

A Technological Overview of Anaerobic Biofilm Digester in Reducing Greenhouse Gas Emission and Providing Energy Efficiency for Municipal Solid Waste Management in Malaysia

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ABSTRACT

Municipal solid waste is one of the major problems faced by developing countries such as Malaysia where final disposal is usually at landfills. Two of these waste disposal problems are the first, almost half of them are organic waste that is perishable food, while the second problem in landfill is leachate production. Anaerobic biofilm digester is seen as a technology that can solve this problem. For practical operation, the proposed process for food waste is in the form of household kits, while for leachate disposal is a decentralized system at landfill sites. Both studies were successfully conducted at the National University of Malaysia. This study investigated the performance of a 160 L anaerobic biofilm single-stage reactor in treating food waste. The reactor was operated at different hydraulic retention times (HRTs) of 124, 62, and 35 days under mesophilic conditions. The maximum biogas and methane yield achieved was 0.934 L/g VS_{added} and 0.607 L CH₄/g VS_{added}, respectively. The highest VS (79%) and COD removal efficiency (80%) were achieved at an HRT of 35 days. In UKM, a pilot-scale anaerobic biofilm digester treating young leachate under reduced hydraulic retention times shows great removal efficiency of COD (98%), BOD₅ (99±1%) and total phosphorus (92±8%). This showcase of high performance is because of the biofilm technology used which has successfully retained 67±4% of solid TSS contents in the digester, leading to long solid retention times which are 105, 91, 97 and 56 days for hydraulic retention time of 30, 25, 20 and 10-day respectively, keeping the microbial community in the digester ready for optimum young leachate treatment. This study demonstrates that the stability and performance of the AD process, namely biogas production rate, methane yield, intermediate metabolism, and removal efficiency, were significantly affected by HRT.

Keywords: Anaerobic biofilm digester, biogas, food waste, leachate.

INTRODUCTION

An ever-expanding population and high rates of economic development in Malaysia resulted in the generation of vast amount of waste. It is estimated about 25,000 ton/day of waste generated in Peninsular Malaysia with an average per capita generation of 0.85 kg/ca/day, and about 1.5 kg/cap/day in the city of Kuala Lumpur. Our Local Authorities are the implementing agencies and have direct responsibility over solid waste collection, treatment and disposal. About 76% of waste generated are collected. A percentage of 1-2% is recycled and the remainder is taken to disposal sites. Land filling is the cheapest and simplest waste disposal option. According to the Malaysian Ministry of Housing and Local Government website, as of January 2011, there are 296 landfill/dump sites in Malaysia, of which 166 are still in operation, including 9 sanitary landfills [1].

Organic waste constitutes 47% of the overall MSW in Malaysia [2]. Food Waste (FW) is among organic waste that is a challenge to be disposed of properly without polluting the environment. Indeed, food waste can decompose naturally, but if left alone or discarded at will, it would have disrupted the scene while waiting for it to break down. A study by Baroutian et al. [3] who reported that the total amount of FW produced by every single person is 160-295 kg/year all over the world. Since FW creates harmful impacts at the environmental level, appropriate management and treatment of FW is the major purpose encountered by numerous countries across the world. FW generates greenhouse gas (GHG) not only during activities associated with food production, processing, manufacturing, transportation, storage and distribution but also during final disposal in the landfills, resulting in contributing to climate change [4]. They reported that agriculture is the cause of approximately 22% of GHG emissions compared to livestock production (about 18%). Final disposal of FW in landfills is one of the principal environmental effects. Clercq et al. [5] revealed that considerable amounts of GHG including methane (CH₄) and carbon dioxide (CO₂) are produced when FW is disposed of in landfills. They showed that the emission of GHG into the atmosphere contributes to global warming, where methane is a potent GHG having a greenhouse effect 25 times more than that of CO₂. According to [6], the carbon footprint of food produced and not eaten is

calculated at 3.3 billion tons of GHG every year, which assist in reaching FW the third position after the USA and China for GHG emissions.

Leachate excreted from municipal solid waste is one of the complicated waste waters to deal with, owing to its highly variant components and substances [7-9]. The technology used for leachate treatment depends on the leachate characteristic which was generally classified as young, medium and old leachate, based on the age of waste disposal sites. To cite an example, biological treatments like aerobic and anaerobic especially, display better performance in treating young leachate due to its high organic compound (e.g. volatile fatty acids) which if treated effectively, could produce profitable green by-products (biogas and bio-fertilizer) [9]. Meanwhile, adsorption and ion exchange systems are more effective in treating old or matured leachate that contains more non-biodegradable compounds such as humic acids and heavy-metal impurities [10]. Even though Nano filtration and reverse osmosis are the most efficient technologies in treating all kind of leachate [11], because of the expensive cost, these systems are not even an option in the first place for high-strength wastewater treatment especially for developing countries.

Both food waste and leachate are organic in nature. The Anaerobic Digester (AD) is an excellent alternative for organic waste treatment, energy supply, and environmental protection [12]. There are numerous benefits related to the AD process such as decreases in GHG emission, reduces dependence on inorganic fertilizers, small footprint, generates high-quality renewable fuel [13]. However, the drawback of the AD process makes some limitation for widely implementing this process such as relatively high capital costs, long retention time, some key parameters (e.g., pH, temperature, feed rate, alkalinity) need to be controlled [13]. This is because; these two constraints coming from conventional anaerobic process have been overcome with the use of high rate anaerobic digesters that engages cell immobilization techniques like granules and biofilms [7,14,15]. Microbial communities attached on biofilm carriers can circulate freely within the digester and retained by screens at the outlets and inlets [16], thus, avoiding the washout of microbes, a common problem in most of conventional anaerobic systems.

MATERIALS AND METHODS

A. Treatment of Food Waste in a Household Kit Anaerobic Biofilm Digester

Food Waste (FW) was used as a substrate and collected from a cafeteria near the Faculty of Engineering, Universiti Kebangsaan Malaysia, Malaysia. The cafeteria has provided different bins for food waste and other residues where customers have been asked to separate the waste themselves through an earlier campaign. The FW was then grinded to produce waste with a particle size between 4 mm and 10 mm. The compositions and characteristics of the FW used in this experiment are shown in Table I. Fresh cow manure (CM) was used as an inoculum in this study. The pH, total solids (TS), volatile solids (VS), and chemical oxygen demand (COD) of the inoculum were 7.72, 37.70 mg/l, 24.63 mg/l, and 31.55 g/L, respectively. Both the FW and the CM slurry were stored at 4°C in an airtight plastic container to prevent any degradation until its next use.

TABLE I. COMPOSITION AND CHARACTERISTICS OF THE FOOD WASTE USED IN THIS STUDY

Type of food waste	Percentage composition (% wet weight)	
Rice, pasta and noodles	48	
Vegetables	21	
Meat, fish and egg	17	
Fruits and berries	8	
Bakery and grain products	6	
Characteristics of the food waste		
Parameter	Stage-1	Stage-2 & 3
Total solid; TS (g/L)	66 ± 2.41	96.42 ± 0.62
Volatile solid; VS (g/L)	63 ± 2.27	92 ± 0.62
VS/TS ratio	0.96	0.95
pH	4.91 ± 0.16	4.57 ± 0.28
Chemical oxygen demand; COD (g/L)	110 ± 8.16	160.9 ± 1.13
Soluble chemical oxygen demand; sCOD (g/L)	35 ± 3.80	51.6 ± 1.64
Ammonia-nitrogen; NH ₃ -N (mg/L)	104 ± 6.52	112.63 ± 7.52
Total Kjeldahl nitrogen; TKN (mg/L)	356 ± 10.7	377.63 ± 12.58
Total volatile fatty acid; tVFA (mg HOAc/L)	3585 ± 99.6	4573.33 ± 144.91

Note: The values indicate average ± standard deviation of duplicate samples.

The configuration of the 160 L single-stage AD system is shown in Figure 1. A single-stage high-density polyethylene anaerobic reactor with a working volume of 124 L was used in this study. The reactor was equipped with a stainless-steel stirrer with four arms to provide sufficient mixing of substrates; performed manually twice a day for 2 minutes. For biofilm attachment, the reactor was filled with 9,000 units of plastic media with 1.6-cm diameter and 1-cm thickness. The outlets of the reactor were installed with stainless-steel sieves with an opening diameter of 0.6 cm, to ensure that the plastic media remained inside the digester. The operational temperature was set between 31°C and 34°C. No external heat exchangers were used to maintain the reactor temperature since Malaysia is characterized by hot and humid weather throughout the year.

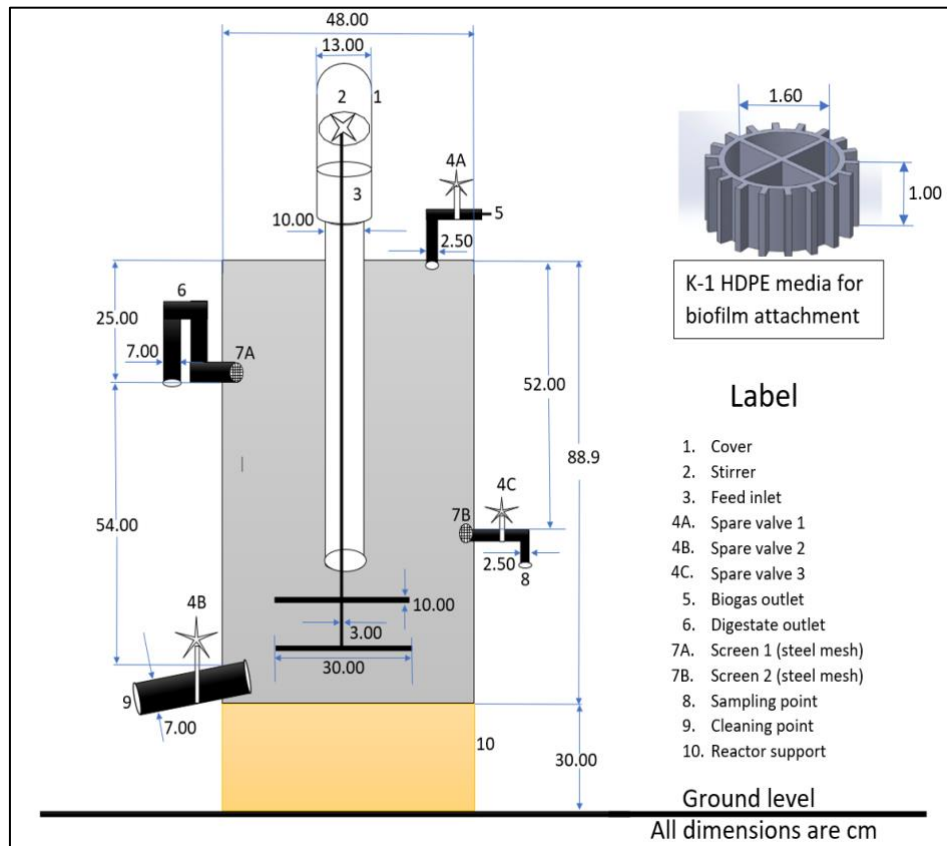


Figure 1. Schematic diagram of the single-stage anaerobic biofilm digester system

In the beginning, the reactor was inoculated with 124 L of the CM slurry. The start-up operation of the reactor was completed for two weeks with synthetic wastewater of 260 mL/day and an OLR of 0.01 kg COD/m³/d. This low strength synthetic wastewater was used to provide low organic stress to the reactor. After a successful start-up, the reactor was operated under a sequence of increasing OLRs of 0.51, 1.4, and 2.45 kg VS/m³/d while consecutively decreasing the hydraulic retention time (HRT) from 124 days, 62 days, and 35 days over 77 days. Throughout the operation, FW was fed into the reactor three days a week. The operational conditions for OLR and HRT are shown in Table II. Sampling was performed using a sampling pipe to measure several parameters including the pH, temperature, volatile fatty acids (VFAs), and ammonia nitrogen (NH₃-N) for monitoring purposes. The effluent from the reactor was used to check the digester's performance throughout its operation. The collected effluents were first stirred to achieve homogeneity and then placed into an HDPE bottle and sampled. The biogas component ((e.g., methane (CH₄) and carbon dioxide (CO₂)) and volume were measured on site using a portable biogas analyzer and supelTM-inert multi-layer foil gas sampling bags, respectively.

TABLE II. OPERATIONAL CONDITIONS OF SEMI-CONTINUOUS SINGLE-STAGE ANAEROBIC DIGESTION SYSTEM

Stages	Duration (days)	Q (L/day)	OLR (kg VS/m ³ /d)	HRT (days)
1	0 - 37	1	0.51	124
2	38 - 63	2	1.4	62
3	64 - 77	3.5	2.45	35

Note: Influent flow rate (Q); hydraulic retention time (HRT); organic loading rate (OLR).

B. Treatment of Municipal Solid Waste Landfill Leachate in a Prototype Anaerobic Biofilm Digester

The pilot scale anaerobic biofilm digestion system consists of anaerobic biofilm digester (ABD) with a working volume of 5.95 m³ and a biogas bio-scrubber as shown in Figure 2. All ABD inlets and outlets have been fitted with a stainless steel screen to ensure 3-D HDPE media are kept in the digester. As for biogas bio-scrubber biogas, its primary function is to clean the biogas produced before use. This paper however will only discuss the digestion of anaerobic biofilm reactor without taking into account the biogas bio-scrubber. After the start-up, the ABD system was run under reduced hydraulic retention time (HRT) of 30, 25, 20 and 10 days respectively for 163 days. To achieve a steady state, the ABD is mostly operated for two or three cycles for each HRT (for example: HRT 30 days, two cycles means 60 days of operation). The young leachate was fed daily into the ABD and was distributed fairly between ABD-A and ABD-B through sludge recycling pump (refer FIG. 1). The discharged ABD effluent (sampling point B) was first stirred gently for homogeneity and then collected into HDPE bottles. Most analyses were carried out within 12 hours and if not, sample storage was done using the EPA Guideline.

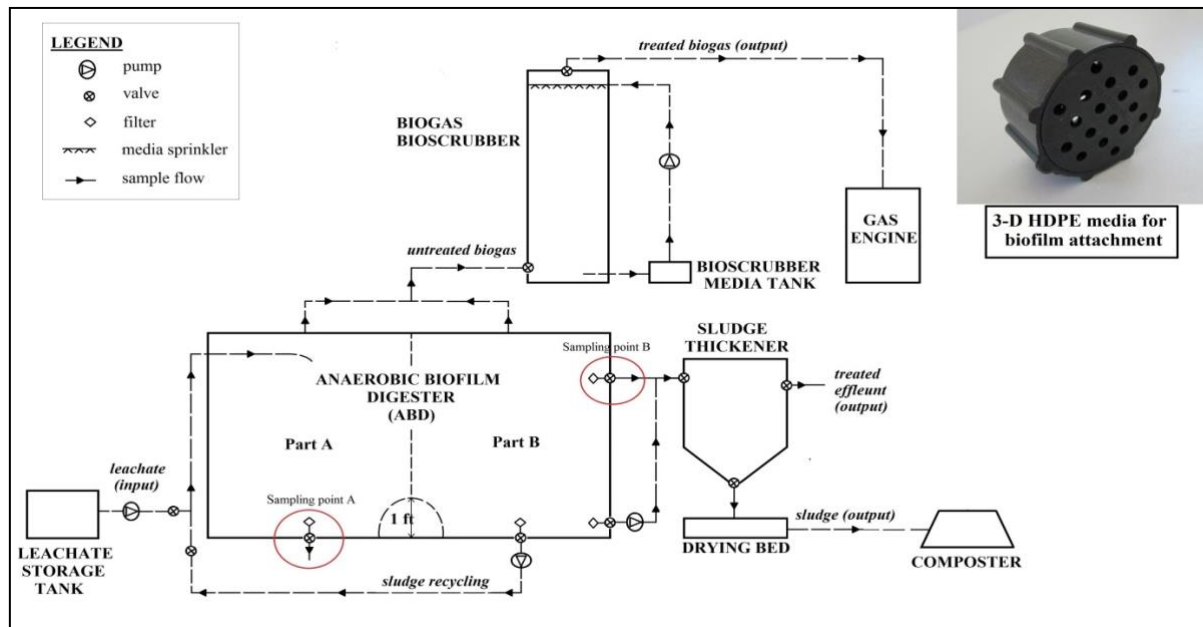


Figure 2. Schematic drawing of a complete pilot-scale anaerobic biofilm digester system

C. Analytical Methods

pH and temperature were determined using test probe while alkalinity, five-day biological oxygen demand (BOD₅) and suspended solid (total, TSS and volatile, VSS) measurements were in accordance with the Standard Method for the Examination of Water and Wastewater [17]. Chemical oxygen demand (COD), total volatile fatty acid (tVFA) and total phosphorus were measured using reactor digestion method (HACH, COD High Range), esterification method (HACH, Method 8196) and acid persulfate digestion method (HACH, Method 8190) respectively. All tests were performed in duplicates to get a constant average. All analyses were undertaken at room temperature of 25±2°C. Meanwhile, for biogas composition and production, the measurement was done via portable biogas analyzer and thermal-mass flow meter respectively. Biogas was collected in gas collection bags (supelTM-inert multi-layer foil bag), whereas the methane and carbon dioxide content in the biogas was measured using a gas analyzer (Biogas 5000, Geotech, UK).

RESULTS AND DISCUSSIONS

A. Performance of the Single-Stage Household Kit AD System

Removal efficiency is considered significant in evaluating the performance of an anaerobic digestion (AD) process. The organic substances of FW were degraded and transformed into biogas during the AD process, which resulted in the fluctuations of TS, VS, and COD concentration (Figure 3). The effluent TS, VS, and COD concentrations during the AD process fell in the range of 19-62 mg/L, 13-42 mg/L, and 22-67g/L, respectively. An average TS destruction efficiency of 38% was observed at an HRT of 124 days, which then sharply increased to 65% and 72% when the HRTs decreased to 62 days and 35 days, respectively. The lowest average VS removal

rate of 58% was observed at an HRT of 124 days and an OLR of 0.51 kg VS/m³/d, respectively. The highest average VS removal of 79% was achieved when HRT was shortened to 35 days and the OLR was increased to 2.45 kg VS/m³/d, respectively. This could be considered a result of the urging of the floating scum that brought the sludge to the upper portion of the reactor as reported by Hu et al. [18]. At an OLR of 0.51 kg VS/m³/d and an HRT of 124 days, the average COD removal was 60%. When the OLR increased to 1.4 kg VS/m³/d and 2.45 kg VS/m³/d and the HRT decreased to 62 days and 35 days, the average removal efficiency of COD increased sharply to 78% and 80%, respectively. A similar observation was reported by Kumar et al. [19], who noted that COD reduction efficiency was increased with a decrease in HRTs and an increase in OLRs, consistent with the present study. This result shows that biogas yield had a negative correlation with TS, VS, and COD reduction efficiency with decreasing HRTs.

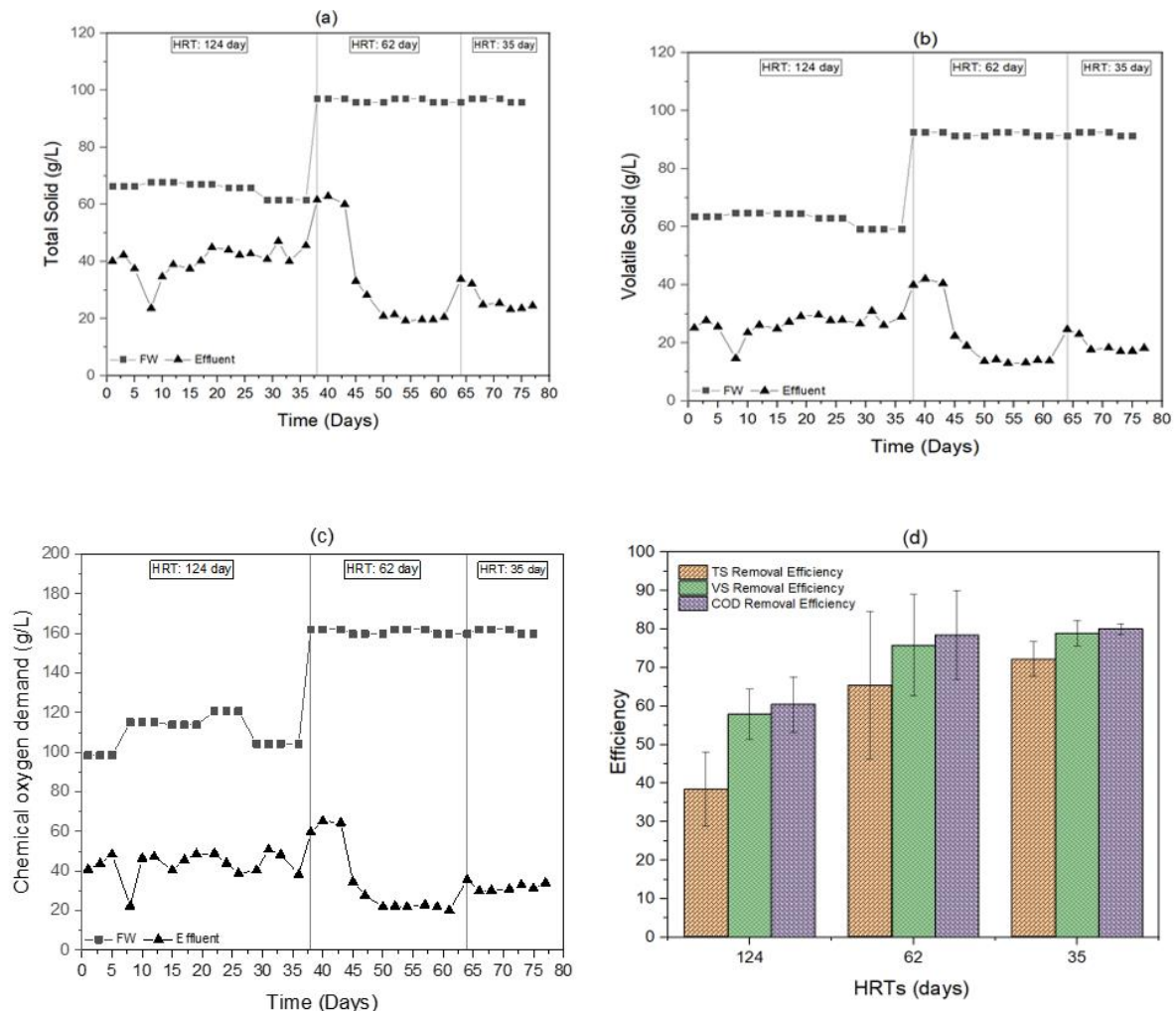


Figure 3. Variations of TS, VS and COD in different operating stages during anaerobic digestion of food waste. (a): TS concentration; (b): VS concentration; (c): COD concentration; (d): average removal efficiency of TS, VS, and COD at different HRTs

The biogas yield and the volumetric biogas production rate (VBPR) at different HRTs are displayed in Figure 4. It is found that the production of biogas started immediately on the first day of digestion after which it began to increase continuously until day 37. After day 37, the biogas yield started to decrease slowly and the production of biogas almost stopped after day 75. At an HRT of 124 days and an OLR of 0.51 kg VS/m³, the maximum biogas yield and the average biogas yield were 0.934 L/g VS_{added} and 0.589 L/g VS_{added}, respectively. When HRT decreased from 124 days to 62 days and OLR increased from 0.51 kg VS/m³/d to 1.4 kg VS/m³/d, the maximum biogas yield and the average biogas yield decreased from 0.934 to 0.715 L/g VS_{added} and from 0.589 to 0.41 L/g VS_{added}, respectively. This shows that the HRT reduction caused a sharp decrease in biogas yield. It is important to note that the accumulation of scum was observed in the reactor at an OLR of 1.4 kg VS/m³/d corresponding to an HRT of 62 days, after day 45. Towards the end of the experiments, the scum layer reached almost 14.5 cm thickness in the upper part of the reactor. A similar result was obtained by Hu et al. [18] who found that increasing OLR could cause the accumulation of scum in the reactor. This is likely due to the shock loading of the feed concentration in the reactor.

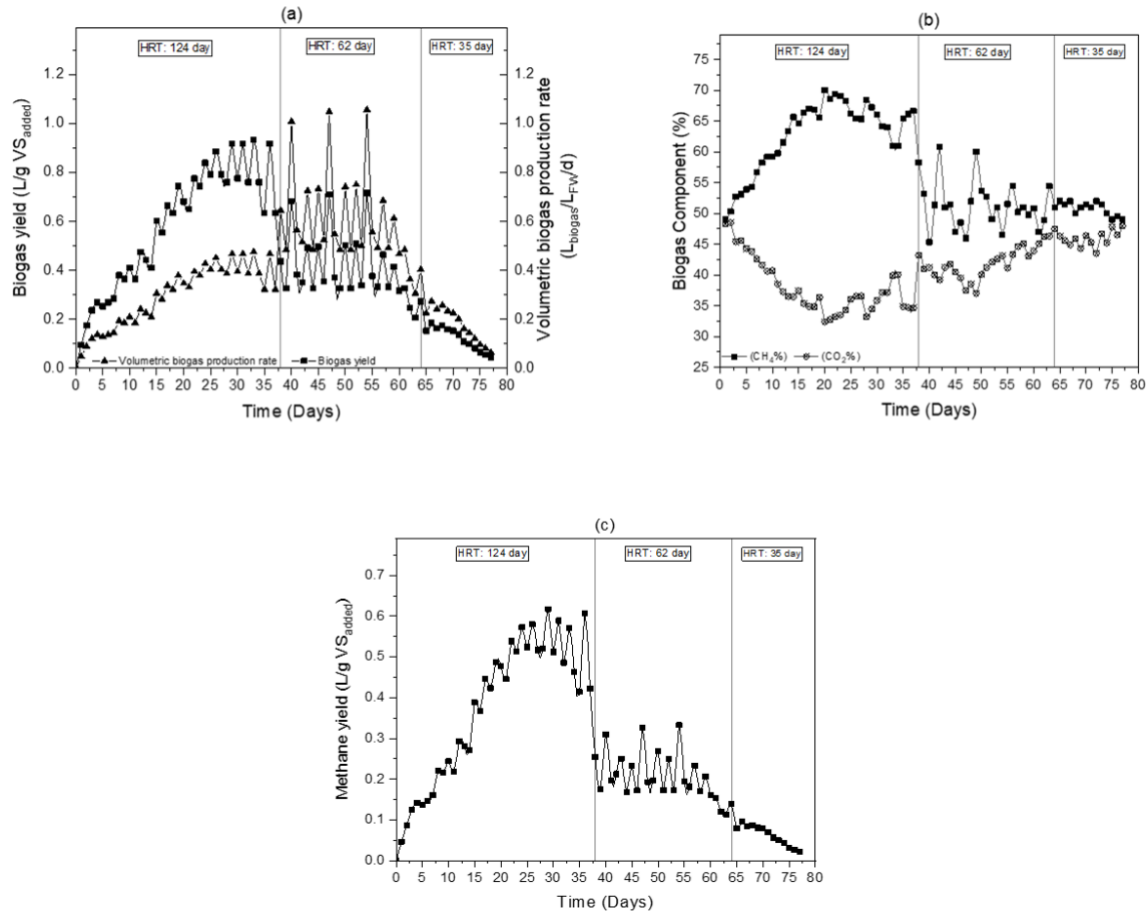


Figure 4. (a) Biogas yield and volumetric biogas production rate, (b) biogas component, and (c) methane yield during anaerobic digestion of food waste.

Methane yield is an important performance index of the reactor's efficiency during the AD of FW. The CH₄ yield declined with increasing OLRs and decreasing HRTs (Figure 4 (c)). A similar result was reported by Liu et al. [20], who observed that when the OLR increased from 1 g to 1.5 g of VS/L/day, the CH₄ yield decreased from 386 mLCH₄/g VS_{added} to 370 mLCH₄/g VS_{added} when FW was used as the substrate under mesophilic condition. Nagao et al. [21] also found that CH₄ yield decreased from 0.25 m³CH₄/kg VS_{added} to 0.05 m³CH₄/kg VS_{added} when OLR increased from 1.4 kg-VS /m³/d to 2.75 kg-VS /m³/d during the single-stage AD of vegetable waste. This was possibly due to the additional active microorganisms that could wash out with a shorter HRT during the removal of effluent and could also increase TS concentration resulting in decreasing mass transfer efficiency [22].

B. Performance of the Pilot Scale Anaerobic Digester System

In Table III, the characteristics of the influent and also the measured parameters for discharged effluent of ABD throughout operation under reduced HRT are presented in average $\pm$ standard deviation values. From the results, the digester, operated in mesophilic temperature, was deemed stable based on the measurements of pH, alkalinity and tVFA which values were within the ranges for stable anaerobic digester as quoted by previous researches [23,24]. Due to its stable condition, ABD performed efficiently thus showing high removal of organic pollutants such as COD, BOD₅ and total phosphorus with efficiency values of 98%, 99 $\pm$ 1% and 92 $\pm$ 8% respectively. The ABD also produced high quality biogas with composition of 57 $\pm$ 12% methane and 26 $\pm$ 6% carbon dioxide at steady production rate of 25 $\pm$ 1 m³/day. This showcase of high performance is due to the biofilm technology used which has successfully retained 67 $\pm$ 4% of solid contents (TSS/TS) in the digester, leading to long solid retention times which are 105, 91, 97 and 56 days for hydraulic retention time of 30, 25, 20 and 10-day respectively, keeping the microbial community in the digester ready for optimum young leachate treatment.

TABLE III. AVERAGE VALUES OF SEVERAL MEASURED PARAMETERS FOR YOUNG LEACHATE (INFLUENT) AND EFFLUENT THROUGHOUT OPERATION HRT 30, 25, 20 AND 10-DAY

No.	Parameter	Value (Avg $\pm$ SD)		Remarks (optimum range, standard discharge, etc)
		Influent	Effluent	
1	pH	4.28 $\pm$ 0.19	7.53 $\pm$ 0.14	7.0-7.8 ⁸
2	Temperature (°C)	30 $\pm$ 2	33 $\pm$ 5	35-45°C (mesophilic) ⁸
3	TSS (g/L)	8 $\pm$ 6	4 $\pm$ 6	0.05 g/L (standard leachate discharge in Malaysia) ⁹
4	VSS (g/L)	7 $\pm$ 5	2 $\pm$ 4	-
5	tVFA (g HOAc/L)	80% of organic compound	0.1 $\pm$ 0.1	< 1 g/L for stable digester ⁸
6	COD (g/L)	38 $\pm$ 3	0.9 $\pm$ 0.2 (*98%)	0.4 g/L (standard leachate discharge in Malaysia) ⁹
7	BOD ₅ (g/L)	28 $\pm$ 5	0.3 $\pm$ 0.3 (*99 $\pm$ 1)	0.02 g/L (standard leachate discharge in Malaysia) ⁹
8	Total phosphorus (g/L)	0.7 $\pm$ 0.2	0.04 $\pm$ 0.02 (*92 $\pm$ 8%)	-
9	Alkalinity (g CaCO ₃ /L)	-	11 $\pm$ 2	2-4 g/L for properly operating digester ⁷
10	Biogas production rate (m ³ /day)	-	25 $\pm$ 1	-
11	Biogas composition (%) Methane; CH ₄ Carbon dioxide; CO ₂	- - -	57 $\pm$ 12 26 $\pm$ 6	-
12	Solid content [TS]; (%)	-	67 $\pm$ 4	> 10% for other system except for CSTR ⁸
13	Solid retention time; SRT (days) HRT: 30-day HRT: 25-day HRT: 20-day HRT: 10-day	- - - -	105 91 97 56	During HRT 25-day, there was leakage in sludge recycling pump that might cause loss of solid during distribution, thus decrease in SRT.

Avg: Average; SD: Standard deviation; (*): Removal efficiency in percentage

CONCLUSIONS

The AD of FW at HRTs of 124 days, 62 days, and 35 days were investigated under mesophilic conditions. The highest biogas and methane yield were obtained in Stage-1 with an OLR of 0.51 kg VS/m³/day and an HRT of 124 days. It was observed that the biogas and methane yield decreased when HRT decreased from 124 days to 62 days. When HRT was decreased to 35 days in Stage-3, the AD process became unstable and the biogas production decreased sharply due to VFA and ammonia accumulation. The shock loading, temperature fluctuation, irregular mixing and stepwise feeding type (i.e. three days in a week) may be the reason for the VFA and ammonia accumulation inside the reactor. For the leachate treatment, the monitoring done on ABD indicated a stable system throughout reduced HRT operations which led to high removal efficiency of 98%, 99 $\pm$ 1% and 92 $\pm$ 9% for COD, BOD₅ and total phosphorus respectively. This suggests that almost all of the organic pollutants could be removed by ABD. In addition, this ABD system produced high quality biogas with compositions of 57 $\pm$ 12% methane and 26 $\pm$ 6% carbon dioxide and volumetric generation of 25 $\pm$ 1 m³ biogas/day throughout operation. From the monitoring and performance results, this pilot scale anaerobic biofilm digester exhibited great potential in becoming major substitute treatment for young leachate and it could be further improved so as to receive higher organic loading in shorter hydraulic retention time for industrial use.

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