Potential of Plug Flow Digesters for Biogas Production in the Sri Lankan Domestic Context

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Abstract— **Biogas production through anaerobic digestion is widely used to convert domestic and industrial waste into energy. In order to successfully adapt this technology for Sri Lankan domestic usage, it is necessary to identify the necessary operating conditions for optimum biogas generation. This study focused on analysing the effect of co-digestion ratios and organic loading rates on processing local domestic waste. Experiments were conducted on a laboratory scale plug flow anaerobic digester setup. The best methane yield was obtained with a co-digestion ratio of garden to kitchen waste of 70:30, at an Organic Loading Rate of 3.1 kgVS/day/m^3. The energy potential of the generated biogas was evaluated in comparison to the average demand of households in the country, to establish the viability of biogas substitute to conventional energy sources. Future work is needed to validate the experimental results through mathematical modelling.**

Keywords— Anaerobic digestion, Plug flow reactor, Waste management, Co-digestion, Organic loading rate, biogas

I. Background

Anaerobic digestion involves a chemical process wherein the decomposition of organic matter produces biogas, which is mainly composed of Methane (CH_4) and Carbon Dioxide (CO_2) [1]. This technology is popularly used in waste-to-energy applications, and various digester types are used in domestic and industrial settings [2], [3].

Sri Lanka has considerable waste resources which can potentially be used in biogas generation, and management of waste in an environmentally sound manner has been a growing concern in the recent years [4]. Although biogas technology has been utilised in the country since 1975, there is a lack of scientific research regarding design and operation in terms of key parameters of digesters within the country, thereby leading to underperformance in the currently operating digesters [5]. Lack of process control, technical capacity, quality assurance and knowledge on characteristics of waste matter all adversely influence the effectiveness of the digestion process, leading to subpar methane generation [6]. In addition, it can be observed that anaerobic digestion has been adapted popularly to industrial situations, and it has not made similar progress at the domestic level.

Multiple parameters affect anaerobic digestion that include physical and chemical process characteristics and properties of input substrate used as feedstock. Temperature is one physical parameter that significantly affects the microorganism activity and rate of reactions [2]. Hydraulic Retention Time (HRT) refers to the number of days the substrate material is retained within the digester [2]. The time that microbes reside in the digester unit, referred to as the Solid Retention Time (SRT) is another critical parameter analogous to HRT [7]. The organic loading rate (OLR) is a measure of the total daily organic solids in a unit volume of the digester's daily influent [8]. Optimum growth of microorganism occurs within the neutral range of pH values, from 6.8 to 7.2 [2]. The total solid (TS) concentration of the digester influent can be categorised as low, medium or high, depending on the percentage of water in the feed, while the volatile solids (VS) indicate the digestible organic compounds [9]. Simultaneous anaerobic digestion of a mixture of multiple substrates is referred to as co-digestion [2]. Effective control of these key parameters would help to obtain a higher yield from a digester.

In order to maximise the potential of biogas energy with relevance to the Sri Lankan domestic context, it is necessary that the digestion process parameters are adapted to the local environment and available waste resources. Thus, this study investigates the effect of co-digestion ratios and OLR on biogas generation to determine the most favourable conditions for an improved biogas yield in the domestic context.

II. Methodology

The selection of the most suitable digester type for the local context through literature and current technology review was followed by analysing the selected process parameters. This was conducted through an experimental approach in a laboratory scale digester setup using a model of plug flow digester. The plug flow digester model was selected as the research focus on account of its suitability for Sri Lankan household usage due to lower installation and maintenance costs and technical simplicity [9], [10], elimination of the short circuiting problem [9], higher gas production as well as increased capacity of handling high solid concentrations in the substrate [11] and easier loading [8]. Finally, the biogas generation potential of the digester model for household use was evaluated by extrapolating the experimental results.

A. Experimental Setup design

A laboratory scale digester setup fabricated with standard PVC piping as depicted in Fig. 1 was used in semi continuously fed experiments for the analysis of the selected process parameters.

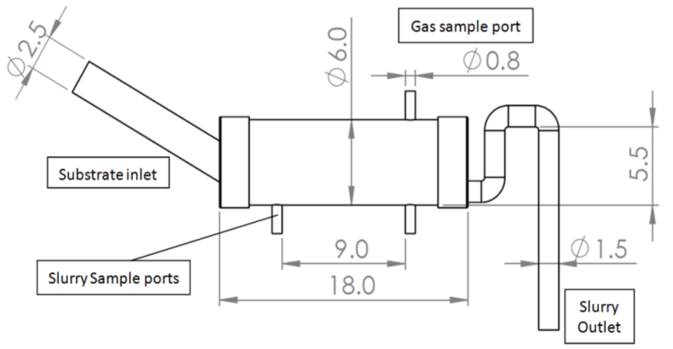

Fig. 1. Schematic diagram of the experimental model

The reactor length to diameter ratio was 3:1, with a total inner volume of 8340 cm^3 containing 344 cm^3 of headspace.

The geometrical parameters were selected based on previous studies and literature on plug flow digester to suit the purpose of this experiment [8]. The substrate inlet was designed with a 60° angle to the vertical, and the slurry outlet path was designed to prevent digestate from being ejected before the inner volume is completely filled, ensuring that each new insertion of substrate acts as a plug that seals the chamber. The joints were sealed to prevent any gas leakages or entering of air into the setup. A gas collection port set on the top side was used to collect the biogas generated through the anaerobic digestion process, and the volume of the gas was measured by the water displacement method where the gas was collected in a volumetric cylinder immersed in a water bath through flexible tubing, as depicted in Fig. 2.

In order to evaluate the Methane content of the generated gas, the gas mixture was sent to a second volumetric cylinder immersed in a concentrated Sodium Hydroxide solution to separate the CO_2 which dissolves in NaOH [12]. A control valve was used in the tube connecting the two volumetric cylinders so that the gas flow from one to another would only take place when the valve was opened. A smooth action roller clamp on the kink resistant tubing acted as the control valve. Fig. 3 demonstrates the testing setup with the two digester units and the gas collection mechanism.

B. Testing Procedure

The experiments were conducted by varying the parameters to be tested in a controlled environment. The HRT was set to 20 days with a daily influent volume of 400 ml in all experiments

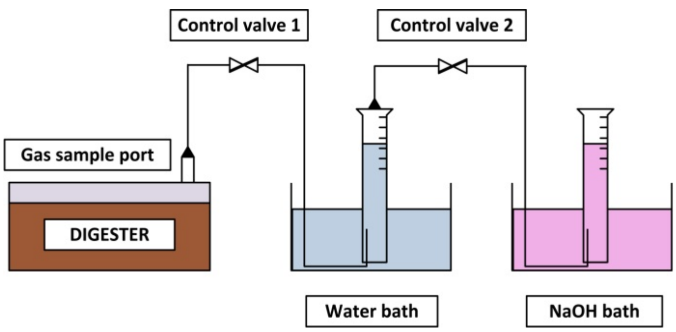

Fig. 2. Gas collection method

. The temperature of the digestion process was not controlled due to the tropical climate in Sri Lanka which allowed for the mesophilic operating temperatures to be easily achieved [8], [13]. To supply the startup inoculum, anaerobic sludge was obtained from a currently operating biogas reactor fed to the digester setup.

1) Substrate preparation and feeding

In the first set of tests, domestic garden and kitchen waste types were used as co-substrates in the experimentation to determine the best co-digestion ratio between the two. The kitchen waste was defined by cooked food waste, while the garden waste was characterised by Gliricidia leaves. Study of related literature revealed that *Gliricidia* S*epium* has a higher methane generation potential compared to other types of plant based matter as a co-substrate [14] in comparison to other locally available substrates such as dairy manure, rice straw [15] and Water Hyacinth [16]. The ratios of garden waste to kitchen waste were 70:30, 50:50 and 30:70 by weight, making up a total daily waste mass of 100g.

The waste types were mixed and ground into smaller particles and water was added and mixed to make up 400 ml of input. Table I shows the test conditions used. After the best co-digestion ratio was selected from the first set of experiments, that ratio was used for OLR test substrates. The feedstock preparation for the second set of tests involving OLR followed the same pattern with an influent volume of 400 ml, and the solid content of each loading rate was varied by the wet weight of the waste co-substrates in a unit volume of the feedstock. Four test samples were prepared by concentration as 200 g/L, 300 g/L, 400 g/L, 500 g/L as shown in Table II.

The gas outlet tube was sealed by a control valve before the input of the substrate mixture into the digester through the sloped inlet pipe at all times. Once the feeding was completed, the inlet was sealed off again to prevent air from entering the digester and disrupting anaerobic conditions within it, and the gas collection tube was reopened.

Fig. 3 demonstrates the testing setup with the two digester units and the gas collection mechanism. The input feedstock was tested to characterise the substrate in terms of Chemical Oxygen Demand (COD value), Total Solids (TS%), and total volatile solids (TVS%).

TABLE I. CO-DIGESTION RATIO SUBSTRATE CHARACTERISTICS

Co-digestion testing[a]	**Garden : Kitchen**		
Ratio (by mass)	70:30	50:50	30:70
HRT (days)	20	20	20
Input volume (ml)	400	400	400
Input mass (g)	100	100	100
TS % of feedstock	21.528%	24.340%	27.152%
TS % of input volume	5.87%	6.49%	7.18%
VS % of feedstock	96.13%	95.22%	94.44%
ODM in input (kg/day)	0.0207	0.0232	0.0256
Digester volume – total (m^3)	0.0083	0.0083	0.0083
Figester volume - filled (m^3)	0.008	0.008	0.008
OLR (kgVS/day/ m^3)	2.59	2.90	3.21

a. (ODM – Organic dry matter; TS – Total solids; VS – Volatile Solids; g/L – grams per Litre)

TABLE II. ORGANIC LOADING RATE SUBSTRATE CHARACTERISTICS

Loading Rate Testing	**Selected co-digestion ratio – 70:30 (G:K)**			
Loading rate (g/L)	200	300	400	500
Input mass (g)	80	120	160	200
Added water (ml)	300	250	190	140
Input volume (ml/day)	400	400	400	400
HRT (days)	20	20	20	20
TS % of feedstock	21.53%	21.53%	21.53%	21.53%
TS % of input mass	4.53%	6.98%	9.84%	12.66%
VS % of feedstock	96.13%	96.13%	96.13%	96.13%
ODM in input (kg/day)	0.0166	0.0248	0.0331	0.0414
Digester volume (m^3)	0.008	0.008	0.008	0.008
OLR (kgODM/day/ m^3)	2.07	3.10	4.14	5.17

2) Data recording

The displacement of the water within the first volumetric cylinder (Fig. 2) was used to evaluate the generated volume. In order to find the methane content in the collected gas, 200 ml of the gas was sent to the second volumetric cylinder filled with concentrated NaOH after closing the inlet valve from the digester which is control valve 1 in Fig. 2, and opening the outlet valve denoted as control valve 2 in Fig. 2, to the connection of water bath to the NaOH bath. Passing of 200 ml was identified by the upward displacement of water in the 1st volumetric cylinder. As the CO_2 dissolves in the NaOH solution, the residual CH_4 volume was collected in the 2nd volumetric cylinder. The presence of other gases (H_2, N_2, NH_3, O_2) was considered negligible as there is only a miniscule amount of those present in a given biogas volume.

III. RESULTS

A. *Co-digestion ratios*

Out of the three co-digestion ratios tested, the 70:30 garden to kitchen waste demonstrated the highest cumulative biogas generation as well as the highest CH_4 content in the biogas.

The total gas generation for co-digestion ratios 70:30 and 50:50 garden to kitchen waste increased smoothly and stabilised, whereas 30:70 garden to kitchen waste did not demonstrate stability during the period considered. The cumulative gas production increased with the percentage of garden waste in the influent sample as illustrated in Fig. 4.

Fig. 3. Laboratory scale digester setup – two sets

The measurements were taken before and after the HRT for eight days in total in order to allow the system to stabilise before measuring, so that the full generation potential was realised. The methane generation volumes for the different co-digestion ratios have been illustrated in Fig. 5, while Fig. 6 shows the methane generation as a percentage of the generated biogas.

Observations on the hourly rate of gas production showed a sudden increase in the rate of production just after the input of the substrate, and afterwards a decrease with time for all three composition types as shown in Fig. VII was observed. The average gas generation values (Table III) for the three tested co-digestion ratios were calculated using the observations acquired after the gas production stabilised. The specific methane generation potential of the experimental setup by the input mass and the reactor volume have been summarized as per Table IV.

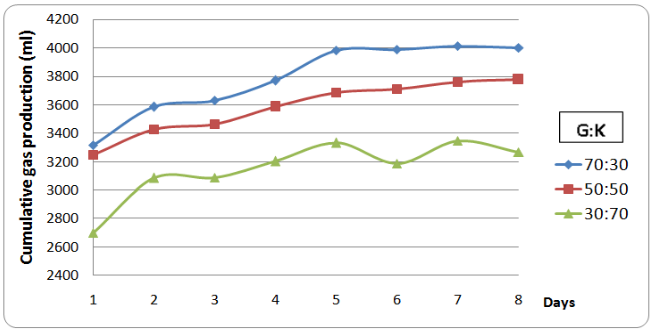

Fig. 4. Cumulative gas production for co-digestion ratios

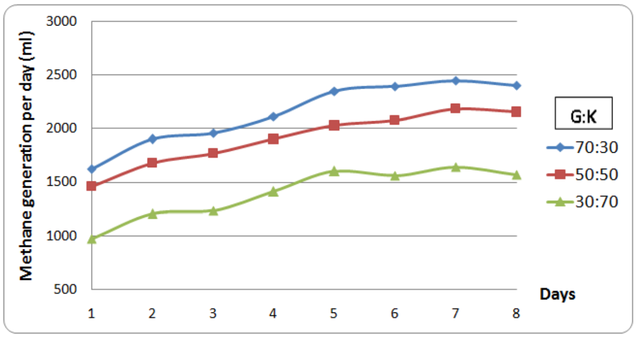

Fig. 5. Methane generation for different co-digestion ratios

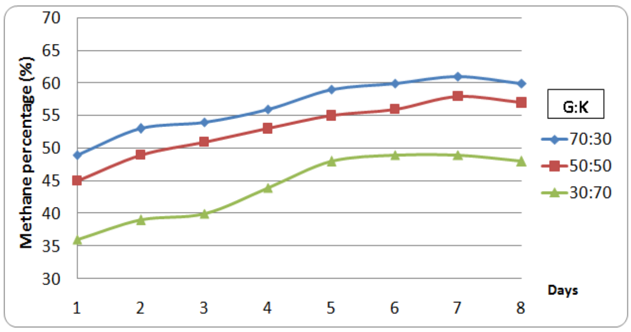

Fig. 6. Methane percentage for different co-digestion ratios

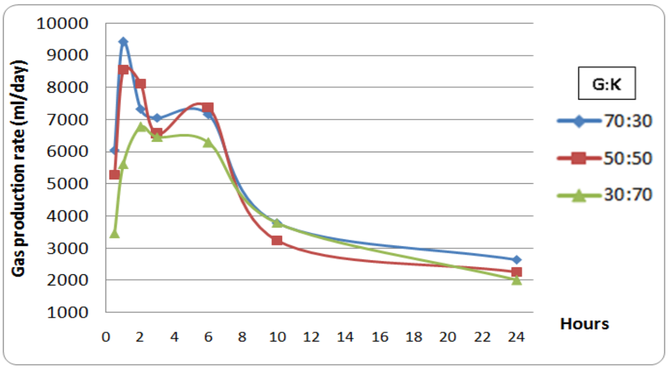

Fig. 7. Daily gas production rate calculated for hourly basis

Specific Biogas Generation (by mass) was calculated daily biogas production (m^3/day) divided by organic input rate (kgVS/day). Specific Methane Production was defined as the daily volume of biogas produced per unit digester volume.

B. . Organic loading rates (OLR)

Table V provides the summarised data for the tested OLR samples. The concentration has been defined by the wet mass of the input. The total daily gas production is higher for OLR 2 and OLR 3 compared to the other two rates after process stabilisation, as indicated in Fig. 8. The OLR 3 sample indicated a slightly higher cumulative gas yield during the period of observation. A co-digestion ratio of 70:30 garden to kitchen waste was used in the loading rate experimentation as it yielded the best results in the first set of tests. Fig. 9 shows that the methane content in the biogas was higher in OLR 2 and OLR 3 compared to the other two loading rates.

TABLE III. CO-DIGESTION RATIO SUBSTRATE CHARACTERISTICS

Co-digestion ratio (Garden : kitchen)	**Average gas generation (ml)**	**Average CH_4 gas generation (ml)**	**CH_4 %**
70:30	3997	2398	60
50:50	3733	2110	57
30:70	3284	1593	48

TABLE IV. SPECIFIC CH_4 GENERATION FOR TESTED CO-DIGESTION RATIOS

Co-digestion ratio (Garden : kitchen)	**VS mass (kg)**	**Specific biogas generation by mass (m^3/day/kg VS)**	**Specific CH_4 generation by mass (m^3/day/kg VS)**	**Specific CH_4 generation by volume (m^3/day/m^3)**
70:30	0.0207	0.1931	0.1159	0.2997
50:50	0.0232	0.1611	0.0910	0.2637
30:70	0.0256	0.1281	0.0621	0.1991

TABLE V. SAMPLES TESTED FOR ORGANIC LOADING RATE

Sample	**Concentration (g/L)**	**Mass of substrate in input (g)**	**OLR (kgVS/m^3/day)**
OLR 1	200	80	2.07
OLR 2	300	120	3.10
OLR 3	400	160	4.14
OLR 4	500	200	5.17

The Methane percentages in the biogas is presented in Fig. 10. Table VI provides the summarised data on the total gas generation and the Methane content in the biogas for the tested loading rates. The specific gas generation values by mass and volume are included in Table VII.

The extrapolation of the specific methane generation of the 0.008 m^3 laboratory scale digester setup to realistic digester capacity applicable at a household level with a reactor volume of 1 m^3 gave the results shown in Table VIII. A co-digestion ratio of 70:30 between garden to kitchen waste at an organic loading rate of 3.1 kgVS per day/ m^3 has a potential daily CH_4 production of 0.3265 m^3. Assuming a combustion efficiency of 50%, this generated biogas can provide nearly 50 kWh of energy per month if utilised in thermal applications.

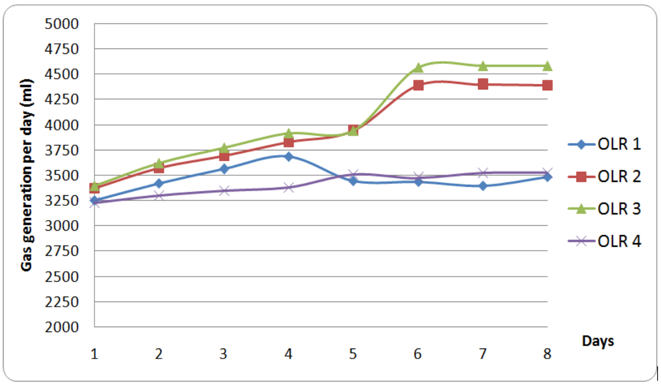

Fig. 8. Cumulative gas production for loading rates

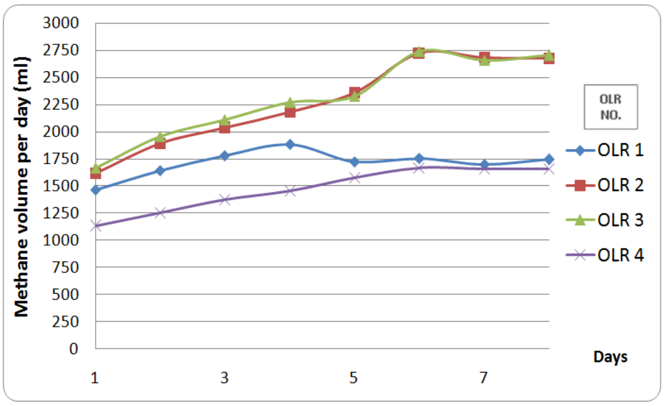

Fig. 9. Methane generation for different loading rates

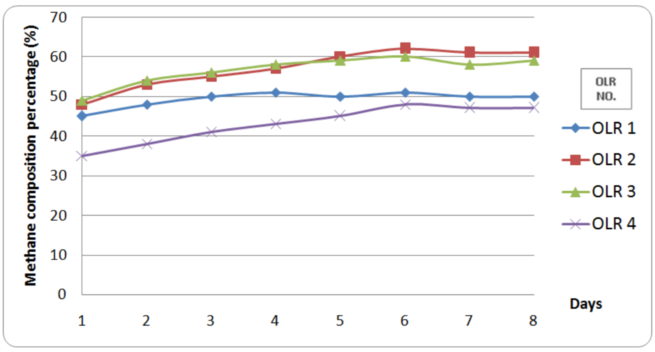

Fig. 10. CH4 Percentages for different loading rates

TABLE VI. AVERAGE GAS GENERATION VALUES FOR TESTED LOADING RATES

Sample	OLR ($kgVS/m^3$/ day)	Mass of substrate in input (g)	Average gas gen. (ml)	Average CH_4 gas gen. (ml)
OLR 1	2.07	80	3443	1730
OLR 2	3.10	120	4280	2612
OLR 3	4.14	160	4420	2608
OLR 4	5.17	200	3448	1612

TABLE VII. SPECIFIC METHANE GENERATION BY MASS AND VOLUME FOR TESTED LOADING RATES

Sample	VS mass (kg)	Specific biogas generation by mass (m^3/day/kgVS)	Specific CH_4 gen. by mass (m^3/day/ kgVS)	Specific CH_4 gen. by vol. ($m^3/day/m^3$)
OLR 1	0.0166	0.2079	0.1045	0.2162
OLR 2	0.0248	0.1724	0.1052	0.3265
OLR 3	0.0331	0.1335	0.0788	0.3260
OLR 4	0.0414	0.0848	0.0389	0.2015

TABLE VIII. ESTIMATED ENERGY GENERATION POTENTIAL OF 1 M^3 PLUG FLOW REACTOR

Average daily CH_4 volume (m^3)	Energy content in CH_4 (kWh/ m^3)	Daily Energy generation (kWh)	Monthly energy generation (kWh)
0.3265	10	3.265	98

IV. DISCUSSION

Co-digestion enhances the usage capacity of a digester by accommodating several different types of waste while increasing the gas yield as well as improving the nutrient content of the resulting digestate slurry [17]. It can be used to overcome process deficiencies such as nutrient imbalance, inhibition and rapid acidification [14], [18]. The co-digestion ratio 70:30 garden to kitchen waste showed the highest cumulative gas production after stabilisation as well as the highest CH_4 content in the generated biogas sample, and therefore based on the observations in Fig. 4, 5 and 6, it can be inferred that a higher percentage of garden waste in the domestic waste matter leads to an improved biogas production, as well as an increased methane yield. The effectiveness of Gliricidia which was used as a co-substrate representing garden waste in biogas generation has been asserted in previous studies [19]-[21]. While Gliricidia has been selected as a co-substrate to represent garden waste within this study due to its high availability in the Sri Lankan domestic context, additional research needs to be carried out to fully investigate the effect of mixed garden waste collected from home gardens on biogas generation.

The test result from co-digestion ratio 50:50 is slightly lower than the cumulative gas production for 70:30 garden to kitchen waste. This variation could be due to the increase in carbohydrate content in 50:50 substrate mixture compared to 70:30 mixture. The lack of balance of nutrients with the higher concentration of kitchen waste is a possible reason for the significantly lower gas yield in the 30:70 substrate mixture [3], [22]. Similar observations has been made previously on different co-digestion ratios of food and garden waste using a CSTR type digester, with higher gas generation for mixtures containing higher content of garden waste [14]. Related research in the area present findings on a higher content (more than 50%) of yard waste (garden waste) in the influent substrate leading to an increased methane yield and total gas production [23]-[25]. Co-digestion of food waste with other substrates such as sewage sludge and farm manure has been recommended for producing a higher biogas yield than 100% food waste [26].

In the Fig. 7, it is observed that the rate of gas generation increases immediately after the daily feeding. This may be due to the sudden increase in the pressure of the system after feeding, and also due to the arrival of new feeding matter for the micro-organisms in the reactor setup [14].

Organic loading rate (OLR) heavily influences the gas yield of a digester [3]. The experimental results for OLR 1 (2.07 $kgVS/m^3$/day) shows a considerable reduction in gas volume. A possible cause for this is the insufficiency of organic matter, which may reduce the rate of microbial activity. However, OLR 1 achieves the steady state earlier than the other loading conditions. In the case of OLR 4, the amount of gas generation per day is quite low with respect to the feedstock mass. The higher solid concentration of the input substrate may act as a shock load to the system, resulting in unfavourable conditions for anaerobic bacteria and the formation of dead locations within the digester system [27]. The experiments revealed that the highest gas production was from OLR 2 and OLR 3. However, while OLR 2 had a higher total biogas volume, the CH_4 percentage in the generated biogas for OLR 2 is lower than that of OLR 3.

While multiple parameters affect the performance of anaerobic digesters, the above two parameters were selected as the research focus due to the practical importance for the selected context. As the average temperature of the Sri Lankan climate falls within the thermophilic range [2], it is not critical to evaluate the effect of temperature and to provide additional heating to the reaction. While effective control of HRT is extremely important in the designing and operation of anaerobic digesters, the time constraints of this study prevented it from being fully investigated. This is a potential subject for future studies in this area.

The main purpose of this study with respect to co-digestion ratio was to analyse the effect of varying the combination of kitchen waste to garden waste in a practical context. The three test ratios were selected to represent three possible scenarios; a higher kitchen waste percentage, equal percentages of kitchen and garden waste, and higher garden waste percentage. Based on the experimental results, it can be demonstrated that a higher methane generation potential can be achieved by using a substrate with a higher garden waste content. However this requires further verification. Hence, the possibility of a substrate composed of an even higher percentage of garden waste yielding an even better performance in terms of methane generation is a matter for further study.

Replacing conventional sources with biogas energy has obvious potential in the Sri Lankan domestic context, especially considering the availability of waste resources at the targeted domestic level. In Sri Lanka, biogas has another prospect, which is to provide energy to rural areas which are not yet supplied with grid electricity, especially as these rural off-grid communities also have access to organic substrates such as straw, manure and plant based matter from natural vegetation and cultivations. (A higher percentage of plant based garden waste in the feedstock leading to a higher methane generation potential in anaerobic digestion is a positive factor in this context.) Biogas energy can be used to replace Kerosene and other fossil fuels, thereby limiting the impact of rising of fuel prices to the low income communities.

V. CONCLUSIONS

The findings of this study demonstrate that a higher gas production as well as a higher methane content in the biogas can be obtained for a substrate composition with a higher garden waste content. While the gas production increases initially with an increasing OLR, after a certain point the yield decreases due to process inhibitions, and therefore maintaining a mid-range organic loading rate of 3-4 kgVS/day/m^3 delivered improved results in methane generation, thereby increasing energy generation potential.

In order to exploit the full benefit of biogas and to implement anaerobic digestion successfully at the domestic level, it is also necessary to evaluate the waste generation capacity of Sri Lankan households. Future research needs to be carried out on evaluating the quantity and the types of waste available at the household level, so that the biogas generation capacity of Sri Lankan households can be estimated.

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