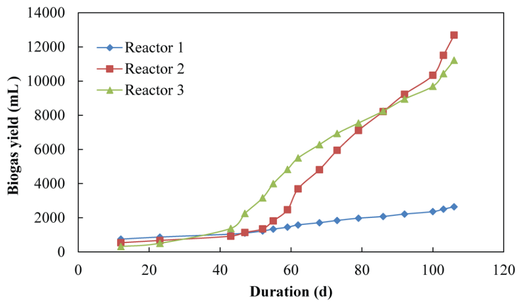

Figure 4: Accumulated biogas yield in the CSTRs throughout the period of the experiment.

Process efficiency

For the purpose of evaluating other conditions suitable for efficient biogas production, p^H, organic loading rate, ammonia and nitrogen content were taken into consideration as the process indicators for accessing the reactors performance. Among all the environmental conditions, p^H is the most sensitive and delicate parameters that should be taken into consideration. For instance, p^H of digester liquid indicates the stability of the system and the variation depends on the buffering capacity of the system [26]. The p^H in each of the three reactors varied as the reactors were operated with different conditions. For anaerobic digestion of organic substrates, it requires a group of microorganisms to work together, from which methanogenesis are the most sensitive to low p^H. If the p^H variation reduces beyond the normal range over a period of time, methanogenic bacteria that are responsible for biogas production will be highly affected and leads to the reduction in methane production.

In this experiment, the initial p^H for the three reactors were all ranged from 6.8-7.2 but after seven days, a severe jump in p^H was observed in the three reactors to 7.8- 7.82 for 4 days as shown in Figure 5, gas production was slow during this period, the production increased as the p^H continue to reduce to point ranging from 7.3-7.4. But gas production in reactor 1 reduced when the p^H condition further declined to 6.9-7.09. A low pH can bring about an accumulation in Volatile Fatty Acid (VFA), which somewhat inhibits digestion, while high p^H leads to an increase in free ammonia, which is toxic for the methanogenic populations. It was deduced that the sudden decrease in p^H in reactor 1 was as a result of the excess loading of the substrate in the system as the microorganisms could not feed or act with the loading set for this reactor. Though, system failure was not observed but gas production remained low throughout the period of the operation. A balance in pH was observed in reactor 2 and 3 with the value 7.3-7.6 from 45th day.

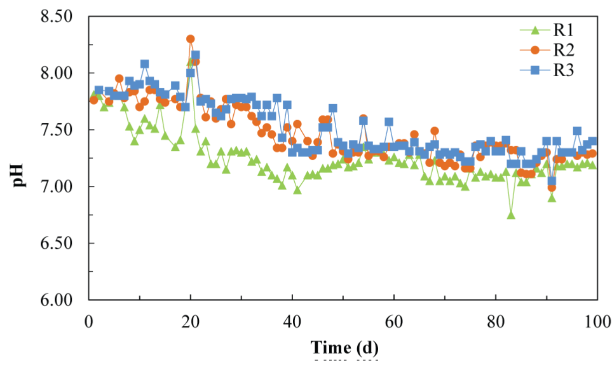

Figure 5: pH variations for the three reactors during the period of operation.

Ammonia is usually formed during anaerobic digestion process as a reduced or reduction product of microbial influenced biochemical degradation of non-protein or protein nitrogenous substances [23]. An investigation was also carried out to optimize solids destruction during anaerobic digestion process of excess municipal sewage sludge and was discovered that the key factor during anaerobic digestion process is the solid retention time [24]. However, ammonia concentration in anaerobic digestion depends on HRT of the system and also relates directly to solids destruction during the digestion process.

From the experiment, ammonia concentrations were found to be directly influenced by HRT and the breakdown of solids. Ammonia composition in anaerobic digestion process increased as the HRT increased while the nitrogen concentration decreased as the HRT increased [24]. In principle, total ammonia in the system is produced during the digestion of substrates. Like VFAs, the presence of ammonia can inhibit the digestion process and decrease its total performance if the composition is too high in the system. The concentration of T-NH3 and TN over 1,500 mg/L has been reported to be inhibitory for digestion process [25]. However, in this experiment, the composition of total nitrogen in the CSTRs system did not reach the inhibition point, the highest recorded ammonia concentration for reactor one was 680 mg/L and the highest concentration of nitrogen was 1100 mg/L.

From the beginning of the experiment when the feed substrates COD was lower than 9.800 mg/L, the ammonia content of the discharged concentrates from the three CSTR was less than 300 mg/L. Ammonia concentration in AD with the range from 50 to 200 mg/L seems beneficial to the process while concentration from 200 to 1000 mg/L does not have an effect on the process. However, if the concentration increases to 1000 mg/L and above 1.500 mg/L, there is a possibility that inhibition will occur because this value is toxic for the microbial activity in AD.

Conclusion

Anaerobic digestion process is a promising approach to reduce the amounts of biodegradable sewage sludge and also an energy producer. The process represents an effective and feasible method to convert the huge amount of sewage sludge recovered during wastewater treatment process to bioenergy. From the results obtained, the reactors had methane composition ranging between 60-70%. Reactor 3 that was operated with 30 d HRT showed stable performance with the highest methane yield of 170 mL/gCOD with volatile solids reduction of around 89%. Reactor 1 recorded lowest methane yield because of the high OLR and shorter HRT. Based on data from this study, 30 d HRT and OLR of 0.6 gCOD/(L.d) was suggested as the designed criteria for ideal methane production from sewage concentrate treated with coagulants (PACl) and adsorbents (PAC) using CSTR with a working volume of about 900 mL. Successful implementation of AD as the method of sewage sludge treatment leads to utilization of renewable energy, as well as the disposal of high moistening content of solid waste.

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