Process Optimization of Dry Batch Anaerobic Digestion of Municipal Solid Waste

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Abstract: *Optimizing anaerobic digestion aim to maximize organic waste stabilization at short digestion period with higher biogas production. This paper presents different strategies to optimize the anaerobic digestion of organic fraction of municipal solid waste in combined process in which early flushing and microaeration were conducted during pre-stage. Also, the influence of substrate particle size reduction and the advantage of thermophilic system over mesophilic in the overall digestion process are presented. Additionally, an attempt was taken to employ sequential staging concept by using a mature (old) reactor which underwent a combined digestion process. Importantly, process evaluation between an optimized combined process and sequential staging concept were evaluated with the main objective of optimizing the process. The process efficiency evaluation was based on biochemical methane potential (BMP) test. The overall result suggest that the combined anaerobic digestion process can be optimized by conducting shorter duration of pre-stage at reduced volume of flushing water with microearation, under thermophilic condition and at reduced substrate particle size of 30 mm. Nevertheless, the sequential staging concept offers an improved operation over the combined anaerobic digestion wherein the higher specific methane yield of 11.9 L CH_4/kg VS.day was achieved. Improved waste stabilization with 86% and 79% mass and volume reduction which corresponds to 84% process efficiency was obtained by sequential staging process.*

Keywords: Anaerobic Digestion, Solid Waste, Biogas, Leachate, Microaeration

1. INTRODUCTION

Direct dumping of municipal solid waste (MSW) in uncontrolled disposal system is a prevalent practice in most developing countries in Asia. The continuous practice of this system would apparently lead to cause serious environmental problems, health hazards and welfare loss. The problem on diminishing land for MSW disposal along with the increasing trend of waste and the depletion of fossil fuels have fostered the need to utilize and transform the waste into usable resources. Thus, biological pre-treatment of solid waste prior to landfill by anaerobic digestion process is considered as the attractive technology for waste stabilization with the generation of valuable byproducts such as biogas and fertilizer. Anaerobic digestion is considered to be an attractive waste treatment option due to its various benefits. This technology is potential in Asian countries because of its suitable waste characteristics. The generation and composition trend of MSW stream in Asian cities is almost similar which consists of high fraction of organic waste with high moisture content [1]. Anaerobic digestion offers a natural waste treatment process which reduces the waste volume/mass and leachate concentration. It also generates renewable fuel (biogas) and sanitized compost or nutrient rich fertilizer with proper post treatment process.

Anaerobic digestion of solid waste can be classified into variety of categories based on solid content, feeding modes, stages of operation, and type of waste. This study features the dry digestion technology of MSW in batch system. In order to shorten the overall digestion duration with maximum process efficiency, the process optimization needs further investigation especially during the start-up stage [2]. The leaching experiment on organic fraction of MSW showed that flushing the waste bed enhanced hydrolysis and acidification and the generated leachate can be used for cross- recirculation [3]. Moreover, the application of microaeration prior to methanization enhanced the hydrolysis rate of carbohydrates and proteins and this could enhance the anaerobic digestion process [4, 5]. This paper presents different strategies to optimize anaerobic digestion of organic fraction of MSW in combined process in which early flushing and microaeration were conducted during pre-stage. Additionally, an attempt was taken to employ sequential staging concept by using a mature (old) reactor which underwent a combined digestion process. Importantly, process evaluation between an optimized combined process and sequential staging concept were evaluated with the main objective of optimizing the process. Moreover, process efficiency evaluation based on biochemical methane potential (BMP) test was performed.

2. METHODOLOGY

2.1 Equipment

This study was performed in pilot scale double-walled stainless steel anaerobic digesters with a total volume of 375 L. The three reactors used in this experiment were equipped with top removable cover for waste loading and unloading in each batch. An optimum mesophilic (37°C) and thermophilic (55°C) condition were maintained by a digital temperature controller wherein hot water from water bath was pumped into the water jacket. Air compressor was used to provide aeration/microaeration into the waste bed. The application of microaeration (limited amount of oxygen supplied in anaerobic zone) was viewed that could increase the hydrolysis rate thereby improving pre-stage performance. The operation of pumps and air compressor were controlled at certain rate and interval by flow meters and timers. Each reactor is equipped with leachate recirculation system which is consist of leachate storage tank connected to a pump which convey the water into the top inlet of the reactor and the sprinkler (placed at 3 cm below the top cover) distributes the water throughout the waste surface. The flushed leachate trickled through the waste and collected to the same storage tank by gravitational force. At the top of the reactor, two inlets are installed, one for flushing and the other for biogas collection system. The biogas produced during methanogenic phase passes first in "U" tube for gas sample collection then it flows through the drum type gas meter were it is measured. In this way, a representative biogas sample can be collected at the "U" tube and is not affected by water in the gas meter.

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2.2 Feedstock preparation and collection

The substrate used in this study was collected from the vegetable market in Rangsit (Thailand). The collected waste was manually sorted to remove bulky and inorganic fractions and was subjected to size reduction by using a mechanical shredder. Representative waste samples were taken for solid analysis. For better process comparison, the waste loaded into the three digesters maintains similar characteristics in terms of average moisture content (MC) of 90%, total solids (TS) of 10% and volatile solids (VS) of 79%. The shredded waste was loaded into the reactors together with bamboo cutlets (10% volume of loaded waste) as bulking agent to create void space in order to facilitate the flow and distribution of flushing water and microaeration/aeration throughout the waste bed. At the end of the process, bamboo cutlets were manually separated from the digested waste and the waste was subjected for solid analysis.

2.3 Process Features

Combined anaerobic digestion process

Fresh market waste was loaded into the reactors and flushed with tap water to produce leachate. The purpose of flushing was to leach out pollutant in order to reduce the constraint of high organic load from the waste bed. Fig. 1 illustrates the three stages involved in combined anaerobic digestion process: (1) Pre-stage: volatile fatty acids (VFA) and other dissolved organic compounds (DOC) produced by the fresh waste were flushed into leachate; (2) Methane phase: biogas production. Start-up was conducted with pH adjustment and seeding. An active methane phase was indicated by 50% methane concentration in biogas and the pH of the system is around 7; (3) Final stage: the waste bed was flushed with fresh air to remove the remaining biogas in the digester before unloading the waste.

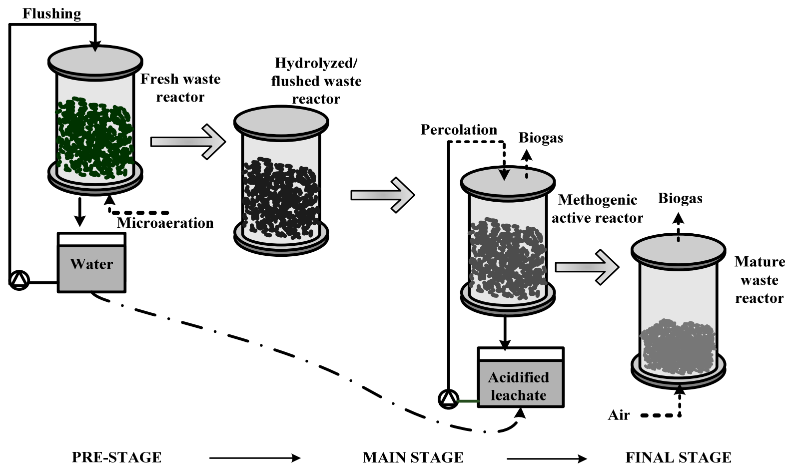

Fig. 1 Combined anaerobic digestion process

Sequential batch digestion process

This concept was employed to compare the optimized combined anaerobic digestion process in terms of overall process efficiency. In sequential batch digestion, the mature waste reactor which underwent a complete combined digestion process and is exhausted of its methane production was coupled with freshly loaded reactor for leachate cross-recirculation (Fig. 2) to provide moisture, inoculum, nutrient, and buffer necessary for the start-up of methanogenic phase. Volatile organic compounds formed during start-up were removed via leachate recycle to the mature reactor for conversion to methane and carbon dioxide. After start-up, the freshly loaded reactor becomes an active methanogenic reactor and was maintained by direct leachate recirculation [6, 7]. The process was ended when the biogas produced decreased significantly.

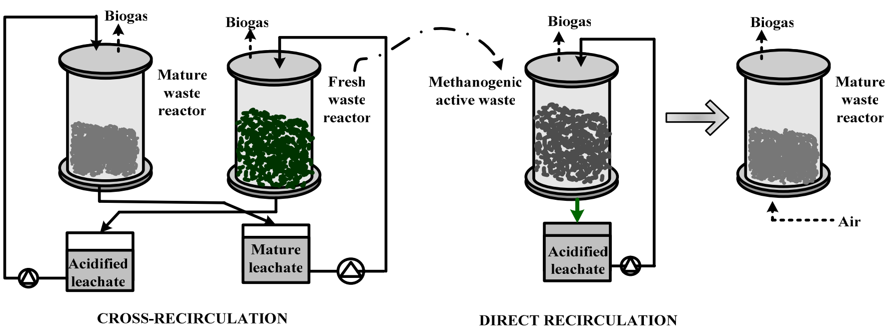

Fig. 2 Sequential batch anaerobic digestion process

2.4 Methodology

This study was conducted in two runs, run 1 dealt with process optimization of combined anaerobic digestion process under two stages. Stage 1 involves process optimization by varying flushing mechanisms and the application mciroaeration during pre-stage under mesophilic condition using 60 mm substrate. In stage 2, the optimization process was studied by using smaller particle size of

30 mm under mesophilic and thermophilic conditions at shorter pre-stage duration. Run 2 employs a mature reactor generated from an optimized combined digestion process coupled with a newly loaded reactor (fresh waste reactor) for leachate cross-recirculation. The cross-recirculation was only stop when the fresh reactor reached an active methanogenic phase and direct leachate recirculation was performed. The process details conducted in two runs are described in fig. 3.

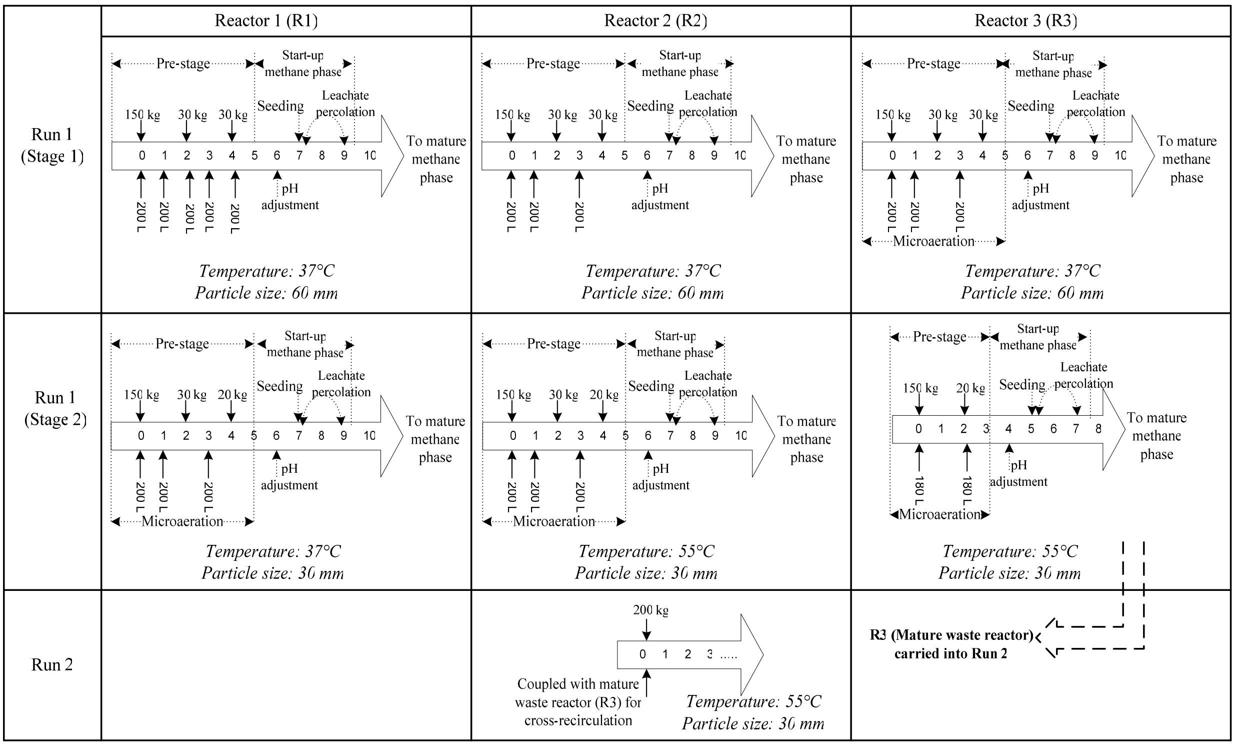

Fig. 3 Process mechanism during pre-stage optimization

The reactors in combined anaerobic digestion concept (Run 1) were loaded initially with 150 kg of waste and the additional amount of waste which corresponds to the available reactor's headspace resulting from waste settlement during pre-stage was loaded. Pre-stage was performed at varying conditions. Daily water replacement during pre-stage enhanced leaching [3]. In this study (Run 1, stage 1), daily water replacement was applied in reactor 1 (R1), whereas in reactor 2 (R2) and 3 (R3), water was replaced after day 1 and on day 3 of operation. As a result, a total of 1000 l water (48.8 l/kg TS) was used for R1, and only 600 l water (29.3 l/kg TS) was used for R2 and R3. Flushing was carried out at a rate of 5 l/min for 4h run/4 h stop. In R3, five days of microaeration was provided at a rate of 1 l/min (0.4 l/kg h) for 2 h run/4 h stop; while in R1 and R2, microaeration was not applied. In stage 2 of Run 1, the flushing operation and microaeration was continuously examined under different temperature conditions (mesophilic and thermophilic) and reduced substrate particle size of 30 mm.

Following pre-stage in Run 1, new condition was provided in order to enhance the start-up of methane phase. The pH of the system was adjusted to around 7.0 and was followed by inoculum addition. Mixture of cow dung, stabilized/digested waste and anaerobic sludge was used as seeding material totally accounting for 16% VS of the loaded waste. Percolation was performed for two days to distribute inoculums throughout the waste bed. Different strategies were applied for three digesters in stage 1 of Run 1; In R1 and R3, leachate percolation was only practiced by the time the reactor shifted to active methane phase and that was on day 40 and 30, respectively. However, R2, leachate percolation was not provided. Pre-stage leachate was percolated at rate of 0.2 l/min for 4 h run/4 h stop and replaced in batch mode. At the end of methane phase, the waste bed was flushed with fresh air for one day before unloading the digester. However, the R3 (Run 1, stage 2) which showed an optimized process among the other reactors was continuously operated and used as a mature reactor to study the sequential staging process. After unloading R2 (stage 2), it was loaded with 200 kg of fresh waste and coupled with R3 (matured reactor) to perform the sequential staging process.

3. RESULTS AND DISCUSSION

3.1 Pre-stage performance

In three digesters (Run 1, stage 1), highest DOC concentration (4 g/l) was noted in the first day of flushing. The result showed that DOC concentration in daily leachate reduced sharply with run time to around 1.5 g/l in five days. Flushing the waste bed using 1000 l of water could generate more pollutant load (DOC=140 g/kg TS; TKN=18 g/kg TS) compared to the reactors flushed with 600 l (DOC=128 g/kg TS; TKN=15 g/kg TS. The importance of microaeration during this stage showed an equivocal result. Morever, comparison of DOC and DOC equivalent of TVFA (Table 1) exhibited that over half of the soluble organic carbon in leachate was acidified into VFA. This showed that acidification was strong over hydrolysis.

Run 1, stage 2 operation, described the importance of reducing substrate particle size. In this case, R3 of stage 1 and R1 of stage 2 can be compared wherein 60 and 30 mm substrate particle size was used, respectively. More DOC load and VFA fraction in DOC can be generated by a reduced particle size. It can be concluded therefore that reducing substrate particle size enhances pre-stage performance. The importance of increasing reaction temperature from 37°C to 55°C could generate more DOC and VFA fraction in

DOC as can be seen in table 1. This emphasizes the positive influence of increasing temperature in enhancing pre-stage performance. The importance of reducing the amount of flushing water from 600 L to 360 L does not exhibit a negative effect in pre-stage performance instead it does enhance the process since it can limit the dilution of leachate concentration. The high fraction of VFA in leachate favored the proposal of feeding it back into the digester during methane phase by leachate percolation. Early extraction of VFA in pre-stage leachate would prevent imbalance between acidogenesis and methanogenesis in methane phase which was normally considered to cause instability in high-solid digestion system [8]. Lower concentration of VFA at the end of pre-stage suggested that strict separation of acidogenesis and methanogenesis could not be achieved at this point and it would be better to shift the reactor to methane stage. In this regard, pH adjustment and inoculum addition was performed after pre-stage in Run 1.

Table 1 Load of DOC and DOC equivalent of VFA in pre-stage leachate

Run 1, stage 1	37°C; 60 mm		
	R1 (1000 l water)	R2 (600 l water)	R3 (600 l water; with microaeration)
DOC	140	128	129
DOC equivalent of TVFA	83	80	88
Run 1, stage 2	37°C; 30 mm	55°C; 30 mm	
	R1 (600 l; with microaeration)	R2 (600 l; with microaeration)	R3 (360 l; with microaeration)
DOC	169	181	188
DOC equivalent of TVFA	147	167	158

Note: unit expressed in g C/kg TS (DOC and DOC equivalent of TVFA)

3.2 Methane stage performance

Run 1; stage 1

Fig. 4 shows the biogas cumulative production in methane stage. During start-up, it was observed the biogas production was low and methane content increased slowly to 50%. The system was successfully started-up after 25 days. Gas production rate in R3 was higher than R1 and R2. The possible explanation was due to early micro-aeration in pre-stage which might have resulted in better hydrolysis/acidifcation during startup of methanization period. Different behaviors could be observed after start-up, in R3, it was observed that cumulative gas production increased immediately after lag phase. Leachate percolation during active methane phase was conducted by batch. Regarding the cumulative gas production, R3 gained the highest biogas production of about 4800 L (256 l/kg TS) after 60 days of operation when compared to R1 (2300 L) and R2 (2700 L). Thus, it can be suggested that though microaeration showed an equivocal results during pre-stage performance, it does enhance methane phase. The importance of leachate percolation during methane phase in R3 enhances biogas production when compared to R2 without leachate percolation.

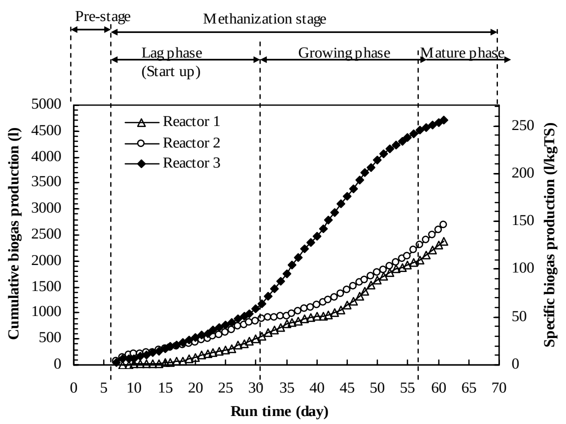

Fig. 4 Cumulative biogas production for Run 1, stage 1 (R1, R3: leachate percolation on day 40, 30; R2: no leachate percolation)

Run 1, stage 2

The importance of reducing particle size from 60 to 30 mm does not only enhance pre-stage performance but also does in methane phase. It was observed in this study that digestion using 60 mm substrate particle size is able to produce approximately 4800 L of biogas after 60 days of operation, while this much of biogas can be produced by using 30 mm substrate after 47 days only. This showed that reducing substrate particle size is able to the shorten digestion time at enhanced process. Moreover, higher methane concentration can be obtained at reduced particle size. Moreover, the importance of increasing temperature from 37°C to 55°C under combined anaerobic digestion concept was verified. The result showed that after 47 days of operation, around 4800 L of biogas was produced by mesophilic reactor while thermophilic reactor produced higher biogas production of 5400 L (Fig. 5). The importance of flushing the reactor at less volume of water was highlighted by R2 and R3 (Run 1, stage 2). A positive shift of methane performance due to less volume of flushing water provides added benefits. A lag phase period of 5 days (after pre-stage) was exhibited by both reactors. However, an active methane phase was obtained earlier by R3. In this case shortening pre-stage operation in combined process does not negatively affect methane phase wherein a likely improve methane concentration can be observed.

The commencement of acidified leachate percolation during active methane phase exhibits a rapid increase of biogas in all studied reactors. This indicates that leachate percolation which causes leachate contact with the waste have a positive influence n the process

[9]. After 47 days of operation R2 produced a total of 5300 L (310 L kg TS^{-1}) of biogas while R3 generates 6300 L (332 L kg TS^{-1}) of biogas after 45 days. The operation of reactors can be stopped after 30 days because of insignificant increase of biogas. The concentrated leachate that was fed into the reactors during an active methane phase offered benefits over the diluted leachate. The result of experiment showed that R3 operation (3 days, 360 L water) was better than R2 (5 days, 600 L water) during pre-stage and methane stage. A possible shift of R3 performance due to pre-stage operation offers advantages such as less volume of flushing water with improved pre-stage operation and does not negatively affect methane phase but it may possibly enhance. Higher specific methane yield was obtained by R3 (7.2 L CH_4/kg VS. day) compared to R2 (6.8 L CH_4/kg VS. day) (Table 2).

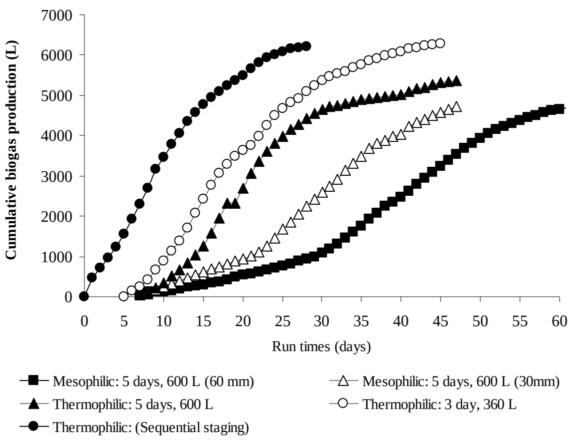

Fig. 5 Comparison of cumulative biogas production from combined anaerobic digestion and sequential staging concept

Table 2 Assessment of methane phase and overall process

Run no/operating parameters			% Mass reduction	% Volume reduction	Methane yield (L CH_4/kg VS.day)	Process efficiency (%)
Run 1	Stage 1 (37°C; 60 mm)	R1 (7 days; 1000 L)	60	-	2.4	33.0
		R2 (5 days; 600 L)	63	-	2.6	38.0
		R3 (5 days; 600 L; microaeration	63	40	4.8	66.0
	Stage 2 (37°C; 30 mm	R1 (5 days; 600 L; microaeration)	66	47	6.1	71.4
	Stage 2 (55°C; 30 mm	R2 (5 days; 600 L; microaeration)	74	58	6.8	80.0
		R3 (3 days; 360 L; microaeration)	84	74	7.2	80.4
Run 2	55°C; 30 mm	R2 (sequential staging)	86	79	11.9	84.0

Note: Process efficiency was calculated based on the BMP test result of 400 L CH_4/kg VS.

Run 2

It should be noted that R3 from Run 1 (stage 2) operation exhibited an optimum process efficiency compared to other reactors in Run 1. In this case, R3 was continuously operated for 2 months before it was coupled with R2 (newly loaded) to conduct the sequential staging anaerobic digestion process. Importantly, pre-stage operation was not performed in R2. After the two reactors were coupled, an active methane phase was rapidly exhibited by new reactor (R2) when compared to previous run. The methane concentration in both reactors increased and was stable to around 50% after 4 days of operation. Also, the pH of R2 started at 5.6 and increase to >6.5 after 4 days and this would indicate that the system was fully started up. The said reactors were uncoupled and direct leachate recirculation on R2 commenced on day 10. During the commencement of direct recirculation, the pH remained above 7 and stabilized at a value of 7.7 during the entire run. The observed decreasing trend of DOC and VFA in leachate accompanied with the increase of biogas may indicate a balance system. The reduction of VFA or DOC concentration from the waste bed may be attributed by removal through leachate recycle and enhanced development of methanogenic microbe population. Moreover, NH_4-N concentration did not increase significantly instead the concentration leveled off at 1 g L^{-1}. Thus, this process is very resilient in which the presence or accumulation of inhibitory substances did not establish and can be better controlled at proper performance evaluation.

Process efficiency

The methane yield in pilot scale digesters was compared to lab-scale BMP test to verify the process conversion efficiency. Methane yield was based from % VS destruction for it offers better representation in the actual process performance [10]. BMP test of the fresh waste generates 400 L CH_4/kg VS. Table 2 represents the overall assessment of methane phase. Comparable result in terms of methane yield and process efficiency was exhibited by R1 and R2 during Run 1 (stage 1) while R3 showed better result. In this regards, it can be suggested that flushing the waste bed using 600 l of water with the application of microaeration during pre-stage plus the practice of leachate percolation are the mechanism that enhanced the combined process during Run 1 (stage 1). Moreover, overall process efficiency of using 30 mm particle size is higher than using 60 mm which corresponds to 66% and 71.4% respectively. Besides, the overall process efficiency even improved when the digestion was conducted under thermophilic condition rather than mesophilic which improves the process efficiency up to 80%. The importance of pre-stage flushing using 360 L of water over 600 L also improved the process wherein methane yield improves from 6.8 to 7.2 L CH_4/kg VS.day. The higher specific methane yield of 7.2 L CH_4/kg VS.day was produced by R3 (Run 1, stage 2) after 45 days of operation indicates that shortening pre-stage under reduced volume of flushing water does not negatively affect the overall process. In this regard, an improved methane generation, mass and volume reduction was achieved by a reduced operation with less flushing water. However, among them, better result was displayed by R2 (Run 2). Improved digester performance in terms of waste stabilization was achieved. Nonetheless, 84% process efficiency was obtained after 28 days of operation with higher specific methane yield of 11.9 L CH_4/kg VS.day).

4. CONCLUSION

The results showed that pre-stage flushing operation for 3 days (1.8 L/kg) is more preferable than 7 days (4.7 L/kg) or 5 days (3 L/kg). Reduced substrate particle size of 30 mm under thermophilic condition exhibited better process performance over 60 mm and mesophilic condition. The concentrated leachate obtained at pre-stage showed beneficial effect during methane phase leachate percolation in improving biogas production. This signifies that reducing pre-stage operation and volume of flushing water does not negatively affect the process performance. But it enhances the maximum removal of organics from waste bed which is beneficial in optimizing the process in combined anaerobic digestion. Nevertheless, leachate cross-recirculation between the old and new reactors directly without conducting pre-stage operation optimizes the overall digestion process. The sequential staging concept offers an improved operation over the combined anaerobic digestion wherein the specific methane yield of 11.9 L CH_4/kg VS.day and 7.2 L CH_4/kg VS.day was achieved, respectively. Improved waste stabilization with 86% and 79% mass and volume reduction was achieved, respectively with higher methane yield of 334 L CH_4/kg VS which is equivalent to 84% process efficiency was obtained.

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