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ENHANCEMENT OF BIOGAS PRODUCTION FROM FOOD WASTES IN A HYBRID ANAEROBIC–AEROBIC BIOREACTOR BY MANURE ADDITION AND LIME-PRETREATMENT OF RECYCLED LEACHATE

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Abstract

The production of food wastes is a serious issue in developed and developing countries. The biogas production technology is one of the most sustainable methods for treating food wastes. Currently, there is a great need to implement suitable methods to enhance biodegradation and methane production. This study investigated the effect of manure addition and leachate lime-pretreatment on the biogas and methane production from spoilable municipal solid wastes using a hybrid anaerobic-aerobic bioreactor as a new method.
Three laboratory-scale columns were constructed to simulate a hybrid anaerobic-aerobic bioreactor without manure addition and leachate pretreatment as control (R1), two hybrid bioreactors with manure addition and without recycled leachate pretreatment (R2), and manure addition and lime pretreatment of recycled leachate (R3). All simulated bioreactors operated as continuous for about 8 months. Biogas and CH_4 production were measured to evaluate the biodegradability of food wastes and efficacy of bioreactors.
The results indicated consistently more biogas production under manure addition and leachate pretreatment (R3). The accumulative methane yield was determined to be 17.46, 53.79, and 283.41 mL/gVS for R1, R2, and R3 bioreactors, respectively, after 8 month of operation. The cumulative methane yield in the R3 bioreactor was 16.23 and 5.27 times higher than in R1 and R2 bioreactors, respectively. Therefore, the food waste biodegradation in R3 was greater than in R1 and R2. These results showed that the manure addition and leachate lime-pretreatment were effective in increasing the biogas and methane production of food wastes.

Key words: biogas, food waste, hybrid anaerobic-aerobic bioreactor, leachate, methane

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1. Introduction

Food waste constitutes a major fraction of municipal solid wastes forming about 50% of total food production due to poor practices in production, transportation, market, and consumer wastage (Nahman and de Lange, 2013). It has long been known as a serious problem to human and the environment since it can produce considerable quantities of pathogenic microorganisms, organic pollutants, and odorants if it is not managed, handled, treated, and disposed properly (Nguyen et al., 2017). Food waste treatment and management issues in developing countries are currently considered to be a major threatening factor for sustainable development (Thi et al., 2015). Therefore, the proper disposal or recovery of food waste is an important issue in environmental health engineering (Kim and Kim, 2013; Pandey et al., 2016).

Currently, the three conventional methods for treating food wastes are composting process (i.e., windrow composting, vermicomposting, powered composting etc.), anaerobic digestion, and landfilling. Composting is an organic matter decomposition

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process, usually aerobic degradation, which requires minimal external energy input to complete the process (Pandey et al. 2016), but this process is not able to recover the energy and produce gas. Anaerobic digestion technologies are an anaerobic process facilitating the production and capture of methane, as an essential advantage in the biodegradation of organic waste, which can be utilized as a renewable energy source (Zhang et al., 2012). Food waste is a suitable substrate for anaerobic decomposition due to high decomposition capacity and higher biogas production compared to digestion of individual substrates (Zhang et al., 2012; Zhen et al., 2016; Vasmara and Marchetti, 2018). This process can be performed in an anaerobic digester or in a landfill site. Working on anaerobic digestion of food waste to methane, Kumar et al. (2016) stated that the food waste could act as a feasible feedstock for the bioenergy production.

Despite numerous methods for wastes disposal, landfilling and its modifications are still the most popular method for disposal of urban and rural solid wastes in both developed and developing countries (Wallace et al., 2015). As these processes are slow and require a relatively large space for the design, in recent years, hybrid bioreactors with a combination of both aerobic and anaerobic conditions have been developed to accelerate and to improve organic waste stabilization (Xu et al., 2014). Therefore, hybrid bioreactors have been capable of converting and recycling food wastes into digested organic matter and biogas in a shorter period. In this bioreactor, the permanent process for organic degradation is anaerobic digestion.

Previous studies suggested that ruminants' manure can accelerate the anaerobic digestion process, as it has already the necessary methanogenic bacteria (Kumar et al., 2017; Rico et al., 2017). Also, the buffer capacity of manure has a positive effect on anaerobic stability (Rico et al., 2017). The results of another experiment revealed that the alkaline pre-treatment of organic portion of urban wastes in anaerobic digester, significantly improved degradation process and consequently increased biogas and methane production (Zhang et al., 2017). Other studies have pointed out that lime pre-treatment is an effective process for increasing the biodegradation of complex organic wastes and methane production using anaerobic decomposition method (Lin et al., 2009).

So far, few studies has been conducted examining the effects of simultaneous use of both manure and the lime-pretreatment of recycled leachate on hybrid anaerobic-aerobic bioreactors for biological degradation and biogas production from different organic wastes. Due to variations in organic wastes properties, especially food wastes properties, more studies would be helpful for better understanding of some parameters, affecting food waste degradation and bio-methane yield.

Therefore, to better understand the potential benefits of hybrid aerobic-anaerobic bioreactor system for food waste degradation and biogas production, and to develop an improved hybrid bioreactor system, a series of lab-scale experiments were evaluated in this study.

Specifically, the objective of this study was to evaluate the performance of a hybrid anaerobic-aerobic bioreactor treating food wastes under manure addition and lime pretreatment of recycled leachate and assess the biogas yields and quality of produced digestate.

2. Material and methods

2.1. Feedstock

The feedstock used was the food wastes fraction of urban solid wastes collected from sources of production. Fresh samples of food waste were obtained from vegetable and fruits shops, restaurants, and residential homes, Karaj, Iran. The food wastes were shredded using laboratory blender into 2-3 cm thick pieces, mixed, and stored at 2-4 °C until used. Cow manure was collected from a dairy farm. In order to prevent organic matter decomposition, the manure was maintained in the refrigerator at 2-4**°C** prior to the experiment (Khairuddin et al., 2015).

2.2. Experimental setup

Three lab-scale bioreactors were experimented to evaluate the biological decomposition of food wastes and biogas production during 240 days of operation. Three lab-scale bioreactors, a hybrid anaerobic –aerobic bioreactor without manure addition and lime pretreatment of recycled leachate (R1) as control, two hybrid bioreactors with manure addition and without lime pretreatment of recycled leachate (R2), as well as manure addition and lime pretreatment of recycled leachate (R3), were constructed to simulate hybrid anaerobic –aerobic bioreactors and to evaluate the effects of manure addition and lime pretreatment of recycled leachate. The initial manure amount of R1, R2 and R3 bioreactors was 0%, 10%, and 10% based on the total wet weight. R2 and R3 bioreactors were evaluated to test the effects of manure addition and lime pretreatment of recycled leachate. The pH of recycled leachate was adjusted to 7.5-9 by adding 2.5 g/l lime dose for pretreatment. The leachate was transferred from the reactors to containers which the lime was introduced and well mixed for 10 min. After 2 h of resting period the leachate was filtered through a cotton cloth under vacuum for preventing the formation of deposits in pipes and the distribution systems. Then, the filtered leachate was pumped to reactors. The lime was added during the whole experiment. This lime dose is sufficient for municipal leachate treatment to provide suitable and acceptable quality (Salem et al., 2008).

As shown in Figs. 1 and 2, the bioreactors were 1 m in height and 20 cm in diameter, and were constructed using PVC. A 10 cm layer of plastic packing was placed at the bottom of each column as a drainage layer. A 10 cm layer of free space was placed on the top of each of the reactors as a gas collector. The total height and height of the digestion tract were 100 and 80 cm, respectively, with 40 cm anaerobic layer and 40 cm aerobic layer. With a few changes in the shape and size of the dimensions, Xu et al. (2015) used this lab-scale hybrid bioreactor in previous studies.

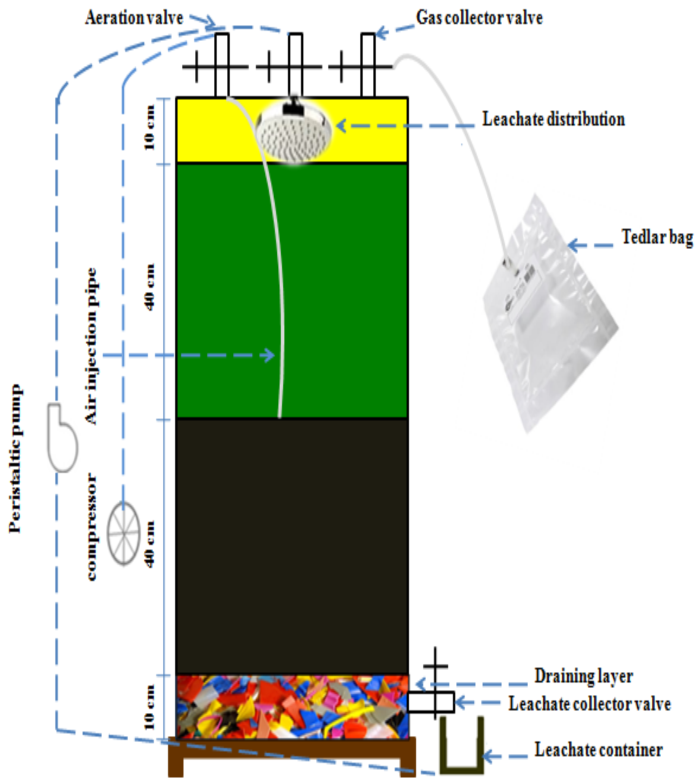

Fig. 1. Schematic image of a lab-scale hybrid anaerobic –aerobic bioreactor and its related accessories with 1 m in height and 20 cm in diameter (All three R1, R2, and R3 reactors are similar in appearance.
(The dark brown and the green color represent the anaerobic and aerobic zones, respectively)

Fig. 2. Three lab-scale hybrids anaerobic –aerobic bioreactors with deference of operation conditions (R1, R2, and R3 bioreactors)

At the bottom of each column, an outlet valve was installed for collecting leachate. At the top of each column, two valves were installed for biogas transfer to tedlar bags (SKC Inc., USA) and other for addition of recycled leachate to reactors. A temperature sensor was installed in the center of each reactor for temperature recording. Food waste was thoroughly mixed before loading the reactors and waste samples were taken for characterization before filling the reactors. Each bioreactor was loaded with 13.38 kg of wet food waste with a moisture content of 74% by weight (the ratio of manure to food waste was 0, 10, and 10% for R1, R2, and R3 Bioreactors, respectively). The density of the loaded waste in each reactor was 533 kg/m^3.

In reactors, using a compressor, the air was pumped into the aerobic layer through perforated pipes. The operational temperature of bioreactors was ambient temperature (25–40°C). Leachate recirculation was conducted in all reactors. The leachate from the bioreactors was fed to the top of reactor at a flow rate of 2 L/h using peristaltic pump (Longer Pump Inc., China). In the hybrid bioreactors, air was injected intermittently (until leachate pH reached 7.0.) for 1 h twice a day by a compressor (Resun Ac-9906) connected to the aeration pipes, with a flow rate of 140 ml/min. Once leachate pH reached 7.0, the aeration was stopped to convert the hybrid bioreactors to anaerobic conditions for biogas generation. According to the pH value, air has been injected in R1, R2 and R3 for 33, 103 and 240 days, respectively. Xu et al. (2015) reported that hybrid bioreactor with this air injection mode could increase the methane yields.

The biogas and methane production potential test were used to evaluate the biodegradability of food wastes and biogas production potential (Khairuddin et al., 2015; Li et al., 2017). Biogas and methane yields were expressed in mL/g VS and mL/g TS.

During the operation (240 days) of the biogas production, it was collected into a tedlar bag (Tedlar bag SKC, USA) and the composition of biogas was measured using a gas chromatograph (GC- varian cp 3800) equipped with a thermal conductivity detector (TCD), similar to the method reported in the previous literature (Zhang et al., 2013).

Finally, the total mass of remained digestate after biodegradation process and its chemical and physical characteristics were measured at the end of the operation (after the 240 days of operation). The digestate was extracted from each reactor mixed in a container to increase the homogeneity. After this procedure, a sample of 500 g was taken and analyzed for each column (Cossu et al., 2016). The digestate from each reactor was analyzed as a clean product for soil amendment.

2.3. Analytical procedure

The measurements of total solids, volatile solids, ash content, total Kjeldhal nitrogen, ammonia nitrogen, COD, total coliform and total phosphorus for characterization of lechate, food waste and manure were conducted according to the procedures outlined in Standard Methods (APHA, 2012).

The pH value was measured by a digital pH meter (Jenway pH Meters – UK). The electrical conductivity (EC) was measured using conductivity meter (4520 Jenway Conductivity Meters, UK). The content of selected heavy metals in the samples (food wastes, manure, and digestate) was measured by electrothermal atomic absorption spectrophotometer (Shimadzu Corp., Japan). The measurement of heavy metals content and digestion of samples was according to the US EPA 3050B method (USEPA, 1996).

Metal standards were supplied by Merck with reagents of minimum analytical grade used in the analysis. The elements such as calcium magnesium, potassium and sodium were also measured.

The food wastes were digested according to Standard Methods prior to TKN, TP and heavy metal analyses. TS and VS results were reported in percentage (%), while the results for TKN, TP and heavy metals were reported as mg/kg.

Carbon content of food waste was determined via dividing the volatile fraction by 1.83 (Adhikari et al., 2008). Other characteristics such as organic matter, crude protein, crude fat, and total hydrocarbons were also measured (Pandey et al., 2016).

2.4. Statistical methods

All the physicochemical properties of biogas, leachate, feedstock, and digestate samples were measured in triplicate and the mean values with standard deviation were presented.

Analysis of variance (ANOVA) was used to assess the significance of differences between the three bioreactors performance (p-value < 0.05). Analysis of variance was performed by SPSS 13.0.

3. Results and discussion

3.1. Composition of food waste and manure

The selected physical and chemical quality characteristics of loaded food wastes and manure into bioreactors are shown in Table 1. The average amount of moisture was 74.09%, suggesting that the food waste contained sufficient moisture for anaerobic digestion. The measured values of total crude hydrocarbons, total protein, total fat, moisture, C/N ratio, and VS/TS lied within the range of the values reported in other literatures for food waste (Bong et al., 2018; Li et al., 2011; Neves et al., 2008; Sridevi et al., 2015).

The results in this study suggested that the total crud hydrocarbons, total protein, and total fat values in feedstock were 72.43, 13.91, and 1.9%, respectively. Bong et al. (2018) who reviewed the characterization and treatment of food waste for improvement of biogas yield, reported values of 11.8-74%, 13.8-18.1%, and 3.78-33.72% for the total crud hydrocarbons, total protein, and total fat, respectively. Neves et al. (2008) showed that the most efficient methane production rate was observed for the waste with an excess of hydrocarbons.

The food waste degradation under methanogenic conditions depends on waste composition (Neves et al., 2008). In this study, C/N ratio was 24.04, revealing that the food waste contained a sufficient C/N ratio for anaerobic digestion.

An optimal C/N ratio is necessary to increase the process stability and biogas yield (Li et al., 2011). The amount of VS was 88.24%, which could indicate a good potential for biogas production. Sridevi et al. (2015) demonstrated that the specific biogas production grows with increase in volatile solids content. Therefore, this feedstock is susceptible to biological degradation and bio-methane production as a renewable energy.

3.2. pH profile

The variations of pH profile of leachate from three reactors over time are presented in Fig. 3. Because of aeration and lime pretreatment, in R3 bioreactor, the pH values started to increase during 33 days whereby the pH became slightly alkaline. This rise of pH occurred during 103 days in R2 bioreactor. The R1 bioreactor remained at acidic phase during the entire operation period. During the initial four weeks, pH levels of leachate for all reactors were lower than 6.0. At an early stage of anaerobic digestion, the organic matter was rapidly converted to fatty acids by hydrolysis, resulting in pH fall (Zhai et al., 2015). In the formation of acidogenic and methanogenic phases, pH plays an important role, such that previous studies have suggested that methanogenic phase could occur effectively at pH 6.5-8.2 while acidogenic phase occurred at pHs 5.5 and 6.5 (Zhai et al., 2015). The peak pH level for R3 bioreactor occurred in week five, when it reached beyond 7.

Table 1. Selected physical and chemical properties of food wastes and manure used for feedstocks of the hybrid anaerobic–aerobic bioreactors

Properties*	***Unit***	***Average*** ± *SD*	
		Food wastes	***Manure***
total crude hydrocarbon	%	72.43±8.9	38.64±4.6
total protein	%	13.91±4.4	11.63±3.2
total fat	%	1.9±0.51	1.88±0.34
Moisture	%	74.09±10.03	79.49±10.03
Nitrogen	%	2.14±0.64	2.64±2.02
Carbon	%	51.59±4.04	58.63±3.12
Phosphorus	mg/kg	3.97±0.57	2.84±0.43
pH	pH unit	6.02±0.15	7.98±0.34
Electro Conductivity	mS/cm	2.86±0.04	3.81±0.25
Total Solids	%	25.91±2.03	20.51±1.93
VS/TS	%	88.24±8.93	82.34±4.43
Ash/TS	%	11.76±1.21	18.66±1.23
C/N	-	24.04±1.07	22.23±1.07

**All the values of properties, except moisture, pH, and electro conductivity, are reported on dry weight basis; VS/TS: volatile solids to total solids ratio, Ash/TS: Ash to total solids ratio, and C/N: carbon to nitrogen ratio*

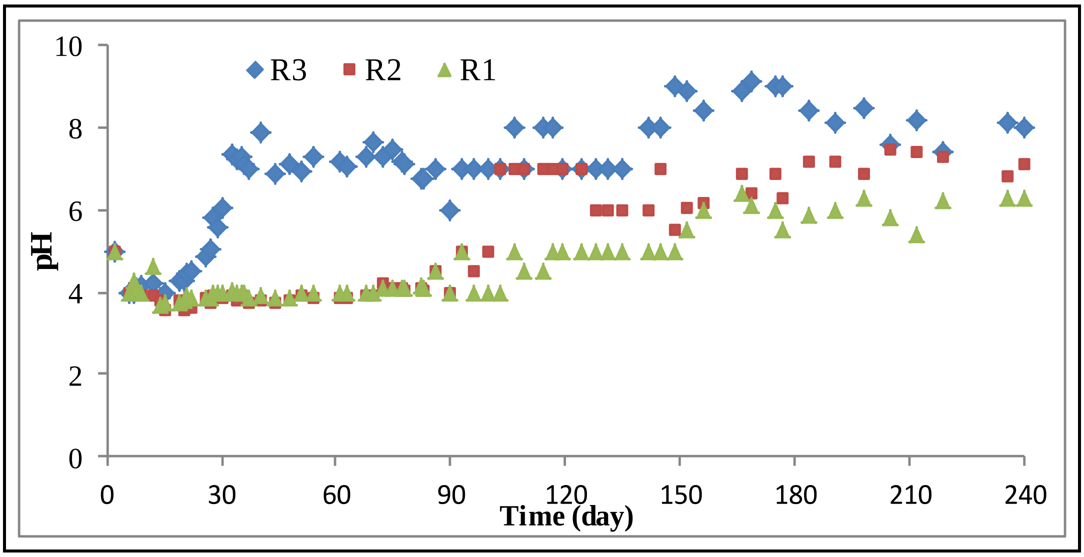

Fig. 3. The variation of pH profile of leachate from R1, R2, and R3 hybrid anaerobic–aerobic bioreactors during the operation time

The R1 bioreactor remained at acidic phase during the operation period (day 240). These results are in accordance with previous studies. A previous study suggested that alkali pretreatment is the best-known method for increasing the pH and enhancing the biogas production in anaerobic digestion process (Lin et al., 2009).

3.3. Temperature profile

The temperature profile in the center of hybrid anaerobic–aerobic bioreactors over time is represented in Fig. 4. Environmental temperature was within 25-40ºC. The results indicated that thermophilic temperatures were achieved during several months for R3 reactor but R1 and R2 reactors were mesophilic during the operation times.

One of the most significant parameters influencing biological process such as anaerobic digestion is temperature (Zhang et al., 2014). A peak in temperature was observed after 75 days of experiment for R3 reactor, which probably was due to changes in the aeration rate, manure addition, and lime pretreatment.

Thus, it can be concluded that the R3 bioreactor performance grows with elevation of temperature, showing its higher metabolic rates, specific growth rates, and rates of the destruction of pathogens and viable weed seeds along with greater biogas production (Zhang et al., 2014). Yu et al. (2014) pointed out that the biogas production under thermophilic conditions was greater than the output under mesophilic conditions.

3.4. Cumulative biogas and methane production in hybrid anaerobic–aerobic bioreactors

The cumulative yields of biogas and methane in experimented bioreactors with different operation conditions are demonstrated in Figs. 5 and 6.

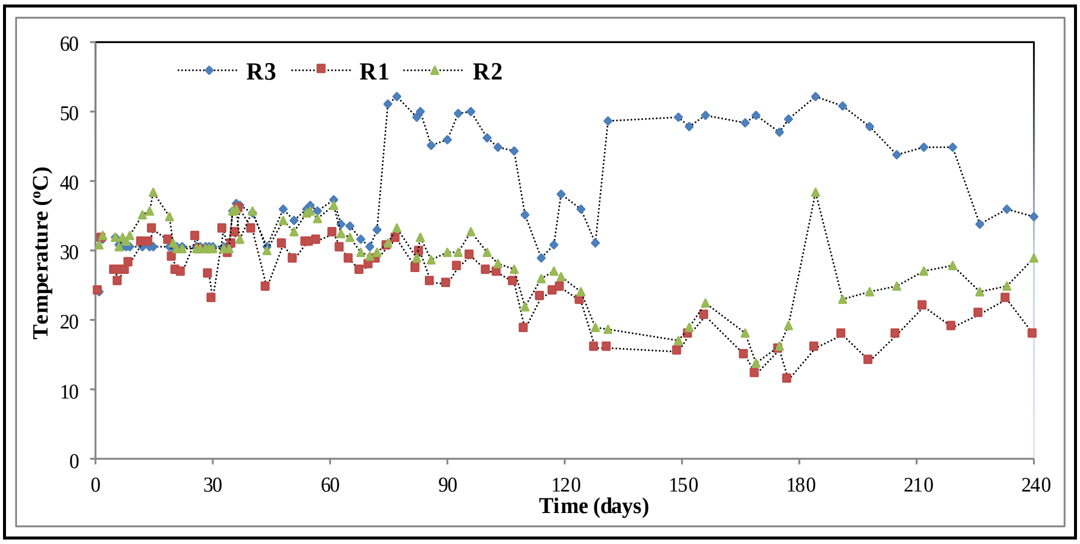

Fig. 4. The temperature profile of hybrid anaerobic–aerobic bioreactors during operation time for R1, R2, and R3 bioreactors

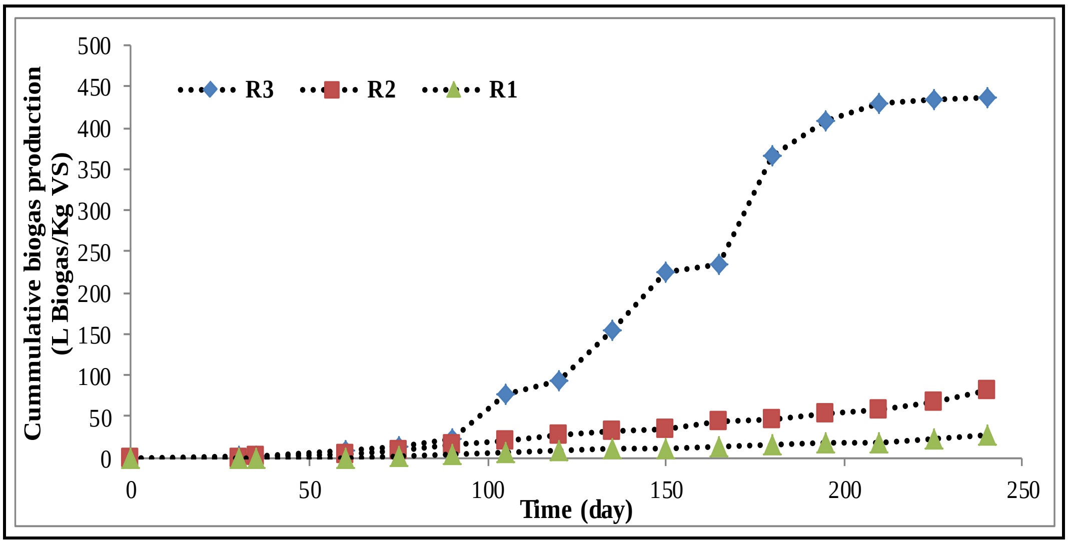

Fig. 5. The cumulative production of biogas with different operation conditions for R1, R2, and R3 hybrid anaerobic–aerobic bioreactors during 240 days of operation

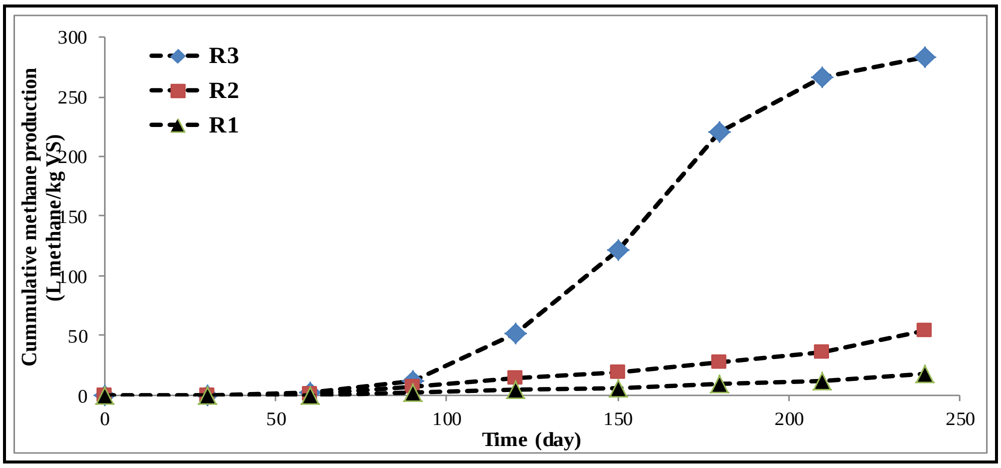

Fig. 6. The quantity of methane gas production in the three hybrid anaerobic–aerobic bioreactors with different operating conditions for R1, R2, and R3 reactors during 240 days of operation

The cumulative biogas production was 26.87, 82.76, and 436.02 L biogas/initial kg VS for R1, R2, and R3 bioreactors, respectively during 240 days of operation. The statistical analysis showed that the biogas production of R3 hybrid anaerobic–aerobic bioreactor was significantly different from that of R1 and R2 hybrid anaerobic–aerobic bioreactors ($p<0.05$). Also, there was a significant difference between R2 and R3 bioreactors ($p<0.05$). The results of this study indicated that the cumulative biogas output in the R3 bioreactor was 16.22 and 5.27 times higher than that in R1 and R2 bioreactors, respectively. In order to increase biogas production from food waste degradation, some studies had been conducted. Yang et al. (2015) indicated that increase in biogas yield could be achieved by pH adjustment and thermophilic anaerobic digestion from food wastes. The lowest cumulative biogas yield was observed in R1 bioreactor (without lime pretreatment and manure addition). This reactor had pH lower than 7 at during the operation. Montañés et al. (2014) reported that low pH would stimulate acidogenic activity and inhibit methanogenic activity.

The cumulative methane gas production yields of R1, R2, and R3 bioreactors under different operation conditions are shown in Fig. 6. The R3 bioreactor had the highest methane yield, compared with the R1 and the R2 bioreactors.

Statistical analysis results indicated a significant difference between the amounts of methane gas produced in the R1, R2, and R3 hybrid bioreactors ($p<0.05$), such that gas production in R3 was greater than in R1 and R2. A similar observation was also obtained by Lin et al. (2009) in laboratory-scale experiments.

They found that alkaline pretreatment on anaerobic digestion of the biodegradable fraction of urban wastes caused a significant increase in methane production up to 172 % over the control without pretreatment.

The R3 bioreactor had the highest biogas yield, compared with the R1 and the R2 bioreactors. After 240 days of operation, methane yield was calculated to be 17.46, 53.79, and 283.41 L methane/ initial kg VS for the R1 and R2, and R3 hybrid anaerobic–aerobic bioreactors, respectively. This result agreed with a previous study reporting that simultaneous digestion of food waste and animal manure under anaerobic digestion may improve the performance of anaerobic process and the biogas and methane production efficiencies (Zhang et al., 2013). In recent years, co-digestion of food waste with other substrates has been a common strategy to enhance the process performance and biogas generation (Bong et al., 2018).

Use of some additives such as animal manure can significantly reduce the lag phase of bacteria growth in food waste degradation processes and produce higher biogas generation (Gaur and Suthar, 2017). Other researchers have experimented that inocula type directly affects the degradation of organic matter and biogas gradation process in anaerobic co-digestion. The animal manure accelerates the bioremediation process in anaerobic co-digestion mainly due to its high nutrient load and anaerobe microbial diversity (Gaur and Suthar, 2017). The results indicate that a hybrid anaerobic-aerobic bioreactor with manure addition and lime pretreatment of recycled leachate can improve the biogas production yield.

Producing more biogas in R3 bioreactor was confirmed with the results of pH and temperature changes profile for this reactor as two major factors in biological degradation. Some recent studies on this topic will be given herein below and listed in Table 2. The methane yields **(**ml CH_4/g VS) were comparable with the previous studies. At the end of this research, after 240 days of operation, about 283.41 L methane/kg VS were generated in R3 hybrid bioreactors. Some studies have shown higher levels of methane production, while other studies revealed less methane production.

The variation of methane yields mainly resulted from the differences of physical and chemical properties of wastes, the different operational parameters of wastes digestion, and type of wastes.

4.4. Digestate quality in anaerobic-aerobic bioreactors

The results of physical and chemical quality of digestate obtained from food waste degradation using hybrid anaerobic–aerobic bioreactors (R1, R2, and R3 bioreactors) are provided in Tables 3 and 4. The moisture content on a wet basis was 77.51±2.48, 78.18±4.17, and 73.20±2.70 for R1, R2, and R3 bioreactors, respectively.

Table 2. Methane generation of food wastes in selected studies

Type of wastes	*VS/TS (%)*	*Objective*	*CH_4 yield (ml CH_4/g VS)*	*References*
Municipal Solid waste	64	Comparing simulated anaerobic and hybrid bioreactors for biogas generation	113.2 and 133.4	Xu et al. (2015)
Food waste and rice husk	84.80	Assessing effectiveness of high solids anaerobic co-digestion of food waste and rice husk for biogas production	446	Jabeen et al. (2015)
Municipal Solid waste	25.8-58.9	Appling the hybrid digestion process for a greater methane generation	75-102	Cossu et al. (2016)
Food waste	61.10	Investigating the impact of inoculation on co-digestion of food waste and biogas production	109	Gaur et al., 2017
Food waste	95- 97	Investigating the influence of carbohydrates, proteins and lipids on the anaerobic digestion of food waste	385–627	Li et al. (2017)
Food waste	91.53	Improving performance of food waste degradation and energy recovery	730	Nguyen et al. (2017)
Food wastes	93.8	Investigating the influence of aerobic pre-treatment to enhance methane generation	357-442 ml	Wu et al. (2018)
municipal solid waste	61.9	Evaluating the effectiveness of aerobic pretreatment of municipal solid waste on accelerating biogas generation	114-384	Ali et al. (2018)
Food wastes	88.24	Investigating the effect of manure addition and leachate lime-pretreatment on the biogas production using a hybrid bioreactor	283.41	In this study

Table 3. The physical and chemical quality of digestate obtained from feedstock degradation using hybrid anaerobic-aerobic bioreactor (R1, R2, and R3 bioreactors)

*Properties**	*Unit*	*Average±SD*		
		R1	*R2*	*R3*
Total hydrocarbons	%	58.68±4.36	47.56±6.80	38.94±2.46
Total protein	%	9.62±1.72	8.75±1.12	8.75±1.23
Total Fat	%	4.70±0.85	1.72±1.80	1.33±0.45
Moisture	%	77.51±2.48	78.18±4.17	73.20±2.70
Nitrogen	%	<1.4	<1.4	1.54±0.02
carbon	%	29.24±2.15	29.05±5.41	25.01±0.54
Phosphorus	mg/kg	-	-	4.07±0.51
pH	pH unit	5.65±0.050	7.19±0.03	7.96±0.03
Electoconductivity	Ms/cm	2.87±0.06	4.69±0.02	4.78±1.20
Total Solids	%	20.49±8.35	19.82±6.42	39.90±11.35
VS/TS	%	72.13±1.36	57.42±5.15	49.03±0.56
Ash/TS	%	27.87	42.58	50.98
C/N Ratio	-	20.88	18.86	17.86

**All the values of properties, except moisture, pH, electro conductivity, and total coliform are reported on dry weight basis; VS/TS: volatile solids to total solids ratio, Ash/TS: Ash to total solids ratio, and C/N: carbon to nitrogen ratio*

Table 4. The average values of certain metal concentrations of feedstock and digestate after degradation (R1, R2, and R3 bioreactors)

*Element**	*Unit*	*Feedstock*	*R1*	*R2*	*R3*
Fe	(mg/kg)	0.3±0.4	0.24±0.1	0.41±0.0	0.13±0.10
Pb	(mg/kg)	ND	0.003	0.004	0.004
Al	(mg/kg)	0.1±0.0	0.01	0.23	0.09
Cd	(mg/kg)	ND	ND	ND	ND
Zn	(mg/kg)	0.02±0.02	0.005	0.007	0.03±0.02
Cr	(mg/kg)	ND	-	-	ND
Cu	(mg/kg)	0.01	-	-	0.01
Ni	(mg/kg)	ND	-	-	ND
Na	(mg/kg)	0.03	-	-	0.05
Mg	(mg/kg)	0.08	-	-	0.09
Ca	(mg/kg)	0.13	-	-	0.1

**All the values are reported on dry weight basis*

The average total hydrocarbons, nitrogen, C/N Ratio, phosphorus, for R3 were 38.94±2.46, 1.54±0.02, 17.86, and 4.07±0.51, respectively.

The total weight of the digested feedstock from R3 bioreactor was 9.48 kg (on wet weight basis) at the end of the operation time. The total solid reduction amount was 26.98% which can be due to the biological degradation of organic matter, with volatile solids, C/N ratio, proteins, fats and hydrocarbons reduction (Tables 1 and 3) and biogas production (Fig. 1 and Fig. 2) in R3 reactor confirming this. In R3 bioreactor, the total hydrocarbons, nitrogen, and C/N ratio decreased from 72.43% to 38.94±2.46%, 2.14% to 1.54%, and 24.04% to 17.86%, respectively. The total amounts of hydrocarbons, nitrogen, volatile solids, and carbon to nitrogen ratio reduction in R3 bioreactor were about 43.61, 29.68, 44.06, and 25.14%, respectively. The decrease in total hydrocarbons, nitrogen, and C/N Ratio could be a result of mineralization in organic fraction of food waste (Hirata et al., 2012).

The VS reduction is an important indicator of the degree of waste stabilization (Xu at al., 2015). The VS/TS values of feedstock and digestate from each bioreactor was presented in Tables 1 and 3. Compared to the initial VS/TS of feedstock (about 88 %), the VS/TS of digestate in R1, R2, and R3 bioreactor was 72.13%, 57.42%, and 49.03% after 240-day operation, indicating the highest degree of VS reduction was achieved in R3. The greater VS/TS reduction for R3 bioreactor coincided with the greater biogas production.

Heavy metal content is considered another important quality parameter necessary for digestate from food waste degradation (Saha et al., 2010). The average concentration of heavy metals in digestate from all bioreactor remained considerably lower compared to the contents found in digestate from municipal solid wastes and other organic matters (Saha et al., 2010; Tyagi et al., 2018).

The results obtained proved that the mass product from a hybrid anaerobic–aerobic bioreactor with manure addition and lime pretreatment of recycled leachate method could produce acceptable value of nitrogen, phosphorous, and potassium, where the heavy metal was also found to be in desirable limits (Möller, 2015; Saha et al., 2010).

This digestate contained sufficient nutrient contents such as nitrogen, phosphorus, potassium, copper, manganese and zinc. Also, due to the small amount of heavy metals and salinity and a high amount of stabilized organic matter, this final digestate could be used as soil amendment and organic fertilizer after moisture content reduction.

4. Conclusions

A hybrid anaerobic-aerobic bioreactor with manure addition and lime pretreatment of recycled leachate for 240 days operation can effectively decompose food wastes with significant biogas production and mass recovery as soil conditioner. The biogas and methane production yield of R3 bioreactor was far higher than that of R1 and R2 bioreactors. The cumulative biogas yield (283.41 ml CH_4/g VS) of R3 bioreactor was 16.22 and 5.27 times higher than that of R1 and R2 bioreactors, respectively. Therefore, a hybrid anaerobic–aerobic bioreactor with manure addition and lime pretreatment of recycled leachate may hold a strong potential for food waste biodegradation and methane generation. By controlling the pH through the lime-pretreatment process in the hybrid anaerobic-aerobic bioreactor, conditions can be improved for biological decomposition and biogas production. Although only lime was used in this study, the use of other alkali is recommended in other studies for comparison. In this study, cow manure was used with a constant ratio of 10%. Also, in other studies, different types of manure and different proportions can be studied.

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