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Original Research

Performance Comparison between Anaerobic Hybrid Reactor and Anaerobic Continuous Stirred-Tank Reactor for High-Strength Fresh Leachate Treatment

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Abstract

This study aimed to examine the performance of an anaerobic hybrid reactor (AHR) and an anaerobic continuous stirred tank reactor (CSTR) for treating high-strength fresh leachate. As the organic loading rate (OLR) was increased in both systems, the pH decreased, with the lowest pH corresponding to an OLR of 25-30 kgCOD/m^3·d. The AHR system demonstrated instability in total volatile fatty acids when the OLR increased to 20 kgCOD/m^3·d. The highest methane (CH4) content was achieved when the OLR was 15 kgCOD/m^3·d. Moreover, the AHR showed excellent sediment retention. When the OLR increased, volatile suspended solids (VSS) in the system increased. The CH_4 content tended to increase as the OLR increased up to 20 kgCOD/m^3·d. The highest CH_4 content in the AHR was 68%, which was higher than that of the CSTR. The CSTR could not produce biogas when the OLR was 20 kgCOD/m^3·d. The optimal OLR for the operation of AHR and CSTR treating fresh leachate was found to be 15 and 10 kgCOD/m^3·d respectively.

Keywords: anaerobic hybrid reactor, waste transfer station, fresh leachate, biogas

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Introduction

Leachate from landfills is generated from moisture in the waste or with rain that comes into contact with it, causing it to flow and seep out. The physical characteristics of leachate are a foul odor, a viscous and sticky appearance, and often a dark color. The chemical oxygen demand (COD), biochemical oxygen demand (BOD_5), and other organic compounds may change over time, while the leachate is stored in the landfill [1]. However, fresh leachate coming from waste transfer stations exhibits a higher BOD_5 and COD than those found in landfills because it has not yet undergone substantial decomposition [2]. A common component of leachate is organic matter, heavy metals, nitrogen, and inorganic salts [3]. In municipal solid waste (MSW) transfer stations, for instance, the MSW may be compacted before transportation to the landfill. The leachate generated by this process is considered one of the most highly polluted wastewater, with substantial environmental impacts [4-6]. Untreated landfill leachate transported directly from the transfer station to the landfill will cause odors and leaks [7]. Samples of MSW leachate contain humic- like materials, which are hardly biodegradable organics. Due to their compounding with heavy metals, including copper, chromium, and zinc, these persistent compounds are poisonous even in low quantities [8]. If the leachate is not properly managed, it may threaten human health, ecosystems, and the natural water environment. However, leachate is also a source of greenhouse gases (carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O)), which are the cause of the global-warming effect. Lertyingcharoenchai et al. reported that a leachate model showed that CO_2, CH_4, and N_2O from leachate had average monthly concentrations of 78.40, 0.33, and 0.03 ppm, respectively [9]. High COD and BOD are characteristics of leachate [10], [11]. Therefore, fresh leachate can produce a high biogas yield through suitable treatment. The pH values of young leachate are in the range of 3.34-6.50. Because of its simple design and construction, the anaerobic continuous stirred tank reactor (CSTR) can be considered a feasible treatment option for high-strength fresh leachate at MSW transfer stations. Nevertheless, its operation must be optimized to achieve desirable performance, especially under high organic loading rate (OLR) conditions [12].

Fresh leachate from MSW transfer stations is commonly treated using a CSTR. However, the CSTR has a higher volume requirement and higher operating costs because of the energy required for agitation, making it less favorable than other high-rate reactors. Furthermore, influent with a high organic content may lead to the failure of CSTR systems, making them incapable of achieving a high OLR compared to other high-rate systems such as the up-flow anaerobic sludge blanket (UASB) and up-flow anaerobic filter (UAF). The benefits of UASB include a high loading rate, a long solid retention time, and flexibility of process operation. The advantages of UAF include a high microbial content in a small-volume reactor and stability under shock-loading tolerance conditions [13]. The advantage of UASB technology is that it works efficiently and can treat wastewater with high COD values. However, its limitation is that it can not retain microorganisms effectively. In contrast, in UAF systems, the supporting media remains on top of the reactor, thus improving the retention of microorganisms [14].

The anaerobic hybrid reactor (AHR) is a column-type reactor that combines the UASB and UAF systems to improve leachate treatment and biogas production efficiency. This hybrid system utilizes high-rate anaerobic digestion to effectively reduce COD levels and maintain active microorganisms that are resistant to toxins. Chaiprasert et al. studied the performance of AHR for treating cassava starch wastewater with various densities of supporting media. As a result, the COD removal efficiency was 70-87% and the total biomass in the reactors with supporting media was also high [15]. However, leachate from MSW transfer stations differs from other wastewaters because of its high strength, low pH, high acidity, and high content of organic and inorganic substances. The composition of fresh leachate is variable and complex. Therefore, fresh leachate requires a treatment system that is highly resistant to variability. Fresh leachate should be collected at the leachate collection point, where waste is compressed before sending it to landfills. No studies on the use of AHR with high-strength fresh leachate have been published. Therefore, urgent action should be taken to address this challenge to effectively treat fresh leachate in a manner that is efficient, environmentally friendly, and capable of generating energy in return. Hence, the objective of this study was to examine the performance of an AHR and an anaerobic CSTR for treating high-strength fresh leachate.

Materials and Methods

Fresh Leachate

Raw fresh leachate was obtained from a waste transfer station in Bangkok, Thailand**.** The fresh leachate in this study was collected between May to October (i.e., from the end of summer to the rainy season). The fresh leachate had a COD value of 100**,**181 mg/L and a BOD_5 value of 71,000 mg/L. The BOD_5/COD ratio was 0.70 and the pH was 4.36. All the parameters were determined following the guidelines in Methods for the Examination of Water and Wastewater (23rd ed.) [16].

Seeding Sludge

Anaerobic granular sludge collected from a CSTR operating at a leachate treatment plant in Thailand was used**.** AHR and CSTR were initially provided with the same amount of seed sludge at 15% (v/v).

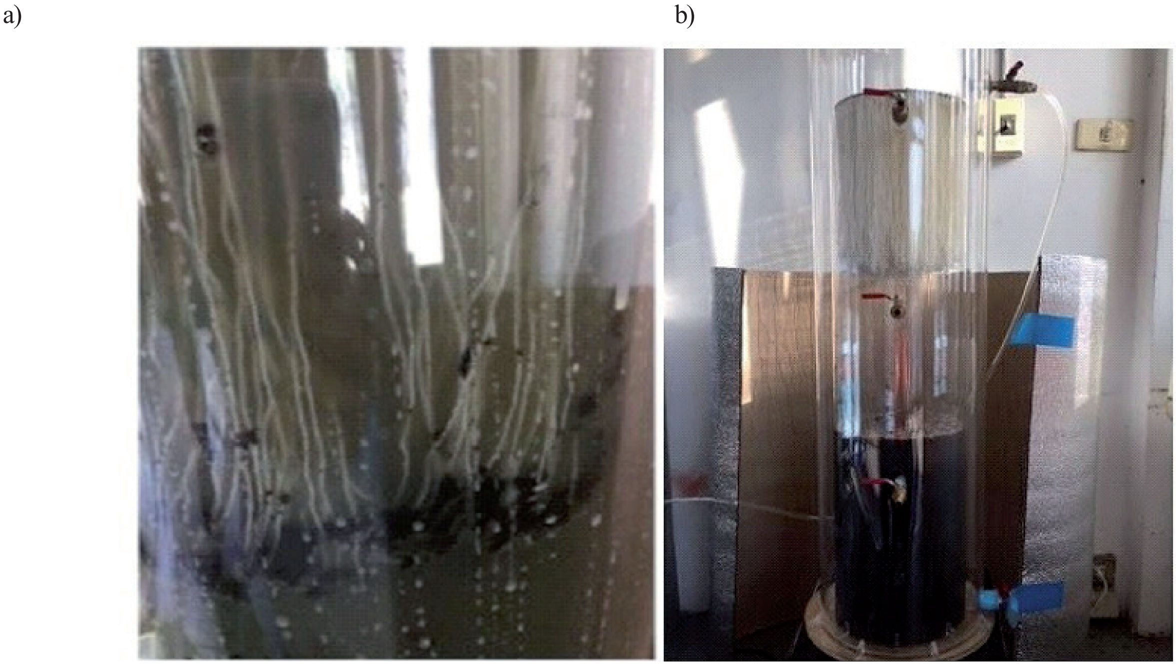

Fig. 1. Synthetic organic chemical carriers a) nylon fiber in AHR; b) lab-scale AHR

Carriers in the Anaerobic Fixed Film (AF)

AHR carriers have a general function as support media. It has a high area-to-volume ratio, a porous and rough surface to allow for bacterial adhesion with suitable mechanical properties for biological processes [17]. The carrier material (nylon fiber) was hung vertically in the reactor. The density of the carrier was 33 kg/m^3 (Fig. 1a).

Reactor Preparation

The lab-scale AHR and CSTR were made from acrylic. The AHR and CSTR had a cylindrical shape with a diameter of 20 cm and a height of 100 cm. The working capacity of the reactors was 25 L. Fig. 2 shows the schematic diagram of the CSTR reactor (Fig. 2a) and AHR reactor (Fig. 2b).

Lab-Scale Operation

This study was carried out for 210 days. In the start-up stage, reactors were fed with a leachate concentration of 1,000 mg COD /L and an OLR of 1 kg COD/m^3·d. This stage took approximately 60 days with granular sludge and fresh leachate addition. Next, after the start-up period, the COD concentration of the fresh leachate increased from 1,000 to 30,000 mg/L. Hydraulic retention times were reduced from 30 to 5 days in CSTR and AHR. The sludge retention time (SRT) in the AHR and CSTR were fixed at 15 days. Both AHR and CSTR

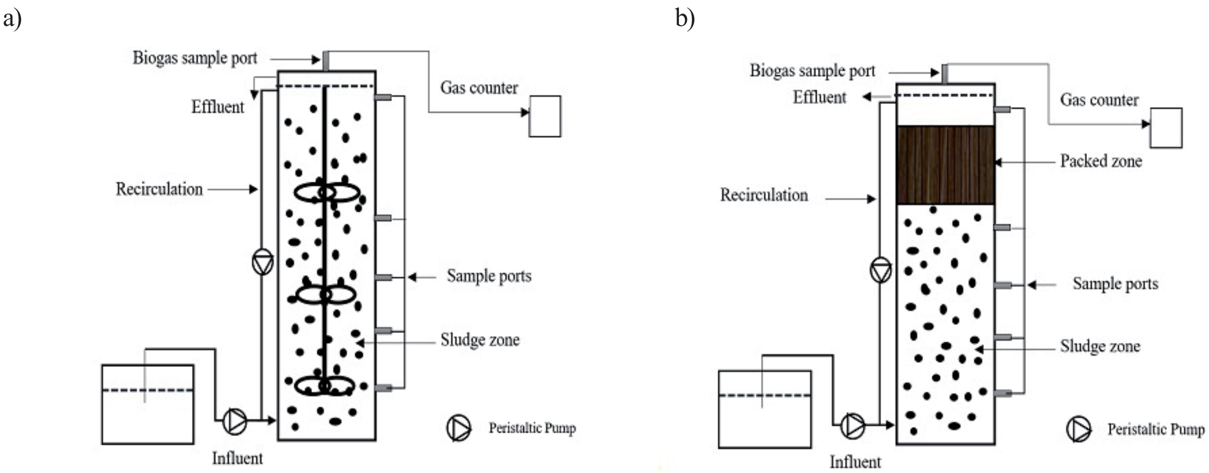

Fig. 2. Lab-scale anaerobic digestion: a) CSTR schematic diagram; b) AHR schematic diagram

were operated in parallel with fresh leachate influent. The OLR condition was stepwise increased from 1 kg COD/m^3·d (days 0-60) to 5 kg COD/m^3·d (day 61-100), 10 kg COD/m^3·d (day 101-130), 15 kg COD/m^3·d (day 131-160), 20 kg COD/m^3·d (day 161-180), 25 kg COD/m^3·d (day 181-200) and 30 kg COD/m^3·d. (days 201-210). Those operating conditions were referred to as conditions 1 to 7 respectively. The reactor performance was evaluated in terms of biogas production and COD removal efficiency achieved under those operating conditions.

Sampling and Analysis

The leachate samples were stored at 4ºC. Before analysis, the leachate samples were filtered through a glass microfiber filter (GF/C). The characteristics of the leachate were analyzed according to standard methods for examining water and wastewater. The analytical parameters comprised the positive potential of hydrogen ions (pH), BOD_5, COD, suspended solids (SS), total Kjeldahl nitrogen (TKN) [18], total suspended solids (TSS), volatile suspended solids (VSS), total volatile fatty acids (TVA), and heavy metals. The total biogas volume was determined using an optical gas bubble counter. The gas samples were then analyzed for their CH_4, CO_2, and N_2O concentrations, using a gas chromatograph (Shimadzu Clarus 580) with an electron capture detector (ECD) and Biogas 5000 analyzer. The efficiency of the bioreactors was determined by estimating the removal percentage of COD by applying Equation (1), as reported by Morales et al. (2021) [19].

$$\%\text{Removal} = ((\text{Cin} - \text{Cf})/\text{Cin}) \times 100 \quad (1)$$

Where: Ci, initial concentration of COD (mg/L); Ceff , final concentration of COD (mg/L)

Statistical Analysis

The average and standard deviation of all experimental data were analyzed and reported. To determine significant differences between the efficiency of AHR and CSTR reactors, a statistical test (T-test) was used to compare average values of COD removal efficiency and biogas production in those reactors. The testing was performed using one-factor variance analysis (ANOVA) with 95% confidence and linear regression using Excel 2010.

Results and Discussion

Characteristics of Fresh Leachate

Fresh leachate commonly shows high BOD_5, COD concentration, and BOD_5/COD ratio. Compared to fresh leachate, the pH and VSS values in intermediate and mature leachate, which contain less organic matter and heavy metals, are slightly higher (Table 1). The BOD_5/COD ratio is an important parameter for MSW leachate as it shows the biodegradability of organic substances. Initially, fresh leachate contains high concentrations of easily biodegradable materials, leading to a high BOD_5/COD ratio. However, this ratio tends to decrease as the leachate ages. Mature leachate is usually characterized by a more basic pH (>7.5), lower COD (<4000 mg/L), and lower biodegradability (BOD_5/COD<0.1) [18]. Fresh leachate from the MSW station had a BOD_5/COD ratio of 0.50-0.71 and an alkalinity of 1,350 mg/L, confirming its similarity with young leachate and the need for biological treatment [20].

Positive Potential of Hydrogen Ions (pH)

The initial pH of the fresh leachate ranged from 3.60 to 4.36 and was thus acidic before treatment. However, during the AHR and CSTR processes, the pH increased to 6.5-7.5. Optimal conditions for anaerobic digestion of the MSW leachate included a pH range of 6.6-8.1 and a temperature of 35ºC. The experiments were conducted using different COD loading levels (ranging from 1,000 mg/L to 30,000 mg/L) in a closed 25 L anaerobic for both the AHR and CSTR reactors. pH, TVA, and alkalinity were the principal environmental factors that affected the anaerobic microbial conversion rate [21]. These three factors were therefore measured every day during the experiment. The pH tended to decrease as the OLR value increased in both CSTR and AHR systems. This finding agrees with the biodegradation processes described by Ding et al. (2021) [22]. The rapid decomposition of organic matter, such as lipids and proteins in leachate, can result in the accumulation of VFAs and a subsequent decrease in pH. The pH was found to be in the lowest range when the OLR was 25-30 kg COD/m^3·d. The relationship between pH and the TVA/ALK ratio exhibited an exponential decline pattern. The pH value exhibited a decrease limited to a certain threshold when the ratio between total volatile acidity (TVA) and alkalinity (ALK) rose. The correlation study findings for the pH and TVA/ALK ratio in the AHR and CSTR systems (with R^2 values of 0.38 and 0.57, respectively) are illustrated in Figs 3(b-c). However, when comparing the buffering capacity of the CSTR and AHR, we found that the AHR performed better. Fig. 3. shows the pH inside both the AHR and CSTR systems.

Total Volatile Acid, Alkalinity, and TVA/ALK Ratio

Typically, to maintain a pH at or near neutral during anaerobic treatment, alkalinity concentrations in the range of 2,000-4,000 mg $CaCO_3$/L are required [23]. During the 60-day start-up period of the AHR and CSTR experiments, alkalinity was maintained in the range of 700-1,700 mg $CaCO_3$/L. With an OLR of 1 to

Table. 1. Characteristics of fresh leachate from the MSW transfer station.

Parameter	Concentration[a]	Unit
pH	4.36±0.02	-
Total COD	100,184±2,045	mg/L
Soluble COD	75,298±4,496	mg/L
BOD	71,000±1,409	mg/L
TSS	119,900±16,155	mg/L
VSS	55,154±2,259	mg/L
Alkalinity	1,350±79.90	mg/L as $CaCO_3$
Total Volatile Acid	2,700±136	mg/L as acetic acid
Total phosphorus	310.30±41.75	mg/L
Total phosphate	185.60±3.46	mgPO_4^{3-}/L
Chloride	1,235±72.92	mg/L
Calcium	1,850±90.92	mg/L
Magnesium	290±31.86	mg/L
Sodium	2,230±185.65	mg/L
Cadmium	ND	mg/L
Copper	ND	mg/L

Note: Number of samples was 4 for different day (November 7, 14, 21, 28, (2019))
ND Not Deteced (limit of detected was 0.001 μg/L)
[a] Denotes average concentration±SD

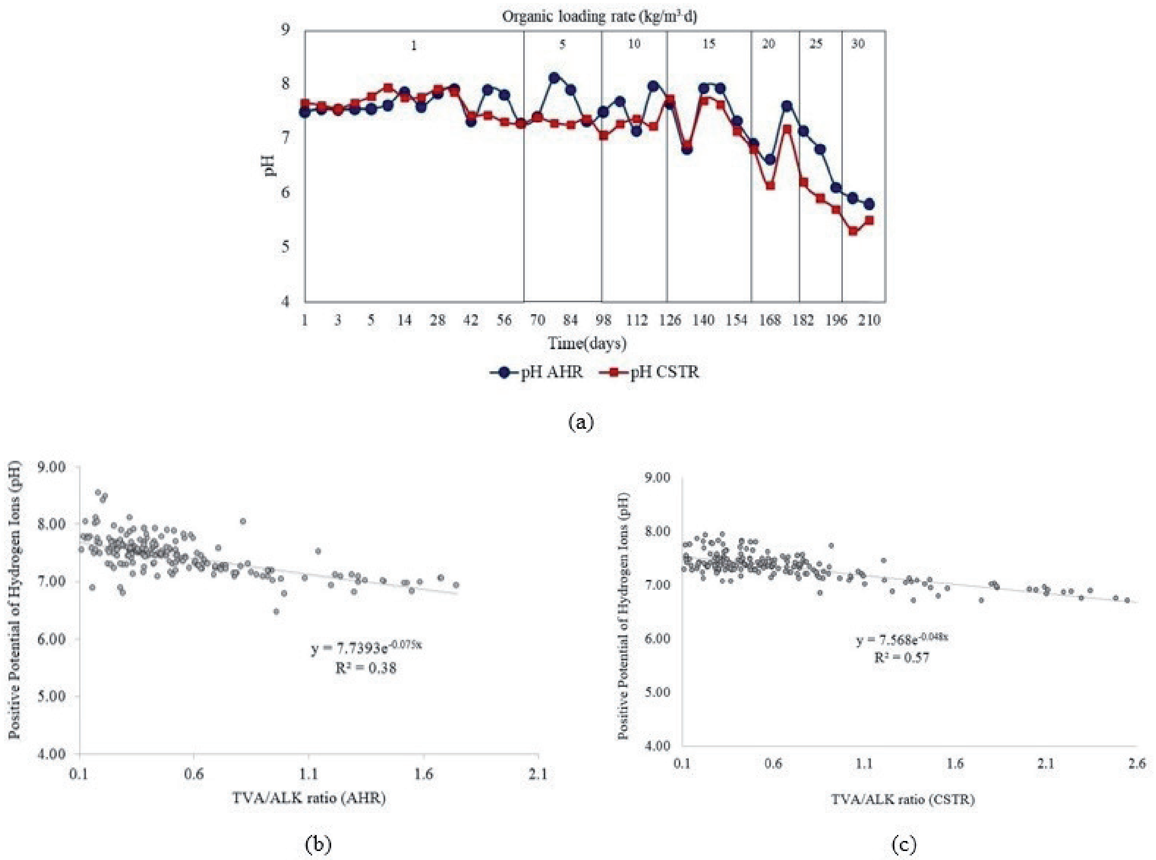

Fig. 3. a) pH inside the AHR and CSTR systems b) Correlation between pH and TVA ALK ratio of AHR system c) Correlation between pH and TVA ALK ratio of CSTR system

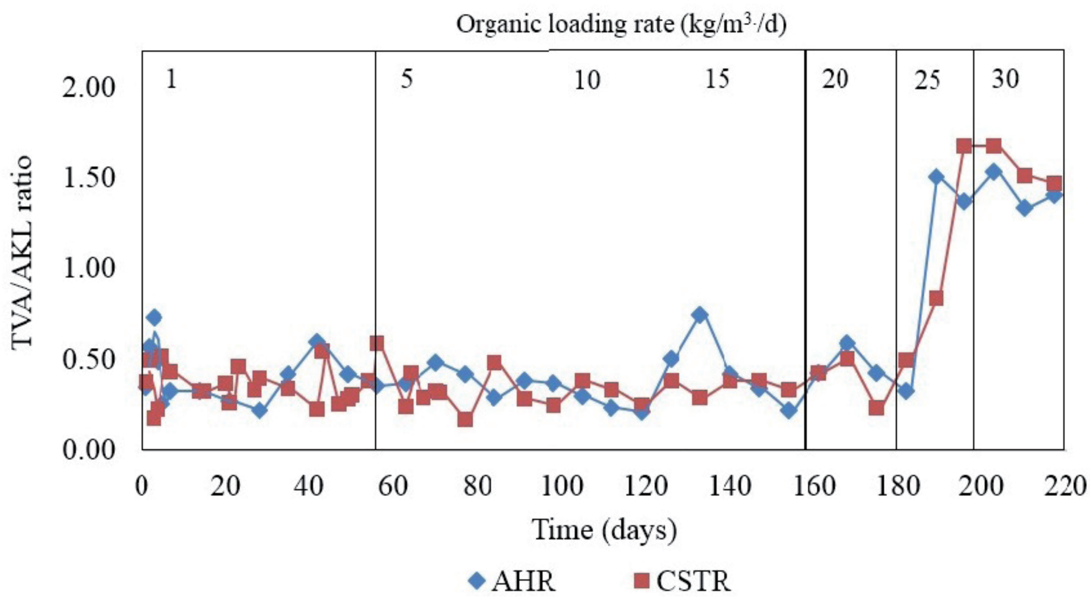

Fig. 4. TVA and ALK ratios of CSTR and AHR

15 kg COD/m^3·d, both reactors had a TVA/ALK ratio of less than 0.4. However, when the OLR was increased to 20-30 kg COD/m^3·d, the TVA/ALK ratios exceeded 0.4. As a result, after 180 days, both AHR and CSTR failed because the TVA/ALK ratios continuously increased (1.0-1.5), as depicted in Fig. 4.

VS concentration

The VS concentration was found to be highest at the bottom of the AHR and CSRT reactors. The mid-portion showed a lower VS concentration, and the lowest VS concentration was found at the top of the reactors. The sediment retention of the AHR was excellent, and no significant differences in the VS values of the reactors were observed. The findings are illustrated in Fig. 5. On the other hand, the CSTR had a high concentration in the system, with a VSS/TSS ratio within the range of 0.45-0.75 that tended to decrease. By contrast, the VSS/TSS ratio of the AHR was in the range of 0.25-0.85. An increase in OLR increased the VS in the systems, resulting in an increased biomass in systems. An increase in OLR led to an increase in the VS within the systems, which subsequently resulted in an enhanced biomass in these systems. Figs 5(a-b) depict a logarithmic curve, illustrating the curvilinear relationship between OLR and VS. This relationship suggests that as OLR increases, VS also increases, reaching its peak at the highest level the system can support biomass. The correlation analysis results between OLR and VS concentrations in both AHR and CSTR systems, with R^2 values of 0.56 and 0.90 respectively, are presented in Figs 5(a-b). These findings align with the studies conducted by Yilmaz et al. 2012 and Pereira et al. in 2022 [24, 25].

COD Removal Efficiencies

COD concentrations of both CSTR and AHR increased as the OLRs increased from 1 to kg COD/m^3·d.

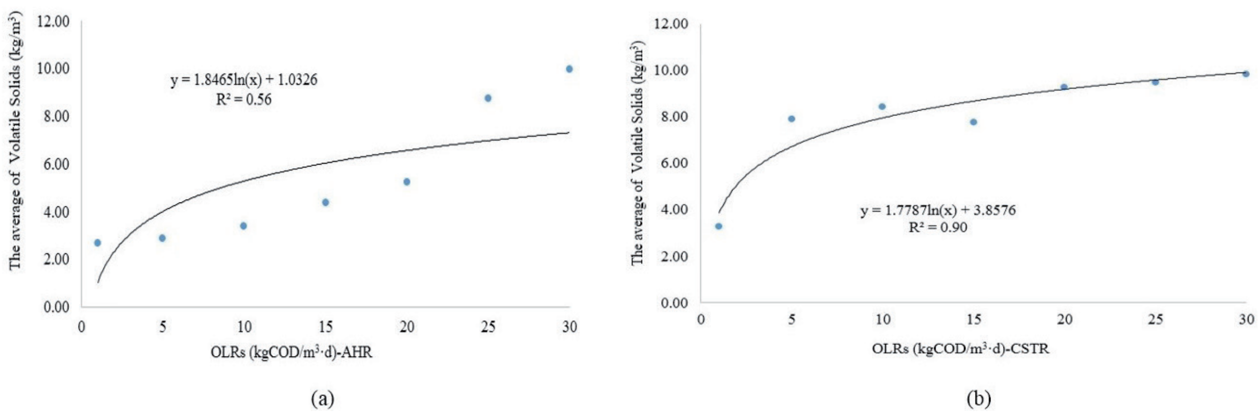

Fig. 5. a) Correlation of OLRs and VS concentration of AHR system b) Correlation of OLRs and VS concentration of CSTR system.

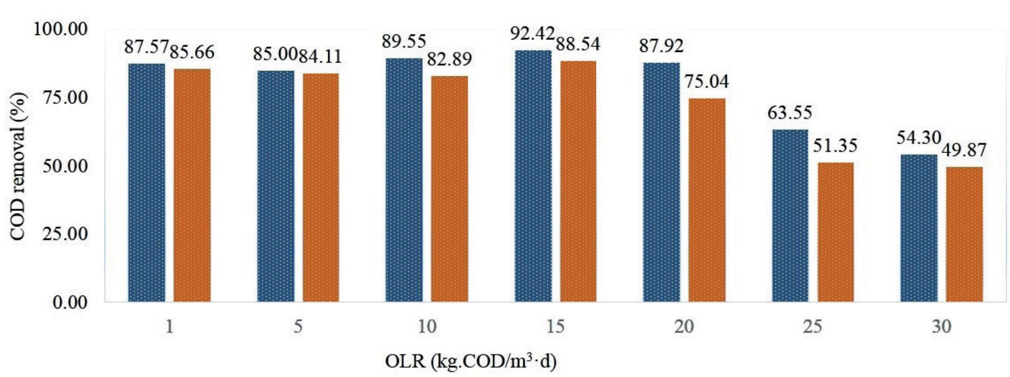

Fig. 6. OLRs and COD removal of CSTR and AHR systems

At an OLR of 1-20 kg COD/m^3·d, the AHR exhibited COD removal efficiencies ranging from 83% to 93%, whereas the COD removal efficiencies of the CSTR ranged from 75% to 89%. Hence, the AHR demonstrated a higher COD removal efficiency compared to the CSTR. According to, an increase in OLR led to higher COD removal efficiencies Moreover, HRT plays a crucial role in wastewater treatment [26, 27].

Biogas Production

Methane gas production is a crucial indicator of reactor performance and it depends on the metabolism of methanogenic bacteria [28]. During the first phase, AHR was operated at an OLR of 1-5 kg COD/m^3·d and the average biogas production remained low and fluctuating (54.45 L/d, with a CH_4 concentration of 51.80%). The average biogas production in the CSTR was 58.55 L/d, with a CH_4 concentration of 48.00%. The most suitable condition for biogas production in the CSTR was an OLR at 10 kg-COD/m^3·d. An ORL of 15 kg COD/m^3·d. was the most suitable condition for biogas production in the AHR, which produced 86.63 L/d, with a CH_4 concentration of 64.80%. Nevertheless, when the OLR was increased from 5 to 30 kg COD/m^3·d., the AHR produced more biogas than the CSTR. By contrast, the CSTR could not produce biogas when the OLR was increased to 30 kg COD/m^3·d. Therefore, biogas production during anaerobic treatment is associated with OLR. This was noted by a previous study, which also discussed the correlation between OLR and biogas production [29, 30]. From Fig. 7, the performance of CSTR and AHR produced biogas with no difference in volume during the first 60 days (start-up period). When increasing OLR from 5 to 30 kg COD/m^3·d, AHR was able to produce more biogas than CSTR; Biogas in the AHR system is produced in higher quantities than CSTR. The results are illustrated in Fig. 7.

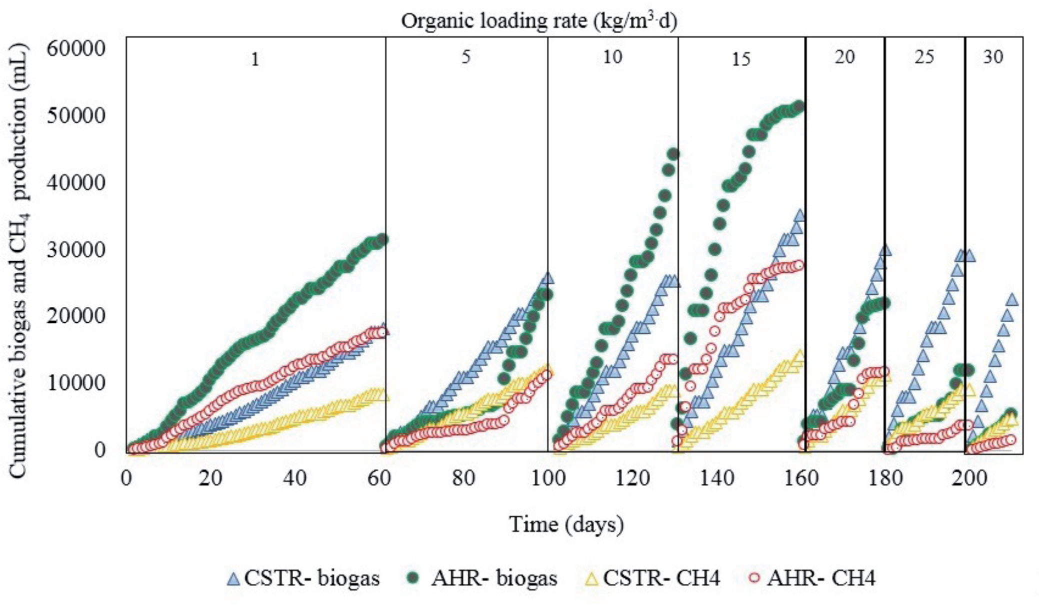

Fig. 7. Biogas production of CSTR and AHR systems

Conclusions

The main objective of this study was to assess and compare the effectiveness of treating leachate using two different systems; CSTR and AHR. The results revealed variations, between the AHR and CSTR systems with statistical significance observed at a value below 0.05. Therefore, There assumed to be more efficient for fresh leachate treatment than CSTR. When the OLR was increased from 1 to 15 kg COD/m^3·d, AHR was easy to operate but CSTR exhibited a reduced COD removal efficiency. Here, AHR was found to be adequate to treat fresh leachate with an OLR up to 15 kg COD/m^3·d. However, at an OLR of 20 to 30 kg COD/m^3·d, the pH and CH_4 generation in the AHR became unstable. As a result, the organic matter decreased, and CH_4 generation ceased. AHR produced high methane content in biogas being highest at 68**%** under OLR of 15 kg COD/m^3·d. The optimal OLR for AHR was found to be 15 kg COD/m^3·d whereas it was 10 kg COD/m^3·d for CSTR. When operated at higher OLR, TVA was found accumulating in the reactors, leading to a decrease in pH and a reduction in methane production. No biogas production was observed in CSTR at OLR higher than 20 kg COD/m^3·d. Therefore, future studies should focus on improving biogas production efficiency with the AHR series to attain efficient biogas production. Waste transfer stations should study the potential of using fresh leachate to produce alternative energy with suitable technology, aiming to reduce the environmental impact and threats to public health.

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Conflict of Interest

The authors declare no conflict of interest.

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