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ORIGINAL ARTICLE

An on-site survey on household-scale anaerobic digestion in Sri Lanka

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Abstract

In this study, household-scale anaerobic digestion (AD) in Sri Lanka was surveyed by visiting 100 AD users. The process flow, material flow, management of biogas and bioslurry, changes in waste disposal, and cost of construction were analyzed in terms of encountered problems. The main motivations to use AD are energy recovery by biogas and proper organic waste management instead of open dumping. On the other hand, several problems are clarified. The AD is mostly uneconomically oversized for the amount of input waste. Maintenance is poor, especially the lack of desulfurizer will reduce the lifetime of gas utilization equipment. The imbalance between supply and demand of biogas is also a problem. The example of low supply includes a case when only a limited part of livestock waste is only fed into AD, and it is necessary to supply accessories for lightning or electricity generation to users. To overcome these problems, technical guidance and assistance by national and local government are necessary. The possible scenario for extending the appropriate use of AD in the future for waste management shows with savings by maximized use of biogas and slurry, the implementation cost of the AD can be recovered mostly within a 6-year period.

Keywords Sri Lanka · Household-scale anaerobic digestion · On-site questionnaire survey · Biogas · Slurry · Cost recovery

Introduction

Sri Lanka is one of the developing countries which lack a proper solid waste management system. According to the estimation of the National Solid Waste Management Support Center, the daily solid waste generation in Sri Lanka was approximately 10,000 t/day in 2014. Even though local authorities (LAs) are obliged by law to manage solid waste, they can collect only 35% of the waste generated. After collecting the waste, 85% of it is disposed of in open dumps, whereas 10% is composted and 5% is recycled. The non-collected waste is managed on-site often using open backyard dumping, burning, burying, or illegal dumping into waterways/roadsides, whereas the usage of biological treatments such as composting and anaerobic digestion is very rare. Solid waste in Sri Lanka comprises a significant amount of organic waste (> 60%) with a high moisture content (60–80%). Hence, improper handling of solid waste causes severe impacts on both the humans and the environment [1–3].

To overcome the impacts of improper waste handling, biological treatment methods have to be introduced. Recently, composting has been implemented by LAs. In a previous study, the composting commenced by several LAs was studied [4]. On the other hand, for the non-collected waste, household anaerobic digestion is a viable solution particularly for rural areas because of its byproducts: biogas and slurry. Currently, 80% of rural households rely on biomass for cooking [5], and biogas can replace biomass. The slurry can effectively reduce the requirement of chemical fertilizers and thus the cost, which would be a relief for rural people whose main source of income is agriculture. In addition, anaerobic digestion can enhance sanitary conditions by directing human and animal waste. Moreover, the implementation of digesters for AD can provide local employment opportunities.

Household-scale AD was initially introduced to Sri Lanka in the early 1970s to address the energy crisis at that time. Then, it was promoted as a support for agriculture. Waste management by AD was then included in implementation initiatives by 2000. According to several resources, around

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only 7,500 AD systems have been already installed, but most of them were not functioning because of the lack of proper implementation and aftercare services provided for troubleshooting problems and because of poor maintenance [6, 7]. However, recent interest in domestic AD is steadily increasing. The Sri Lankan biogas program has been initiated to promote AD. This program subsidizes the construction of digesters particularly for livestock farmers, and interested households (without livestock) are also supported. During the period between 2011 and 2014, this program established more than 3,000 AD systems. However, the implemented household-scale ADs were not well-evaluated with regard to their input, output, operational steps, and their effectiveness in waste management, their use in supplying energy and fertilizers, and cost.

In light of these issues, this research first aims to analyze process flow, material balance, management of biogas and bioslurry, change in waste disposal, and cost to know about the current situation of household-scale AD in Sri Lanka. Because household-scale AD provides the benefit of improving the environmental condition by minimizing inappropriate waste disposal as well as energy recovery from biomass, it is desirable to extend it to the whole country. To extend, possible scenarios are suggested based on the findings of existing conditions.

Methodology

A questionnaire survey was conducted to collect information on household-scale AD.

Selection of AD users for the survey

In Sri Lanka, there is no centralized database to hold information about the implemented AD systems. Therefore, five institutions (Janathakshan Organization, HELP-O Organization, National Engineering Research and Development Center, Sri Lanka Sustainable Energy Authority, and Department of Agriculture and Livestock Development) were identified by a literature review as institutions working on AD and requested from them the users' names, addresses, telephone numbers, and digester information (type, year started, and capacity). However, only the names and addresses of AD users in five provinces were available. Those were obtained via email from the first two institutions, whereas the latter three institutions provided data after being visited.

The surveyed AD users were selected covering all five provinces and considering the traveling distance. Districts that had the largest number of AD users were selected out of the five provinces from all the lists obtained. The users were then chosen randomly within districts after considering the traveling distance. Finally, 100 users were selected and the questionnaire survey was conducted during a visit between July 10 and August 16, 2016.

Question items

Questions to the users consist of the following items in six sections.

The section of background of AD users includes household details (number of members, main income/occupation), the availability of grid-connected electricity, the type and size of available crops and livestock, and motivation behind using the AD.

The second section determines the details of digesters being used for AD (type, capacity, operation start year, and current condition), the operation steps (stirring, removal of condensed water, cleaning of cookers and lamps), the monitoring steps (monitoring of gas pressure and gas leaks), and the problems encountered. Additionally, the training/orientation received with regard to operations is requested.

The third part inquires about waste input for AD. The amount of kitchen waste (KW) and livestock waste (LW) are requested as a feeding ratio (input:total), and approximate input amounts are asked for other types of waste (e.g., yard waste). Human waste (HW) is fed directly by connecting toilets with digester, so the input amounts are not requested. The added water for KW, LW, and other types of waste is requested as a volume ratio. For cases of HW, the questionnaire determines whether the water used for toilet flushing is adjusted or not to simplify estimations (if not, then the general water consumption in toilets is used in the calculations) and determines the types of detergent used in toilets. Furthermore, previous disposal methods for the respective wastes are requested.

The fourth part discusses the use of biogas and slurry, including the resulting reductions in previous fuel and fertilizer consumption as a percentage. Finally, the resulting cost savings are also asked.

The cost section asks for the construction (including any subsidy received) and maintenance costs.

The final section determines user satisfaction (satisfied or not, willingness to recommend anaerobic digestion to others) and future modifications (any desire to use the output for other purposes and wish to deal with other wastes such as HW).

General outline of the visited AD systems

User groups

On the basis of background, the 100 AD users were divided into the following five groups: (1) household (17 users), (2) households with livestock such as cattle, buffalo, swine, goats, and poultry (74 users), (3) commercial settings that comprise two small hotels and one food café (3 users), (4) Buddhist temples (4 users), and (5) swine farms (2 users).

Most people in the second group had a lower educational/income background (because of being farmers) compared to the first group which mostly comprised people with good education/income (doctors, engineers, lawyers, government officers, and teachers). According to group 1, they were mostly (15 out of 17) informed by friends or service providers about AD, whereas group 2 (71 out of 74) were told by the government (veterinary officers). This result could be related to the difference of users' educational/income background and it highlights the importance of government guidance for popularizing AD among less educated/lower income people.

All five groups were connected to the electricity grid. Water was provided from either public connections or wells. In addition, 14 of the first group, all of the third group, and a temple were located in areas with waste collection services.

Input waste and AD structure

Table 1 shows the relation between AD capacity and input waste. LW (livestock waste) was the primary waste input for groups 2 and 5, and KW (kitchen waste) and HW (human waste) were often used in other groups. Only one used KW and water hyacinth (WH), received from nearby areas in group 1. No clear relation was seen between waste type and capacity, which suggests that the digester's capacity was not selected considering the type of waste.

Types of digesters for AD consisted of 94 Chinese fixed-dome types and six other types (four plug flow types, one plastic floating drum type, and one tunnel type). The type was just a decision of the installer. In Chinese fixed-dome type (see Fig. 1), waste is fed in from the inlet, and the digested mixture (slurry) flows out from the outlet. The inlet, outlet, and digester are made of concrete. The upper part of the digester is used for gas storage; when the gas production starts, the slurry inside the digester is displaced into the outlet because of the hydraulic pressure created by the accumulated gas in the storage. The displaced slurry then moves again into the digester when the gas pressure decreases due to its utilization. Other types of digesters have different configurations, but operations are similar to the Chinese model.

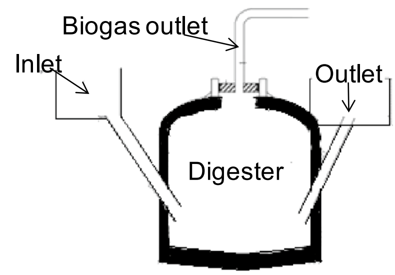

Fig. 1 The Chinese fixed-dome digester

LW, KW and WH (after being chopped) were fed for AD after mixing with water at the inlet. HW was fed by directly linking the toilet with the digester, and users were aware of not using any chemical detergent for toilet cleaning. The water volume used for mixing with LW, KW and WH was approximately similar to the waste volume. None of the HW feeders had adjusted water volume for toilet flushing.

Operations and maintenance

Among 100 visited AD systems, nine (including newer and older ones) were nonoperational. Minor reasons are no LW to use because the livestock has been recently sold, removal of AD to provide space for a house extension, and just constructed. Other three AD systems are more serious cases.

Table 1 Relation between AD capacity and input waste

Group	Input waste	Capacity, m^3							Total
		< 8	8	10	12	15	20	> 20	
1. Household	KW	1	1						17
	KW and HW		4		2		8		
	KW and WH		1						
2. Household with livestock	LW	1	32	14	5	7	1		74
	LW and KW		13						
	LW, KW and HW			1					
3. Commercial settings	KW							1	3
	KW and HW						2		
4. Temples	KW	1	1						4
	KW and HW						2		
5. Swine farms	LW					2			2

KW kitchen waste, *HW* human waste, *LW* livestock waste, *WH* water hyacinth

One system has biogas leak from digester's top due to excessive gas pressure and/or the failure of digester construction, and two systems do not have gas production during the three preceding months. The users of these three systems have already asked their service providers several times to solve these issues, but to no avail so far. This suggests that the aftercare services were inadequate.

Overall, maintenance of AD systems is insufficient. Stirring hinders scum formation but was practiced in only four users of the second group using a rod that was inserted in a different position from the inlet. Stirring was rarely practiced although the recommended frequency was every 15 days. Monitoring gas pressure is vital for protecting the digesters against high gas pressure. High pressure can result in cracks in the digester's walls, which cause leaks. The gas pressure was monitored in 62 AD systems using manometers (42 users) or pressure meters (10 users), or both manometers and pressure meters (9 users).

Condensed water in the gas outlet pipe can be problematic. Ten AD systems were equipped with dehydrators to remove condensed water, but they were not used. However, water can naturally flow back into the digester or to the manometer because of the pipe's slope. Desulfurizers were equipped in 32 systems, but they were not regularly cleaned. As a result, all users' cooking stoves were corroded, and three users even changed stoves. Seven LW feeders removed scum layers because they disturb the gas flow by forming a lid in the digesters. The possible reason behind this could be the improper mixing of LW with water. However, scum was removed on average only 2–4 times in 10 years, and it was then applied to crops.

Motivation for using AD

The reasons/motivations of users to use AD are presented in Table 2.Waste treatment and energy production were the main reasons.

The reasons behind using the AD for waste treatment were to escape the inconvenience of irregular waste collection for household solid waste (for the first, third, and fourth groups) and to decrease the odor arising from previous livestock dung management (for the second and fifth groups). Table 3 shows the waste disposal methods prior to having AD for each input waste. Waste was mostly disposed of in open dumping, but even when collected by LAs, its final destination was also an open dump. Discharge into a closed pit is also connected to environmental pollution. Livestock owners receive reduced complaints from neighbors about the odor (arising from dung open dumping and the frequent overflowing of swine dung in closed open bottom pits).

The use of energy from AD was considered beneficial as it avoided the difficulties in collecting firewood (for the second and fourth groups) and reduced the cost of liquefied petroleum (LP) gas (for the first, third, and fourth groups).

Table 2 Reasons/motivations of users for using AD

Group	Reasons/motivations				Total
	Ability to produce energy (%)	Ability to produce fertilizer (%)	Ability to treat waste (%)	Availability of subsidies (%)	
First	53	18	88		17
Second	86	30	54	5	74
Third	67		100		3
Fourth	50		75		4
Fifth			100		2

Table 3 Waste disposal before using AD

Previous waste disposal methods	Group and waste								
	First		Second			Third	Fourth		Fifth
	KW	HW	KW	HW	LW	KW	KW	HW	LW
Dumped openly	3		11		61[a]		4		
Disposed into collection services	12					2			
Used to make compost	1		2		6[b]				
Discharged into an open bottom pit		13		1	7[c]			2	2
Total	16	13	13	1	74	2	4	2	2

[a]Cattle/buffalo/goat waste, sometime part of dung used for cultivations

[b]Only cattle and buffalo dung

[c]Only swine waste

Improved indoor air quality (in relation to not burning wood) and time saving (in relation to not collecting wood) are also other benefits. People interested in organic farming only considered the benefits of slurry production. Interestingly, subsidization of AD systems' construction was the least motivational factor even though most users (except 11) received subsidies (around 50% of the construction cost). Sometimes, the lower responses may be related to the respondents' attitudes as they like to highlight only the benefits that motivated them.

Material and cost balance

In this section, 87 of AD systems with the Chinese fixed-dome digesters (mostly encountered type), consisting of 15 in the first and 72 in the second groups, were analyzed (including nonoperational systems). AD systems in the third and fourth groups were excluded owing to difficulties in estimating waste generation (unknown number of people) and the energy (biogas) demand, and the fifth group was excluded because of difficulties in determining the biogas demand.

Size of AD systems

Because different types of waste are fed into AD systems, amounts of KW, HW, and LW were estimated using the generation values in Table 4a. Average generation amount in Sri Lanka and typical values in developing countries of a tropical climate are used for KW and HW generation, respectively. LW generation values are the most used values when designing household AD in Sri Lanka. The amount of KW and HW were estimated by multiplying the number of people and households. LW was calculated using a similar method, but when cattle/buffalo were open-grazed during the day for an average of 8 h, the estimated waste production was multiplied by 2/3. Twenty-four users had a lower feeding ratio, as they added the dung of 16–70% of their cattle/buffalo to the AD and considered it in the estimations. The value used for WH input was provided by each user. The composition was then calculated following the input estimation. According to the estimations, HW: KW in the first group is 80:20, and LW: KW in the second group is 80–95:20–5.

Using estimated input amount, hydraulic retention time (HRT) was calculated as the ratio of the working capacities of the digesters to daily feeding quantities including water. Water to LW or KW ratio was assumed to be 1:1, as the users claimed, and that is the optimum ratio [18]. The average water usage for toilet flushing in Sri Lanka of 20 L/capita/day [19] was used for HW. The working capacity was 90% of the actual capacity for Chinese fixed domes according to Sri Lankan standards [10].

Figure 2 shows HRTs for group 1 and 2 with the daily feeding quantities and the working capacities. A wide variation of HRTs shows that the capacities of digesters were not selected considering the feeding amount. The digestion occurred in mesophilic conditions (25–45 °C) because digesters were at ambient temperature, averagely around 27 °C in Sri Lanka. Compared with the recommended HRT between 10 and 60 days for mesophilic conditions ranges [18, 20], the HRTs in Fig. 2 were mostly longer than the values. Although a longer HRT ensures complete digestion, an extended HRT is the result of the oversized digesters and is uneconomical.

Another reason for long HRTs is a low feeding rate into the AD. 59 users in the second group did not use KW in their AD processes. The reasons were as follows: composting/animal feeding (9 users), thinking that there is no room for KW because of LW (21 users), thinking that it was bad to mix KW with LW (5 users), and the long distance between the house and the digester (4 users). The other 20 users had not been informed of feeding KW into the AD processes. HW was rarely used for the AD as most of the users (73 out of 87) thought that it was not right to use HW-derived gas or slurry. This attitude may be the result of the lack of knowledge about the AD process. In addition, since, mostly AD systems were located close to the livestock shed and not to the household. So, it was difficult to connect toilets with AD systems to feed HW in the second group. Users of low feeding LW implemented open dumping (19 users) to handle the remaining amounts of LW as well as composting (5 users), so LW feed into AD has benefit for improving the environment.

Biogas use

Most users used biogas only for cooking; additional uses included boiling dairy milk (seven users) and preparing swine food (four users). All users said that the flame of the biogas was blue and odor-free. Initially, 17 users (in the second group) wanted to use gas for lighting to reduce electricity bills, but they gave up because essential accessories (such as lamps) were hard to find.

Biogas production was estimated by multiplying the estimated input by the biogas potentials (normally considered values for AD in countries like Sri Lanka) in Table 4a. As per Sri Lankan standards [10], the biogas demand for cooking is 300 L/capita/day; with this in mind, the production-to-demand (P/D) was calculated and compared with fuel reductions percentages given by the users in Table 5.

The P/D was 0.3 for most of group 1 (as both P and D vary only with number of people), and it ranged from 0.2 to 8.0 for group 2. Regardless of P/D value, however, the

Table 4 Values assumed for estimations

(a) Waste generation and biogas production

Type	Generation		Biogas production	
	Assumed values	References	Assumed value, (L/kg-wet)	References
Kitchen waste	0.36 kg/capita/day	[1]	160	[8]
Human waste	1.3 kg/capita/day	[9]	28	[9]
Cattle dung	10 kg/animal/day	[10]	35	[10]
Buffalo dung	15 kg/animal/day	[10]	37	[10]
Swine dung	2.25 kg/animal/day	[10]	80	[10]
Goat dung	2.1 kg/animal/day	[11]	35	[12]
Water hyacinth			45	[13]

(b) Market price of LP gas, electricity, and fertilizer

Type	Price, (as of October, 2017)
LP gas	120 Rs/kg
Electricity	3.5 Rs/ kWh (for saving 30 kWh/month) 6.2 Rs/kWh (for saving 90 kWh/month)
Urea (contains 46% N)	50 Rs/kg
Triple supper phosphate (contains 43% P_2O_5)	50 Rs/kg
Muriate of potash (contains 60% K_2O)	50 Rs/kg

(c) Daily demands of fuels (four member household)

Use	Daily demands		
Cooking	LP gas	Wood	Biogas
	0.32 kg[a]	4.4 kg[a]	1.2 m^3[b]
	(15.8 MJ)	(79.2 MJ)	(25.2 MJ)
Lighting	Electricity		Biogas
	0.96 kWh [c]		1.2 m^3 [d]

(d) Nutrient content and utilization rate

	Contents of NPK in each waste			Utilization rate of each nutrient (%) [14]
	KW [15]	HW [16]	LW [16]	
TS, %	19	13	20	
Total *N*, (% in TS)	1.6	4.0	2.5	50% (KW) 25% (HW & LW)
Total P_2O_5, (% in TS)	0.3	1.5	1.3	50%
Total K_2O, (% in TS)	1.2	1.1	2.5	75%

[a]Reference [17]

[b]Reference [10]

[c]Assumed four 60W light bulbs for 4 h (=0.06 kW * 4 * 4 h)

[d]A lamp (Model PX-lamp) burns 0.075 m^3-biogas/hr for lighting equal to a 60 W light bulb/h

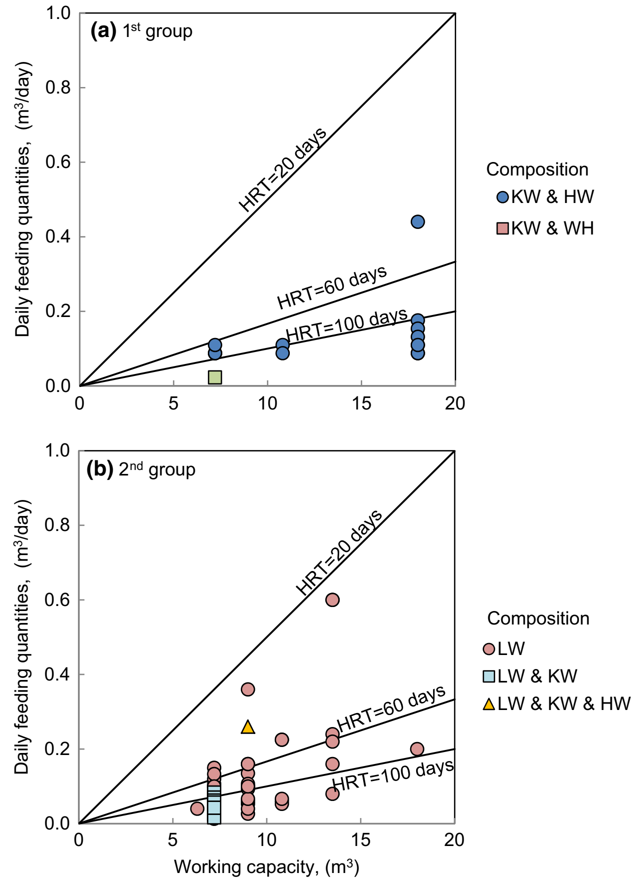

Fig. 2 Hydraulic retention time (HRT) of AD systems

Table 5 Percentages of fuel reductions using biogas

Group	Fuel reductions	Fuel type	
		LP gas	Wood
First	≥ 75%	7 (3)	2 (2)
	75–50%	5	
	< 50%	1	
Second	≥ 75%	7 (6)	53 (48)
	75–50%		7
	< 50%	1	1

Three units were excluded as it did not use biogas yet

() No. of units with 100% reductions

reduction in fuel was mostly higher than 75% which suggest that the actual demand is lower than estimated demand. A high fuel reduction is reasonable with a high P/D values.

Fuel reduction using biogas resulted in cost savings for LP gas users. Although the effect of cost saving was low for wood users, they are in favor of biogas use due to reduced air pollution and time for collecting wood. As a result, 93% of the users in both groups were satisfied with using biogas and encouraged others to use AD.

However, several users in the second group with 100% fuel reductions have higher P/D which means they have extra production. They waste abundant gas by burning in cooking stoves or release the extra amount into the environment by opening the valve at the digester's top. When demand is smaller than production, the accumulation of gas might cause gas leaks by high pressure. There is a need to increase demand in this case.

On the other hand, low fuel reduction households need to increase gas production. In group 2, there are households whose fuel reduction is higher than 75%, but only in 24 users a part of LW is fed to AD system at the same time. These households have a chance of improvement by increasing demand and production both.

Slurry use

48 users of AD used slurry for crops. The slurry was used in crops directly. According to users, the slurry was free of bad odor and insects. In addition, after crop application, no weeds appeared, and the harvest was significantly increased. However, the slurry was mostly applied to small-sized secondary crops (farming for household consumption) rather than to the main crops (cultivating for the main income). This was because subsidized chemical fertilizers were applied to the main crops, which lowered the users' attitude toward employing slurry. Of 48 users, only nine (one in group 1 and eight in group 2) had made cost savings by reducing fertilizers.

The application of slurry for cultivation was achieved mostly using buckets or pumps. In these cases, the slurry was often exposed to sunlight (outlets were mostly uncovered) for a longer duration because slurry was used when the outlets were close to overflow. According to [13], this could lead to the loss of N content in the slurry. In some cases, earth trenches were used to convey slurry from the outlet to cultivation directly, but part of the slurry could be lost by leaching from earth trenches during the slurry flow.

The reasons behind not using slurry were the absence of crops (21 users) and the faraway crop locations (11 users in the second group). They disposed of the slurry into either underground pits (nine users in the first group) or the surrounding area. Two users received complaints from neighbors about releasing slurry into the surrounding area because it flowed onto their land. Underground disposal was conducted when the space was limited.

Cost assessment

Figure 3 shows the construction cost (as of October 2017, 1 JPY = 1.36 Rs) versus the digester's capacity in both groups. The costs were normalized using a construction cost index published by the Central Bank of Sri Lanka.

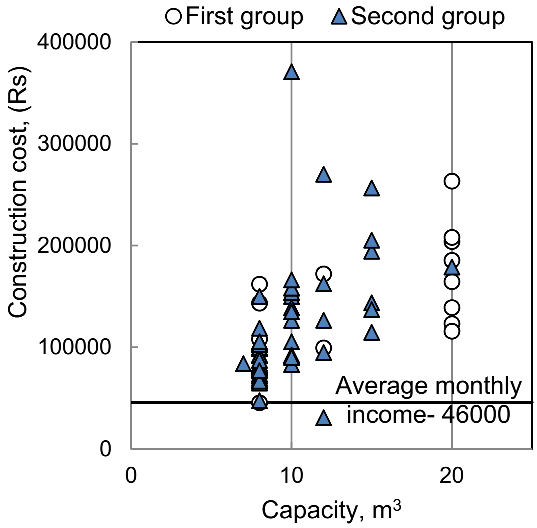

Fig. 3 Construction cost for AD systems

No significant correlation was found, but the cost increases with the capacity of digester. The cost varies with several factors. According to the questionnaire survey, the cost of the material included the transportation cost. Labor cost was decreased by the users themselves supporting construction works, and constructing or upgrading (flooring) the livestock stables increased the cost.

According to the Department of Census and Statistics of Sri Lanka, in 2012/2013, the average monthly household income was around Rs. 46,000. The construction costs shown in Fig. 3 are mostly 2–4 times higher than the monthly income, which highlights the need for subsidies. Actually, except for eight users, all users received on average 44% of the construction cost as subsidies after the completion of the constructions.

On the other hand, of 87 users, 26 and 9 had reduced the cost associated with fuel and fertilizer, respectively. In 26 users, the highest cost savings were obtained for LP gas users than wood users (only 5 in group 2) due to the fuel price. The low fuel reduction percentages shown in Table 5 suggest that there is room to save more fuel costs by increasing gas production. In addition, increasing the biogas production can reduce the electricity cost for lighting and other electrical appliances.

As for slurry, five users applied for the main crops while remaining users used for the secondary crops. There was better saving of cost in the main crop due to the larger dose of chemical fertilizers applied compared with the secondary crops. The rates of chemical fertilizer reductions were low for main crops which suggest further possible uses of slurry and higher cost savings, but people believe that more moderate use of chemical fertilizers hurts the harvest

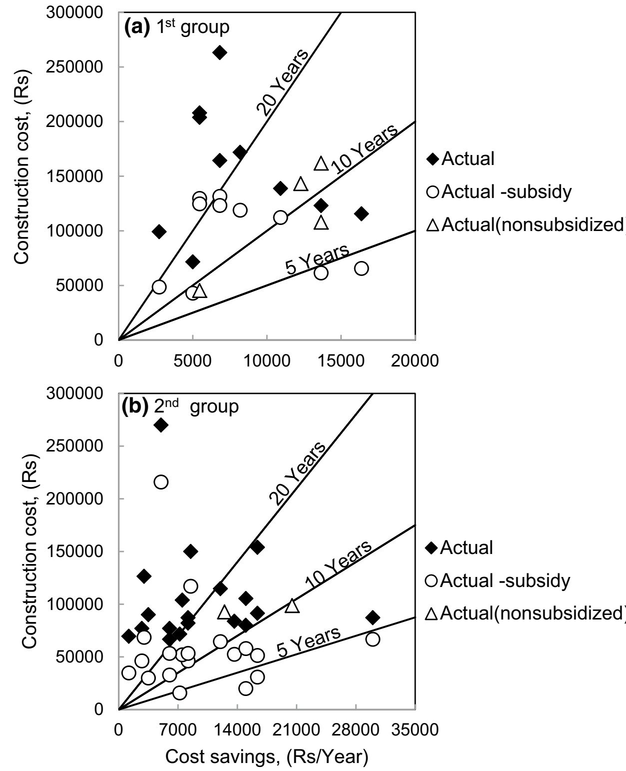

Fig. 4 Years for cost recovery

of main crops. This type of thinking means appropriate instructions to people are necessary to use slurry as the application of slurry creates more cost savings.

Figure 4 shows years for cost recovery (construction cost/annual cost savings) in first and second groups. Two symbols were used for the construction cost and construction cost minus subsidization except for six nonsubsidized AD systems. Both figures indicated that it took mostly over 10 years to recover costs by the reported cost savings, even with the application of a subsidy. To reduce the duration of recovery, cost savings should be increased or the construction cost should be reduced using the correct size.

Future possible scenarios of AD

At present, the use of AD in households is insufficient in number. According to the Department of Census and Statistics, in 2012, 72% of the households carried out improper on-site waste disposal. Out of this, 93% and 7% corresponded to groups 1 and 2 in this study, respectively. In this section, the possibility of using AD in the future is discussed for these households.

Increase of biogas production and demand

Increase of biogas production and demand can increase cost saving. Table 4c shows the daily demands of fuels for each use of a household consisting of four members (average family size in Sri Lanka). For cooking, values for requirements are taken from the literature. Energy values shown in parentheses indicate the low energy efficiency of biogas and wood compared with LP gas (energy values calculated by assuming that LP gas is a mixture of 40% propane and 60% butane, biogas contains 55% of CH_4, whereas the value of energy from wood is obtained from the literature [13]). As for lighting, the use of four 60 W light bulbs for 4 h was assumed, and the biogas demand for lighting replaced by four biogas lamps was calculated on the basis of the manufacturer's data. In case of L2 (described later), where power generation is considered, after cooking, the remaining gas is 2.3 m^3, which can run a generator only for 2 h (since the generator, model PX-1.5 kW, consumes 1.05 m^3 of biogas to produce 1.5 kW per hour according to the manufacturer). The generated electricity is used for lighting and operating electric appliances. With the use of these values, several scenarios are assumed as shown in Fig. 5.

For group 1, gas production presently covers only around 1/3 of the demand for cooking. Gas production can be increased by collecting only KW from four neighbors (case 1), because transporting HW is not feasible. To serve energy for both cooking and lighting, KW of nine households is needed (case 2). In this case, power generation is not practically possible.

For group 2, two subgroups are assumed, group 2L and group 2S, in which the average number of cattle is ten and three, respectively. The present case of group 2L shows that the biogas produced using part of LW (around 40%) is enough to meet the cooking demand. The demand can be increased by introducing lighting (case L1), but around 30% of LW remains. For full utilization of LW for producing gas (case L2), power generation is considered for the use of lighting bulbs and other electrical appliances. In group 2S, presently, gas production is not enough for cooking, so the strategy is the same as in group 1, that is, increasing gas production. Using own KW produces gas to meet the cooking demand (case S1), and both cooking and lighting are possible by adding KW of five households (case S2).

Improvements for slurry uses

To avoid N losses by exposing slurry to sunlight, the outlets should be covered and earth trenches should be replaced by PVC pipes when the slurry is directly conveyed to crops. On the other hand, if there is no use of slurry, composting

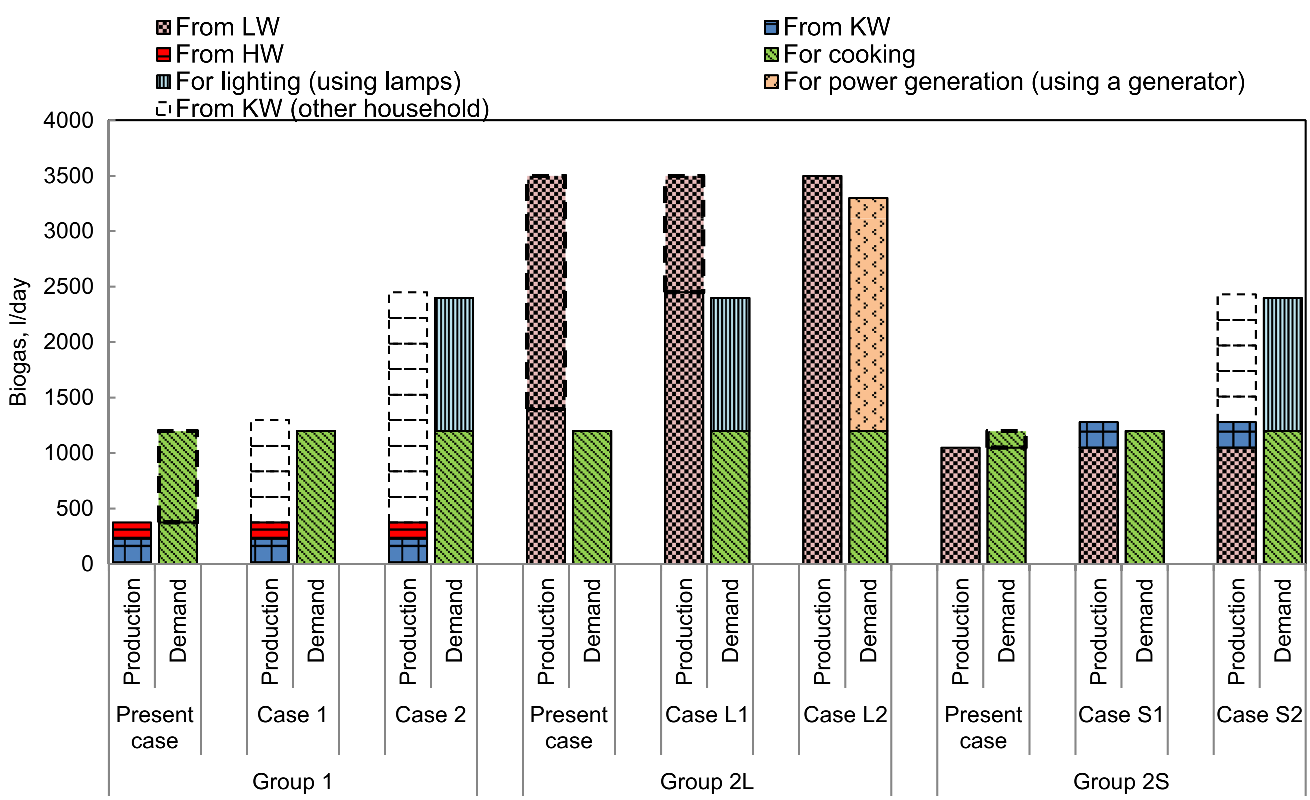

Fig. 5 Biogas production and use under possible scenarios

or disposal into underground pits (when inadequate space for composting) is preferable to prevent surface pollution.

Benefits evaluation

As shown in Table 4c, 1.2 m^3 of biogas replaces 0.32 kg of LP gas or 4.4 kg of wood daily in cooking. Lighting by biogas lamps will save 0.96 kWh/day of electricity. When a power generator is used in case L2, the operation for 2 h produces 3 kWh/day (within 2 h, 0.48 kWh for lighting and remaining power for other electrical appliances) The saving of nutrients (N, P, K) for cultivation is determined using the nutrient content of each waste input and the utilization rate of each nutrient for crops (shown in Table 4d) and the amount of input waste.

Figure 6 summarizes the annual cost savings based on prices in Table 4b. As Fig. 6 illustrates, the highest saving is obtained by replacing LP gas for cooking. Replacing wood is not significant because of the low price of wood. Power generation makes considerable savings in case L2. Even a small saving can be achieved using biogas lamps.

Table 6 shows the cost recovery years of all cases (as of October 2017). The digester capacities are appropriately selected considering the correct HRTs. One percent of the construction cost is considered as the annual maintenance cost [6]. To prevent corrosion, the use of desulfurizers is considered for lamps and generators.

The considered improvements (case 1 and case 2) for the group 1 reduce the cost recovery within 6 years. This means, instead of subsidies, loans can be provided for the most of the future implementations (as group 1 is the largest group),

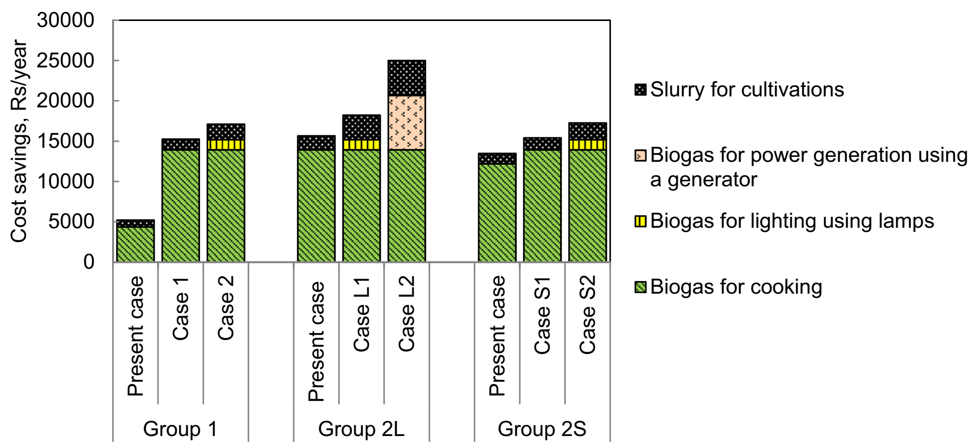

Fig. 6 Annual cost savings under possible scenarios

Table 6 Cost recovery years under possible scenarios

Case	(a) Implementation cost*, Rs				(b) Maintenance cost, Rs/year	(c) Total cost savings, Rs/ year	Cost recover years, years (=a/(b-c))
	For construction**	For lamps	For a generator	For a desul-furization unit			
Group 1 (6 m^3)							
Present case	90,000				900	5219	21
Case 1	90,000				900	15,256	6
Case 2	90,000	4280		1560	900	17,106	6
Group 2L (10 m^3)							
Present case	130,000				1300	15,669	9
Case L1	130,000	4280		1560	1300	18,233	8
Case L2	130,000		73,500	1560	1300	25,009	9
Group 2S (6 m^3)							
Present case	90,000				900	13,494	7
Case S1	90,000				900	15,417	6
Case S2	90,000	4280		1560	900	17,267	6

() Appropriate sizes of the ADs according to correct HRTs

*Implementation cost are as of October 2017

**Includes cost for dehydrators and pressure gauges and it is economically advantageous for the government. The same situation is for group 2S. However, group 2L type households need subsidies for implementation of AD systems as cost recovery is close to 10 years.

Conclusion

This study was conducted to know the current situation of household-scale AD, which is a widely used technology in developing countries, by visiting a hundred of AD users in Sri Lanka. The study found that main motivations to use AD are energy recovery and organic waste management. Biogas use can get the economical benefit to save the cost of fuel and electricity, and disposal of waste in the AD can reduce environmental pollution caused by inappropriate disposal of high organic content waste. On the other hand, however, the following problems were clarified.

Mostly oversized digesters were selected for the actual amount of waste. There are misunderstandings about treatable waste, e.g., kitchen waste was excluded from livestock waste, or only a part of livestock waste was fed into the AD. As a result, the biogas generation amount is not enough for potential need. The opposite case, i.e., demand of gas is smaller than production, is also found. In this case, the generated gas is burned in stoves or released into the atmosphere. To overcome these issues, all types and amounts of waste that can be disposed of into AD should be the critical information for installers to design the AD systems (appropriate digester sizing, deciding the use of biogas and providing necessary accessories according to potential uses). The designing guidance for installers should be given by the government.

Maintenance of AD is not sufficient. The most serious problem is corrosion which will shorten the life of biogas utilization equipments. Desulfurizer should be equipped in AD and it also needs to be cleaned frequently. Monitoring pressure is necessary to lower the possibility of gas leak, and frequent stirring and proper mixing of input with correct amounts of water can reduce scum formation which disturbs gas flow. The instructions should be given by installers of the AD for the users.

The scenarios for future implementations of AD systems shows, implementing one AD to treat 5 or 10 households KW is more economically feasible. To do this, both parties (the owner and the others) may need encouraging by highlighting the advantages (e.g., the owner has increased use and others have received treatment for KW freely) by local governments. To increased practice of the household-scale AD, it is critically important to inform (or advertize) the benefits of AD processes such as potential cost saving by the use of biogas and slurry, available support (loans or subsidy) to construct AD systems, and potential environmental improvements. The informing or advertising can be done using posters, and media advertisements in national language by both national and local governments.

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