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STUDY OF ORGANIC SOLID WASTE MANAGEMENT IN SRI LANKA USING CENTRALIZED COMPOSTING AND HOUSEHOLD SCALE ANAEROBIC DIGSTION

施設堆肥化および家庭規模メタン発酵を用いたスリランカにおける有機性固形廃棄物管理に関する研究

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A dissertation submitted in partial fulfillment of
the requirements for the degree of
Doctor of Philosophy

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CHAPTER 1
Introduction

1. 1 Background

Management of solid waste could be considered as one of a severe headache suffered by developing countries at present. The generation of solid waste is rapidly expanding as outcomes of swelling populations especially in urban areas coupled with unplanned urbanization, booming economies followed by resource exploitations. To cope with increasing solid waste generations, currently available waste management systems of developing countries are not enough and results in serious issues for both human and environment. Sri Lanka is a country where these situations are evident.

Sri Lanka is an island situated next to southern India (see Figure 1-1). It has a 65610km2 land area where over 20 million residents live. According to the World Bank, in 2013 Sri Lanka due to the booming economic activities is uplifted to the lower middle order income category.

According to the database 2014 of National Solid Waste Management Supporting Centre (NSWMSC), the total solid waste generation has been estimated as 3.65 M ton/ year based on per capita waste generation. Even though the management of solid waste in Sri Lanka is a responsibility of Local Authorities (LAs) as obliged by law, LAs can collect only 35% of generated waste (see Figure 1-2). This is mainly due to lack of financial and human resources to widen the collection services. Larger portion; around 85% of collected waste is being disposed into open dumps while the small amount of collected waste is being treated by using composting (10%) and recycling (5%). The open dumps carried out by LAs are mostly just heaps of waste, mostly in low lying areas such as marshes, abandoned paddy fields, without any precautions to control leachate, dust, odor, gas emissions and vermin [1-5].

The waste which is not grabbed by collection services is being handled at onsite by generators themselves. Mostly used methods are dumping and burning. Dumping of garbage usually happens in one of following ways; dump into a pit in the ground, open backyard dumping by throwing garbage in the easiest place, by dumping the garbage into waterways or roadsides. Burning of waste at onsite is done in regular intervals after dumping to reduce the volume of dumped waste [6,7]. Also, composting or anaerobic digestion is being used for waste, but very few practices [8]. Informal waste collectors collect the waste which has recyclable value and sold to collection centers where they are cleaned and sold for recycling by local industrialists, or exported overseas [9]. This is happening in waste collection services in active areas too.

According to the solid waste composition of Sri Lanka, it contains the high portion of organic waste (around 80%) with high moisture content in the range of 60%-80% [1,4,7]. Improper waste handling of this type of waste causes a lot of environmental impacts. Greenhouse gas emission is one of the issues arise from the open dumping of organic waste which adversely affects global warming. According to one study, methane emission from 3.5 hectares sizeable open dump in Sri Lanka was 65.2 GgCO2-equivalent/year (CO2 equivalent methane emission) [10]. Another impact is soil and water pollution by leachate. , and it contains heavy metals which could mix with soil or water sources. According to one study the leachate arises from one open dump has a high BOD value which is in between 15000-25000 mg/l [10]. Apart from that, mishandling of organic waste creates bad odors, the manifestation of flies, disease spreading, loss of land values close to open dumps, flooding situations caused by blocking drainages, channels and other, etc. One survey which investigates the adverse impacts of open dumping in Colombo metropolitan area revealed that people near to dump site as well as rag pickers were at great health risks. Patients with respiratory problems and skin diseases were commonly found among them [11].

To lower the issues of improper disposal of solid waste, it is needed to reduce the waste to landfilling/open dumps. One option is using organic waste for resource recovery since organic waste is largely present in the composition of waste. For that biological waste treatment methods have to be considered. Along the available methods, aerobic composting and anaerobic digestion have a long history as commonly adopted for treating various type of organic waste in developing nations [10].

The composting process involves the breaking down of organic matter into a humus-like stable end product under controlled aerobic situations by microbes such as bacteria, actinomycetes, algae, protozoa, and fungi. The ultimate end product of composting is characterized by relatively short molecular chains, a high degree of pathogen-free and contains abundant humus compounds [12]. The advantage of the composting is it makes stabilized end product which can replace fertilizer requirements in agricultural activities [11]. Also, the little cost on construction as well as operations makes the composting more feasible option for developing countries. Apart from cost, composting is flexible for establishing at different scales from the household level to medium, large-scale centralized facilities [13].

On the other hand, anaerobic digestion is the process in which organic compound is converted into methane by microbial actions in the absence of oxygen. The methane produced by anaerobic digestion could be utilized as a fuel. Also, the resulted residue (slurry) could be used as a fertilizer or soil improvement [11]. Anaerobic digestion has been typically occupied in Asia to treat animal manure, kitchen, and agricultural waste.

According to the situation, the better strategy to handle collected waste by LAs properly is composting when it is compared with anaerobic digestion as shown in Table 1-1. Even though the composting process has certain demerits compare to anaerobic digestion, its merits make the composting more practical than its counterpart because operations of composting are easy and simple which need low implementation cost. Also due to its solid state, the final product can be easily stored and distributed. Compost process is less sensitive to the quality of the feedstock than anaerobic digestion & it also an advantage because mostly collected waste is in the mixed state. Currently, there are ongoing composting processes operated by several LAs to treat collected waste. However, those processes are not well studied, and the composting has to be expanded as the still considerable amount of waste is being disposed of in open dumps (see Figure 1-2).

On the other hand, household scale anaerobic digestion is one of the promising strategies for onsite waste handling than household scale composting as shown in Table 1-2. The household scale anaerobic digestion works not only as a solid-waste disposal method but also as a producer of energy and fertilizer which makes more favorable for households than composting even it has certain disadvantageous. In Sri Lanka, currently, several households are carrying on household scale anaerobic digestion. However, those processes are not well evaluated to identify success, and required improvements and the use of AD has to be widening as most of the on-site waste are managed using improper methods (see Figure 1-2).

1. 2 Objective and methodology

This thesis focuses on studying existing centralized composting processes adopted by LAs for collected waste and household scale anaerobic digestion processes for non-collected waste in Sri Lanka to identify the success and associated problems. Then based on findings, it is aimed to investigate future strategies to extend both centralized composting and household scale anaerobic digestion for the whole country.

In brief, the following items were targeted during the studies of existing practices of centralized composting and household scale anaerobic digestion for organic waste management in Sri Lanka and evaluations of possible future expansions of both processes.

- Process flow
- Material flow
- Cost of the processes

1. 3 Organization of Chapters

This thesis consists of 5 chapters, and the summary of each chapter is as follows.

Chapter 1 talks about the background, the objectives, methodology and the organization of this research.

Chapter 2 studies are composting facilities in two steps. Firstly written survey for 100 composting facilities all over Sri Lanka was conducted and 37 replies were received. After going through the replies, field visits were carried out to 20 of replied facilities to observe the process flow and interview the workers for further clarifications. The process flows were studied, and the material flows were estimated. The costs for composting processes were analyzed. The issues in surveyed facilities were identified.

Chapter 3 investigates the household anaerobic digestion processes in five provinces of Sri Lanka. This survey was performed by visiting 100 households. According to information gathered, users were divided into main two groups and studied process flow and the uses of outputs generated by the AD. In addition to that, the cost of the processes was determined. The associated problems were discussed.

Chapter 4 discusses the future possibility of expanding the composting and anaerobic digestion to stop the current improper waste management. It evaluates possible implementations, required cost and proper use of the outputs generated by both processes. The process flows were decided as issues identified by the Chapter 2 and Chapter 3 are minimized.

Chapter 5 sums up the results of this research and present the conclusions.

Figure 1- 1 Location of Sri Lanka

Source: (National solid waste management supporting centre & Department of census and statistics, Map - www.RFA.org)

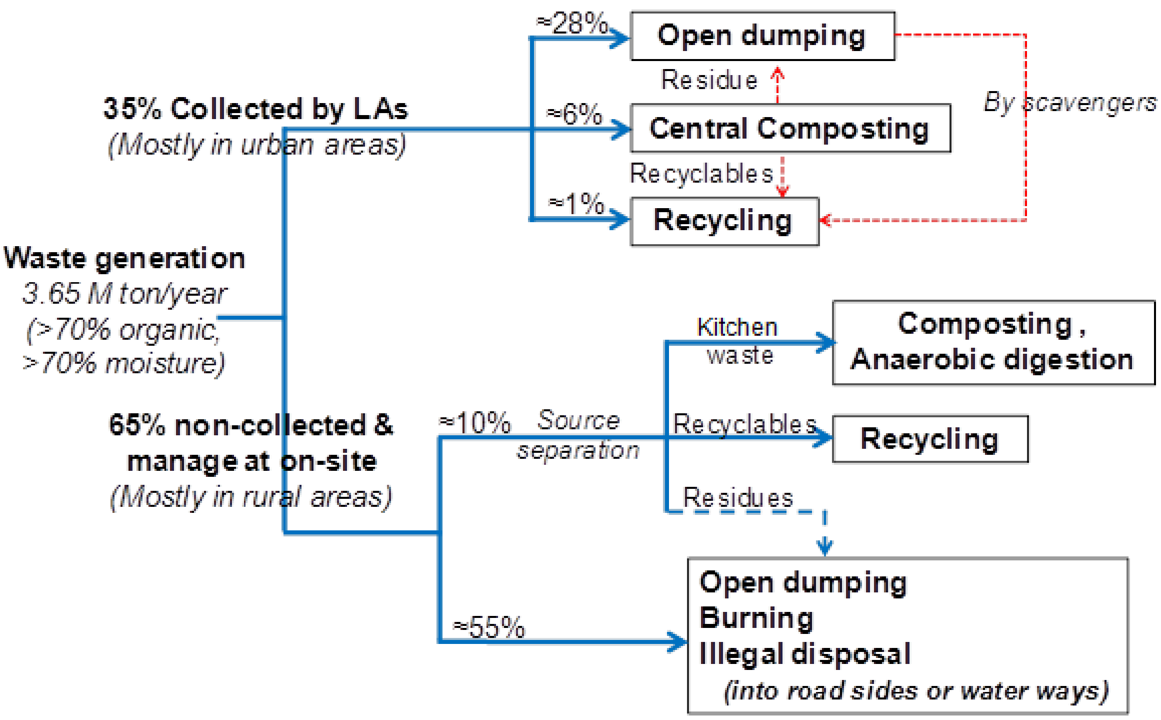

Figure 1- 2 Existing solid waste management in Sri Lanka

Source: (National solid waste management supporting centre & Department of census and statistics)

Table 1- 1 Comparison of composting vs. anaerobic digestion for collected waste

	Composting		Anaerobic Digestion (AD)	
Space	Bad	Large space	Good	Small space
Process	Good	Easy and simple operations	Bad	Complex operations
Output	Good	Have good demand even quality is not good	Good	Good demand of biogas for people (need distribution system
	Good	Easy to distribute due to solid form	Bad	Less demand for bio slurry
Labor	Bad	Labor intensive	Good	Less labor required
Cost	Good	Less construction cost and operational cost	Bad	Expensive construction cost and operational cost
Odor	Bad	Bad	Good	Not so bad

*If located at isolated area, (because people may oppose about implementing a AD system within populated area due to explosion risks) certain issues may encountered such as,
Difficulties in gas distribution to users (long distribution pipe)
Difficulties in gas distribution to users (long distribution pipe)

Table 1- 2 Comparison of anaerobic digestion vs. composting for non-collected waste

	Household AD		Household composting	
Product	Good	Biogas for cooking, lighting, etc, and replace firewood and kerosene	Good	Compost for fertilizer requirements
	Good	Bio slurry for fertilizer		
Odor	Good	Not be a problem because of closed operations	Bad	Be a problem because of open operations
Space	Bad	Certain space is required to construct the reactor	Good	Less space is required
Operation	Bad	Complex	Good	Easy and simple
Cost	Bad	Expensive cost for implementation (cost for reactor constructions, cost for gas pipes, cost for gas utilizing instruments etc)	Good	Less cost for implementation (just for composting bin or barrel)
	Good	Save the purchasing cost of energy		
	Good	Save money for fertilizer	Good	Save the purchasing cost of fertilizer
Other benefits	Good	Reduces deforestation by lowering the firewood demand	No additional benefits	
	Good	Save time for women to collect firewood		
	Good	Sanitation conditions could be improved by allowing toilet waste and animal husbandry waste into reactors		

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CHAPTER 2

Centralized composting for collected solid waste

2. 1 Introduction

To reduce the potentially harmful impact of open dumps, the organic content in collected waste requires diversion using biological treatment methods. Among the available biological treatment methods, composting is seen as a low cost method, while the product has agricultural applications. In recent years, an increasing trend of composting by Local Authorities (LAs) in Sri Lanka has been evident, mainly through aerobic windrow composting [1].

A number of studies on the composting of solid waste in Sri Lanka have been carried out recently such as, determine the applicability of composting for collected waste in Sri Lanka as a disposal method [2], evaluate different composting systems [3-4], evaluate the cost benefits of composting by market analyses [5], determine the optimum pile dimensions in windrow composting to maintain thermophilic conditions [6], and evaluate the mass balance analysis of one composting facility [1]. The majority of these studies were carried out using the composting process on an experimental basis. Even though composting for collected waste has become popular among the LAs, after implementation of composting facilities, the process of composting has not been well evaluated.

By evaluating existing facilities, essential improvements can be identified and potential solutions could be suggested for processes which require modifications. Therefore, the objectives of the current study were to gain an overview of process flow and material flow, and to perform a cost analysis of the existing composting systems in Sri Lanka.

2. 2 Methodology

2.2.1 Centralized composting facilities in Sri Lanka

According to the 2012 annual report of the National solid waste management supporting centre (NSWMSC), there are more than 100 composting facilities operated by LAs across Sri Lanka. Figure 2-1 shows the capacities of that facilities and the year that each the facilities started operations. The numbers of composting plants have been increased over the last decade as the government of Sri Lanka has initiated a subsidiary system for establishing composting facilities through a nationwide program from 2007 with the aid of the Japanese International Cooperation Agency (JICA). Figure2- 1 shows that the windrow method is the most dominant practice used and facilities are mostly in small capacities.

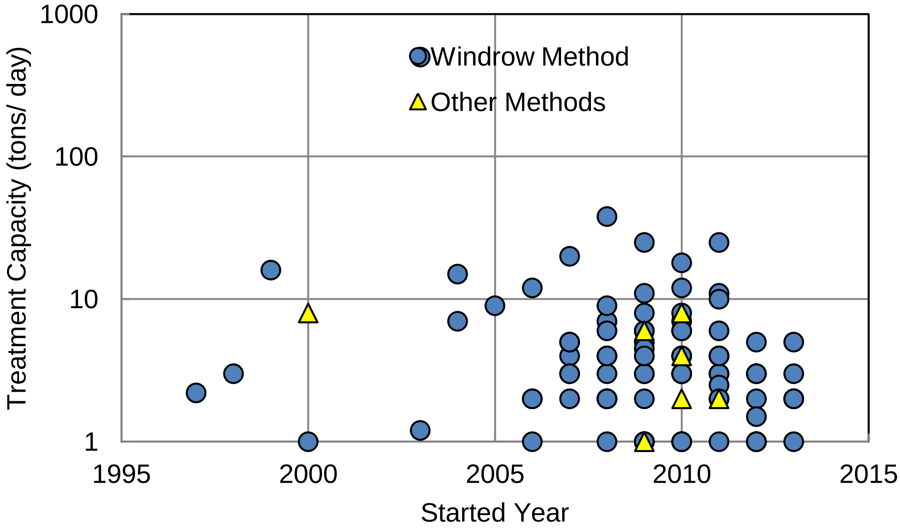

Figure 2- 1 Processing capacities and year of commencement of the composting facilities up to 2013

(Other methods consisted of two locally developed methods)

2.2.2 Questionnaire survey

To collect information on the operations, material flow, and cost of composting processes operated by LAs, a questionnaire survey was conducted as such details are not available in the literature. Table2-1 lists the questions included in this questionnaire. The questionnaire consisted of questions related to operations (type, capacity, methods of pretreatment, duration of composting, turning methods, turning frequency, pile heights in windrow composting, duration of maturation, post treatments, moisture control, and odor control), material flow details (type and amount of input and amount of compost and residues), cost (construction cost, cost of utilities with energy consumption, and cost for salaries), and use of compost (type of customers, monthly demand, and selling price).

The questionnaire was provided to the facilities via the postal service and a postage-paid envelope was attached for returning the replies. The addresses of the composting facilities owned by LAs were obtained from NSWMSC by written request. The questionnaire was prepared in the main native language of Sri Lanka to obtain better recovery. In the northern and eastern parts of the country, an alternative language is widely used. Hence, the LAs situated in these parts of the country were excluded from this survey due to language translation difficulties. Finally, 100 of the LAs were selected and questionnaires were sent to them on the May 20, 2014.

Table 2- 1 Summary of the questionnaire survey

Category	**Item**	**Content**
Process Details	Capacity Method used Pre and post treatment	Daily waste handling capacity ISG, SAT, Windrow (turning method, frequency, duration of composting stage, Maturing method, maturing duration, Odor controlling etc. Method (Sorting by hand, Sieving etc)
Input	Organic fraction of MSW Other waste Bulking material	Amount, Moisture content Type (livestock waste etc) Amount, Moisture Content Type (Rice husk, Saw dust etc.), Amount
Out put	Compost Residue	Amount, Moisture content, Price of selling Amount, Disposal method
Utilities	Electricity, Water, Fuel	Monthly consumption
Cost	Construction Running	Amount Personnel, Repairing
Usage of the produced compost	Usage	Customers (Farmers, Home gardeners etc.),

2.2.3 Facilities studied

Thirty-seven replies (37% reply rate) were received within 1.5 months of period from the date of questionnaire were sent. Among these replies, 32 facilities were in operation (Locations of studied facilities were shown in Figure 2-3). Two replies indicated that their composting operations had already ceased due to sorting difficulties. One reply indicated insufficient data to be able to answer the questionnaire as operations had just begun, and two facilities replied that their operations had not yet started.

Of the 32 replies, 30 facilities used the simple windrow methods, whereas others used locally developed methods. The current study concentrated only the windrow composting facilities since this is the most prevalent method of composting.

2.2.4 Process flow of windrow composting

The main steps of windrow composting are sorting, composting, maturation, and screening (Figure 2- 2). Received solid waste is sorted to segregate the organic fraction. The sorted organic fraction is then piled up to facilitate composting, and essential aeration is supplied by frequent turning of the pile using mechanical or manual methods. Moisture is added during the composting stage. After the composting stage, compost enters the maturing stage, followed by screening to remove residues from matured compost (Further details were mentioned in Table 2-2). Recovered recyclables are sold, whereas rejects from sorting as well as residues from screening are placed in open dumps.

2.2.5 Field visits and interviews

Field visits were conducted during the period August 20 to September 8, 2014. The objectives of the field visits were to observe the location of the facilities, the condition of the input (feedstock, separated recyclables, and rejects), the condition of the output (compost and residues), the monitoring of temperature and moisture, the management of the leachate, the odor situation, and the condition of the dumping sites. Interviews were conducted with the workers so as to obtain information on the process, about complaints from the public in nearby areas, and the tendency toward use of the compost.

The ease of obtaining permission from the respective authorities to enter the facilities as well as logistical constraints in terms of travel time was factors which limited the field visits to 20 windrow facilities.

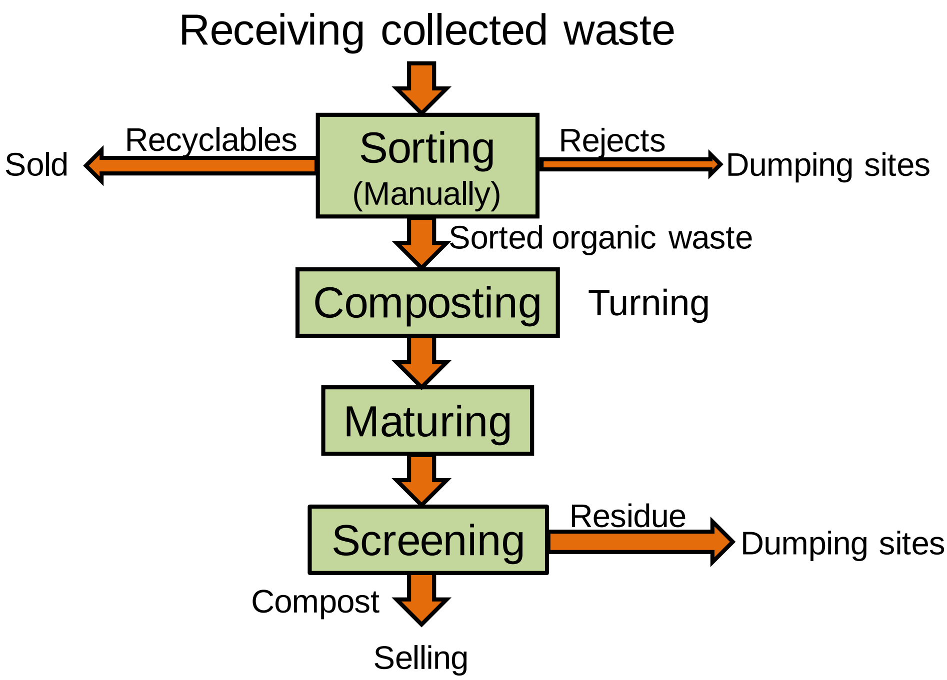

Figure 2- 2 Process flow of windrow composting in all replied facilities

Table 2- 2 Operational details of replied facilities

Facility	Type of the respective LA	Capacity (tons/day)	Characteristics of receiving input	Facility type	Composting Phase				Maturation Phase		Post processing (Screening)
					Windrow height (feet)	Duration (Months)	Turing methods *	Turning **	Method	Duration (Weeks)	
W1	MC	20	Mixed waste	Roofed	4.5	4	BB	1/4 weeks	Windrow	2	Trammel
W2	PS	7	Mixed waste	Roofed	4	2	BH	1/week	Windrow	2	Trammel
W3	PS	1	Mixed waste	Roofed	3.28	3	BH	1/week	Windrow	>4(90days)	Manually
W4	UC	6	Mixed waste	Roofed	5	2	BB	1/2 weeks	Windrow	2	Trammel
W5	UC	5	Mixed waste	Open	4	1.5	BH	1/week	Windrow	1	Trammel
W6	PS	1	Mixed waste	Roofed	2.5	2	BH	1/week	Windrow	1	Vibrating table
W7	PS	4	Mixed waste	Roofed	6	1.5	BB	1/2 weeks	Windrow	2	Trammel
W8	PS	2	Mixed waste	Open	5	1.5	BH	1/week	Windrow	>4(60days)	Trammel
W9	PS	2	Mixed waste	Roofed	4	3	BH	1/2 weeks	Windrow	>4(90days)	Manually
W10	PS	5	Mixed waste	Open	5	2	BH	1/week	Windrow	2	Trammel
W11	PS	2	Mixed waste	Open	5	1.5	BH	1/week	Windrow	2	Trammel
W12	UC	20	Mixed waste	Roofed	6	1.5	BB	1/week	Windrow	2	Trammel
W13	PS	6.5	Mixed waste	Roofed	5	3	BH	1/week	Windrow	>4(120days)	Vibrating table
W14	PS	4	Mixed waste	Roofed	5	1.5	BH	1/week	Windrow	>4(30days)	Vibrating table
W15	MC	40	Mixed waste	Roofed	2.5	2	BB	1/week	Windrow	2	Trammel
W16	PS	4	Mixed waste	Open	4	2	BH	1/week	Windrow	2	Trammel
W17	PS	4	Mixed waste	Roofed	4	4	BH	1/week	Windrow	2	Trammel
W18	PS	1	Mixed waste	Open	4	2	BH	1/week	Windrow	2	Manually
W19	PS	1	Mixed waste	Roofed	4	2	BH	1/week	Windrow	2	Vibrating table
W20	PS	3	Mixed waste	Roofed	5	2	BH	1/week	Windrow	3	Vibrating table
W21	PS	3	Mixed waste	Roofed	6	2	BH	1/2 weeks	Windrow	2	Trammel
W22	PS	1.5	Mixed waste	Roofed	4	2	BH	1/week	Windrow	>4(30days)	Trammel
W23	PS	1	Mixed waste	Open	3.28	3	BH	1/2 weeks	Windrow	>4(30days)	Vibrating table
W24	PS	3	Mixed waste	Roofed	2.5	2	BH	1/week	Windrow	2	Trammel
W25	PS	6	Mixed waste	Roofed	5	2	BH	1/week	Windrow	2	Manually
W26	PS	4	Mixed waste	Roofed	4.92	4	BH	1/week	Windrow	2	Manually
W27	MC	10	Source separated organic waste	Roofed	4	2	BB	1/week	Windrow	3	Trammel
W28	PS	9	Mixed waste	Roofed	5	3	BB	1/2 weeks	Windrow	>4(90days)	Vibrating table
W29	PS	6	Mixed waste	Roofed	3	3	BH	1/week	Windrow	1	Trammel
W30	PS	9	Mixed waste	Roofed	3.5	2	BH	1/week	Windrow	>4(60days)	Manually

Visited facilities   * BH: By hand, BB: By bobcats   ** 1/week= once in a week, 1/2 weeks= once in 2 weeks, 1/ 4 weeks=once in 4 weeks

MC: Municipal Council (LAs with a population ≥ 30000),
UC: Urban Council (LAs with a population between 10000 and 30000),
PS: Pradeshiya Sabha (LAs for rural areas)

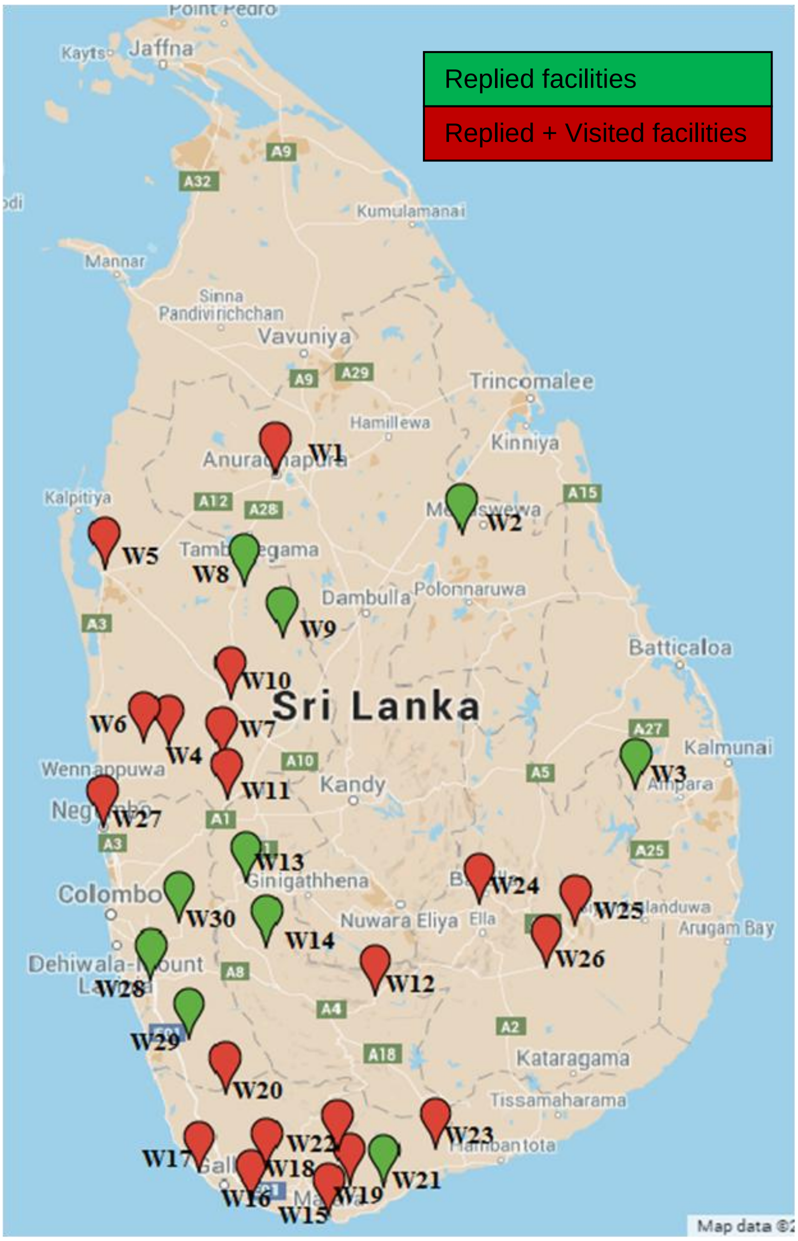

Figure 2- 3 Locations of the studied composting facilities

Source: (Map www.googlemap.com)

2. 3 Problems identified by this study

2.3.1 Sorting of the organic fraction

According to the questionnaire replies, 29 out of 30 facilities received mixed solid waste, which was separated manually (Figure 2- 4) into the organic fraction, recyclable materials, and rejects. The remaining facility received only organic waste, which was collected separately from the sources of origin.

Figure 2- 4 Manual sorting for received solid waste at two facilities

In facilities that received mixed solid waste, sorted feedstock was considerably contaminated with inorganic matter, which might be caused by low separation efficiency due to the high moisture content of solid waste. The facility which received source separated organic waste, also conducted manual sorting to remove inorganic matter prior to pilling and there were significantly lower amounts of inorganic material in feedstock. As noted onsite, the organic fraction of the solid waste at all facilities consisted mostly of food waste from households, restaurants, markets, and institutions.

As explained by operators within the visited facilities, only three facilities decided to conduct source separated waste collection from the start of operation. However, two of them ceased the decision due to unfavourable attitudes of respective households. In contrast, even though the remaining facility was faced with the same situation, awareness programs as well as laws compelling households to dispose of solid waste as requested allowed the facility to continue its original operation. All other facilities did not take any action to perform source separated waste collections; however, a number of the facilities have emphasized a willingness to perform in the future.

2.3.2 Construction of piles

As indicated in the questionnaire replies, sorted feedstock is directly piled without any preprocessing steps such as shredding or drying. Furthermore, there is no addition of bulking materials into the feedstock prior to the pile construction.

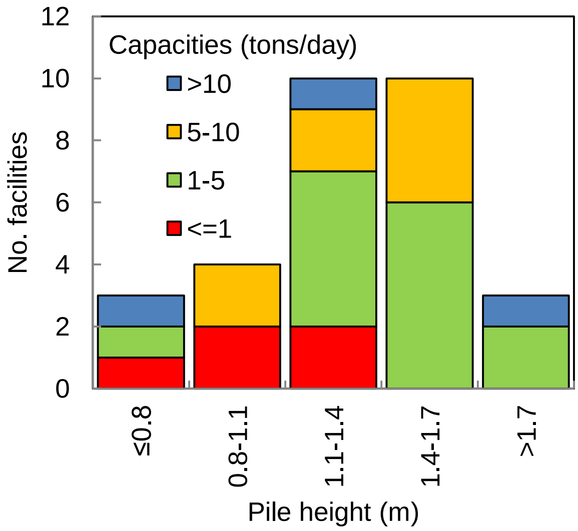

Figure 2- 5 Variation of the height of windrow piles with respective capacities of the facilities

Figure 2-5 shows the variation of the height of piles along with the respective capacities of the facilities taken from the questionnaire. The heights of the piles vary between 0.76 and 1.83 meters. The most frequently encountered height ranges of piles were 1.1-1.4 and 1.4-1.7 meters, representing 33% of the facilities, respectively. In regards to capacities, 46% of the facilities could process 1–5 t/day, whereas 16% of facilities could process 1t/day or less. Only three facilities showed capacities as high as 10t/day.

Figure 2-5 shows that the heights of the piles do not depend on the capacities of the facilities. As observed, the shapes of the composting piles were mostly of the rectangular block type (Figure 2-6) and were constructed within concreted yards. When the size (area) of the concreted yards is not sufficient for the construction of piles of incoming waste at a lower height, the height of the piles should be increased so as to maximize the use of the available space effectively within the concreted yards. This situation occurred due to the improper estimations of incoming waste.

Figure 2- 6 Rectangular block type windrow piles in one visited facility

As noted during the field visits, feedstock was loosely arranged during pile construction. However, in four facilities, feed stocks were compressed manually (see Figure 2-7) so as to increase the amount accommodated in a single pile, because of insufficient concrete yards.

The construction of taller piles may not be convenient for turning. In addition, taller heights are associated with larger cross sections which may not be able to facilitate natural convection. Application of the compression of feed stock may further reduce natural convection by decreasing porosity inside the piles. The process of composting may be undertaken under anaerobic conditions under these situations.

As stated in the questionnaire replies, the composting stage progressed under a roofed area in 77% of the facilities and as open composting (see Figure 2-8) in the remaining facilities. As observed during the field visits, in roofed facilities, the roofed yards were not only used for composting, but additionally for sorting, maturing, and screening. In open composting facilities, a roofed yard was situated adjacent to the composting area for maturing and screening, whereas sorting was conducted at the composting space. In both of these two types of facilities, a closed building was used to store the produced compost. The use of the roofed area for the composting stage was not correlated with the precipitation of the region (Figure 2-9a), but with the capacities of the facilities (Figure 2-9b). Having more financial capacities may be the reason for larger facilities attribute with a roof. In addition, the control of moisture within open piles may be challenging during the rainy season because the rectangular block shape traps rain water and increases water adsorption. If the shape is peak type, then water adsorption could be reduced because peak shape will promote runoff of excess water as mentioned in US Environmental Agency [7]. This may lead to a reduction of the available free air spaces inside the open piles.

Figure 2- 7 Feedstock compressed by foot at one visited facility

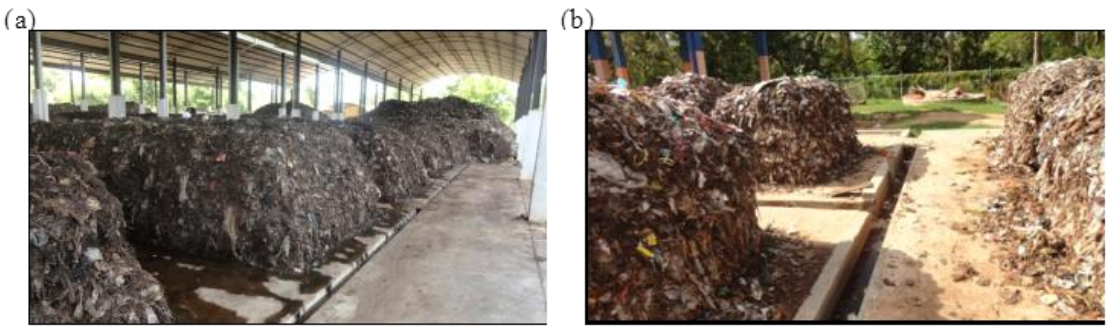

Figure 2- 8 Type of composting (a) Piles under a roof, (b) Piles without a roof- open composting

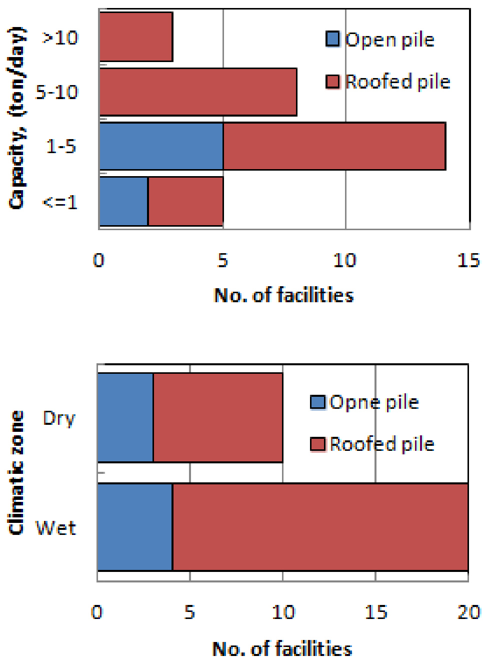

Figure 2- 9 Variation of type of composting with (a) climatic zones of facility located area (b) capacities of the facilities

2.3.3 Operations during composting

Figure 2-10 illustrates the relationship between the turning frequencies and the durations of the composting stage. In 70% of the facilities, the composting stage was confined to a two month period, whereas in three facilities, four or more months were dedicated. In regards to turning frequencies, the piles of 77% of the facilities were turned once per week. As encountered in site visits, mechanical turning (in 23% of the facilities) was performed by front wheel skid loaders (Bobcats-S130) and manual turning (in 77% of the facilities) was performed using shovels (see Figure 2-11). Among the two turning methods, the larger facilities used mechanical turning as in Figure 2-12

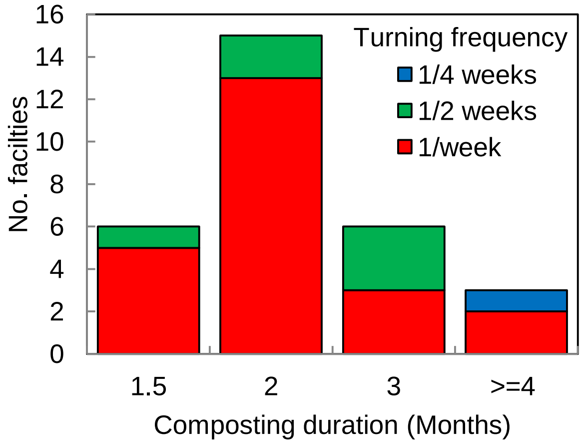

Figure 2- 10 Variation of turning frequency with duration of composting in all replied facilities

The durations of composting were not influenced by the turning frequencies, as indicated in Figure 2- 10. Onsite observations revealed that there was no temperature monitoring, and compost was progressed to maturation after a predetermined time, regardless of stability. This may be the reason why the duration of composting was not influenced by turning frequencies. In addition, without temperature monitoring, the stabilization of the compost could not be identified.

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(a) (b)

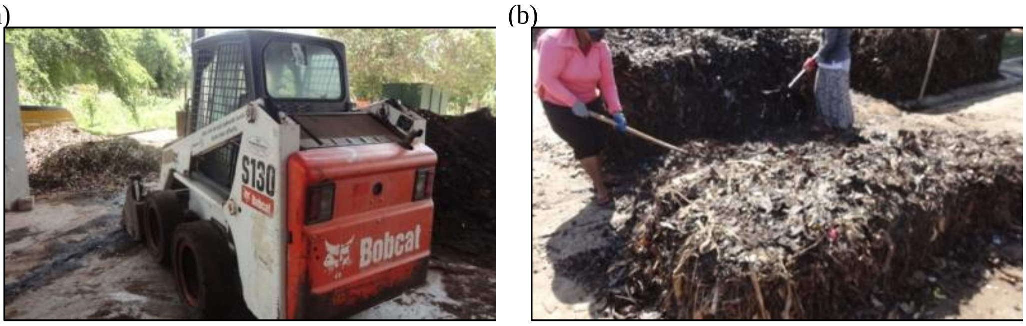

Figure 2- 11 Composting piles turning methods (a) turning mechanically using front wheel skid loaders (bob cats), (b) turning manually using shovels

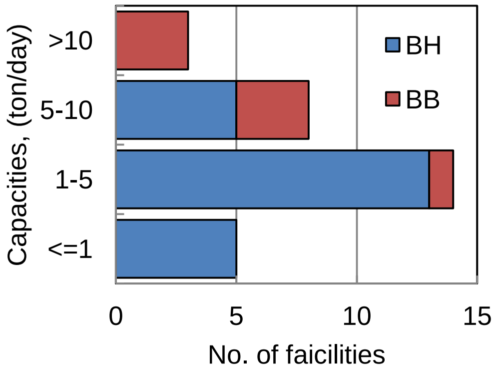

Figure 2- 12 Turning methods variation with the capacities of composting facilities (BH-by hand, BB- by bobcat)

According to the questionnaire replies, moisture addition was performed regularly in 66% of the facilities, whereas it was performed only during dry seasons in the remaining 34%. As observed on site, moisture addition was performed without considering the moisture balance, and as a consequence, a black leachate was drained out from the piles. Addition of excessive moisture reduces the free air spaces inside the piles, which may promote anaerobic conditions.

Figure 2-13 illustrates how the leachate is managed in the visited facilities. Of the facilities, 80% collected leachate by a drainage system into a tank, but recirculation of leachate into piles was done only in 55% of facilities. In these facilities, collected leachate was diluted with waste water from cleaning activities plus rain water before recirculation. Remaining 25% of the facilities did not implement recirculation. Therefore, collected leachate tended to stagnate in the collection tanks, thereby facilitating breeding conditions for insect larvae. In other facilities, no collection or recirculation of leachate occurred, and leachate was instead directly disposed of into the surroundings, which may result in pollution of water sources.

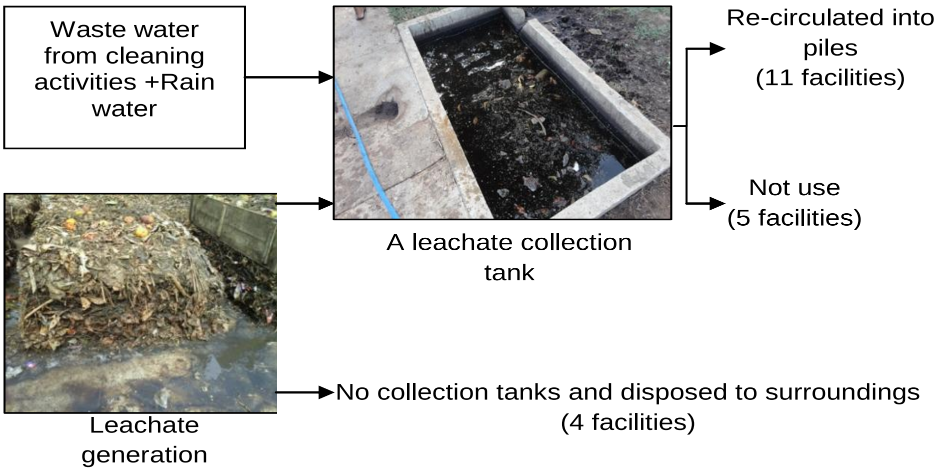

Figure 2- 13 Summary of the leachate management in visited facilities

2.3.4 Odor nuisance situation

During the field visits to 20 facilities, significant malodor situations were experienced. Inadequate porous structures inside the piles, excessive moisture addition with a reduction of free air spaces, and low turning frequencies, especially during the initial stage of decomposition, may constitute possible reasons for malodors by enabling anaerobic conditions.

As experienced during the site visits, roofed composting facilities were more prominent in malodor situations than open composting facilities were. To reduce this situation, before establishing the roofed composting area, the predominant wind direction should be considered to facilitate natural ventilation as experienced within one roofed composting facility.

All visited facilities were located within an isolated area to reduce inconvenience to the public. However, in six facilities after the composting processes had been initiated nearby areas had become populated. Hence, those facilities received complaints against odor and fly infestations as described by the operators. All the windrow facilities were attributed with odor situations because of the food waste content in their feedstock. Hence, it is important to facilitate adequate buffering zones so as to avoid nuisance situations. In addition, if the food waste is collected separately, the exposure of the food waste to open air could be shorting the sorting duration. These steps may further assist to reduce the odor situation.

2.3.5 Maturation

The durations of the maturation phase were considerably shorter than those of the composting durations (Figure 2-14), as the maturation period used was three weeks or less in 70% of the facilities. Therefore, it should be termed storage rather than maturation. During field visits, it was observed that compost was matured under a roof in all facilities after being gathered as large heaps (Figure 2-15), except in one facility. In addition, the application of turning was not encountered.

Shorter durations are not sufficient for maturation. In addition, larger heaps may not facilitate the passive aeration required for maturation. No turning may further limit the necessary aeration. According to US EPA, the minimum duration of maturation should be one month and the maturation piles should be small enough to permit adequate natural air movements [7]. However, as operators described, the duration of maturation may continue until demand appears or space within the maturing shed is filled. Longer maturation durations may enable essential aeration through passive aeration.

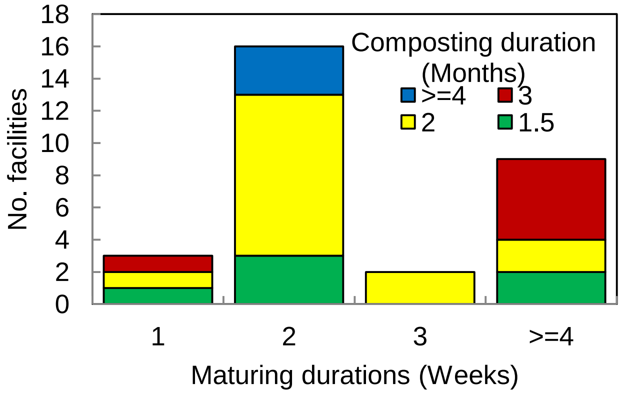

Figure 2- 14 Maturation duration variation with composting duration in all replied facilities

Figure 2- 15 Picture of maturation heap at one visited facility

Figure 2- 16 Maturing as thin layer pile at one visited facility

A thin layered pile which was observed in one facility may allow the necessary aeration within two weeks of maturing. This kind of practice was possible within maturing sheds of sufficient space (see Figure 2-16). In all visited facilities, there was no monitoring of the compost maturity.

2.3.6 Post-treatment and management of recyclables, rejects, and residues

According to the replies of the questionnaires, screening was the only available post-treatment method. In 80% of the replies, it was indicated that trommels or vibrating tables were used for screening, whereas the remaining facilities used manual screening as they did not have an electricity supply (Shown in Figure 2-17).

As seen on site, the residues consisted of coarse particles of compost, incompletely degraded yard waste (especially dried banana leaves from the markets), paper, and non-biodegradable particles (see Figure 2-18). The presence of large compost particles in residues may be caused by inadequate turning frequencies and higher moisture contents.

In six of the visited facilities, a hammer mill-type crusher (in Figure 2-19) was used before screening to reduce the amount of coarse compost particles remaining in residues. Before feeding into the crusher, visible inorganic matter was manually removed. Separated recyclable materials were sold and all rejects resulting from sorting were placed in open dumps, along with residues from screening. However, in 50% of the facilities, residues were used for gardening due to their high content of compost.

Of the observed open dumps, 19 out of 20 were located proximate to the facilities, which may reduce the transportation costs of rejects and residues. In the source-separated organic-waste-receiving facility, the disposal site was not located proximate to the facility. Hence, rejects and residues were transported to a disposal site after a considerable amount had accumulated. Since the amounts of rejects and residues at this site was comparatively less than those at other facilities, the low frequency of waste transportation (generally once in 2 weeks) was feasible.

(a)

(b)

Figure 2- 17 Screening methods used by visited composting facilities (a) A trammel screening, (b) A vibrating table screening

(a)

(b)

Figure 2- 18 Post treatment residues at two of visited facilities

Figure 2- 19 A hammer mill type crusher used for reducing the coarse compost particles in residue

2. 4 Material flow

2.4.1 Composition of Input

Figure 2-20 shows the variation of the amount of rejects with incoming solid waste among the facilities. The values of incoming solid waste and rejects were taken from the questionnaires, and those values were estimated based on the hauling loads by operators.

As shown in the Figure 2-20, the reject ratio (reject/daily waste incoming) varied in the range of 10–40%. The minimum rejection of 3% was recorded in the facility which receives organic waste only.

As noted in the field visits, the rejects contained plastics, as well as long-term degradable materials such as coconut shells and banana stalks. In addition, some rejects were composed of readily biodegradable particles due to inefficiency of sorting.

In facilities using mixed solid waste, the recyclable material recovery ratio averaged 2±1% of incoming solid waste. Recovered recyclable materials mostly consisted of cardboard, plastics, PET bottles, metal cans, and glass, as observed during field visits (shown in Figure 2-21). The low recovery rates may be a result of informal sector recovery before the collection of MSW. In addition, as noted onsite, some possible recyclables were transferred to the dumps as they were heavily contaminated.

2.4.2 Compost utilization rates, usage, and price

In all visited facilities, it was realized that there were inaccuracies in the output data, due to lack of proper information among operators. Generally, only part of the matured compost was sieved to obtain the final product, and a considerable amount of matured compost remained heaped at maturing sheds or storing rooms. In addition, the weighing of compost was only performed when the facilities received demands for compost. Considering these facts, instead of monthly compost production rates (output/input), the monthly compost utilization ratio was calculated as below. In this calculation, instead of dry weight, wet weight was used as the moisture content of compost was not available. Three facilities were excluded from this calculation as they had not yet started selling product.

$$\text{Compost utilization ratio} = \frac{\text{Amount of average monthly demand of compost (tons} - \text{wet/month)} \times 100}{\text{Feedstock into composting process(tons} - \text{wet/month)}}$$

The variation of the amount of average monthly demand of compost for total feedstock on a wet weight basis among the facilities is shown in Figure 2-22.

As Figure 2- 22 illustrates, the utilization ratios were below 10% in all of the facilities. In 40% of facilities, the utilization rates remained at levels equal to or less than 1%. Only four facilities had utilization ratios of greater than 5%. Karunarathne et al, 2014 [6] determined the output to input (compost/sorted feedstock) ratio of one roofed composting facility in Sri Lanka. This facility was not included in our study. But all the operations were similar to surveyed facilities (mixed waste, sorting, two months composting in rectangular piles, mechanical tuning once a week, 4 weeks maturation, trommel screening). By this study the authors measured the output/input ratio on dry basis as 40%. This value would be 21.7% in wet basis if it calculated using the determined moisture contents of input and output,54.5% and 25% by Karunarathne et al, 2014 [1]. Compared to this output/input ratio in wet basis, the utilization ratio of surveyed facilities by our study were very low.

As operators mentioned at the visited facilities, the residues generated from the screening of compost were not measured. However, the amount of residue was roughly equal to the amount of compost recovered, except in one facility with source separated organic waste collection.

According to the questionnaire replies, the produced compost is mainly used for home gardening and agricultural land. As informed by the operators, agricultural applications include tea, rubber, coconut, and vegetable cultivations. The quality (stability, maturity, nutrient content, and moisture content) of the final product was not assessed before selling. Only one facility had received a quality certificate by the agricultural department; however, this was obtained at the very beginning of the operations, and subsequently, such a practice has not been continued.

Figure 2-23 shows the variation in the retail price of 1kg of compost with monthly utilization ratios obtained from the questionnaire. The retail prices of 1kg of compost ranged 5–25Rs/kg (1 USD=132Rs as of July 2015), and the price of compost is affordable considering the average household income (average monthly income of a household in Sri Lanka is approximately 46,000Rs, as indicated by the survey conducted by the department of Census and Statistics during 2013). The most common selling price is 10–15Rs/kg, as implemented by 43% of the facilities. As illustrated in Figure 2-12, the higher utilization ratios were not associated with lower prices.

Two facilities with monthly utilization ratios of >5% conducted marketing programs to expand the demand for compost amongst the public. These marketing programs included small seminars in which the advantages of the usage of organic fertilizers were explained to farmers, home gardeners, and schools. In addition, the utilization ratios were improved through mobile selling stalls and the distribution of leaflets etc. However, no such effort had been undertaken by the other facilities as of our investigation.

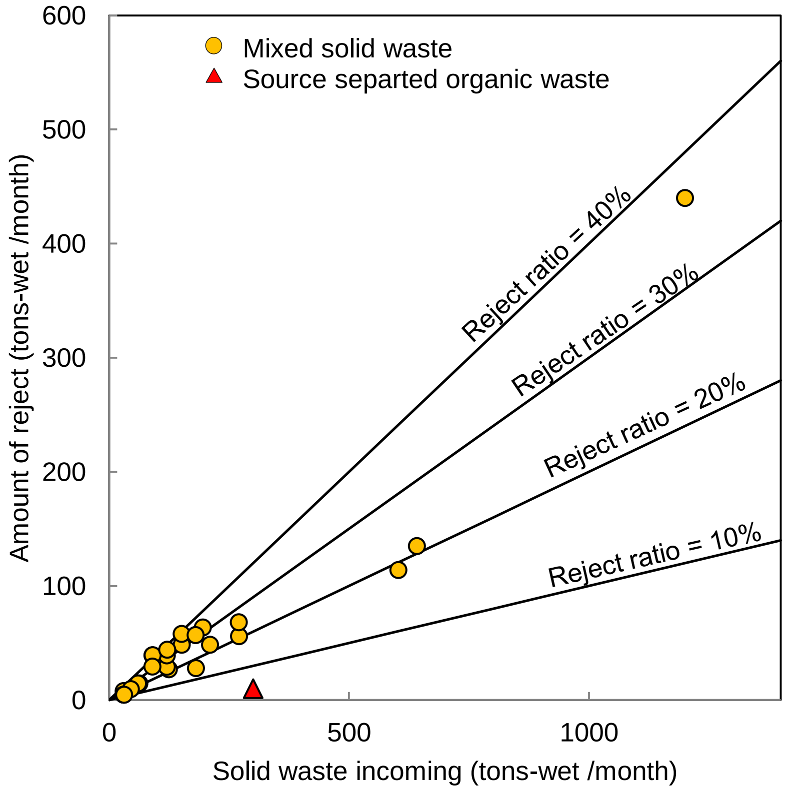

Figure 2- 20 Reject ratios (reject/ solid waste incoming) in all replied facilities

Figure 2- 21Recovered recyclables from sorting (a) Metal cans (b) Glass bottles (c) Cardboards

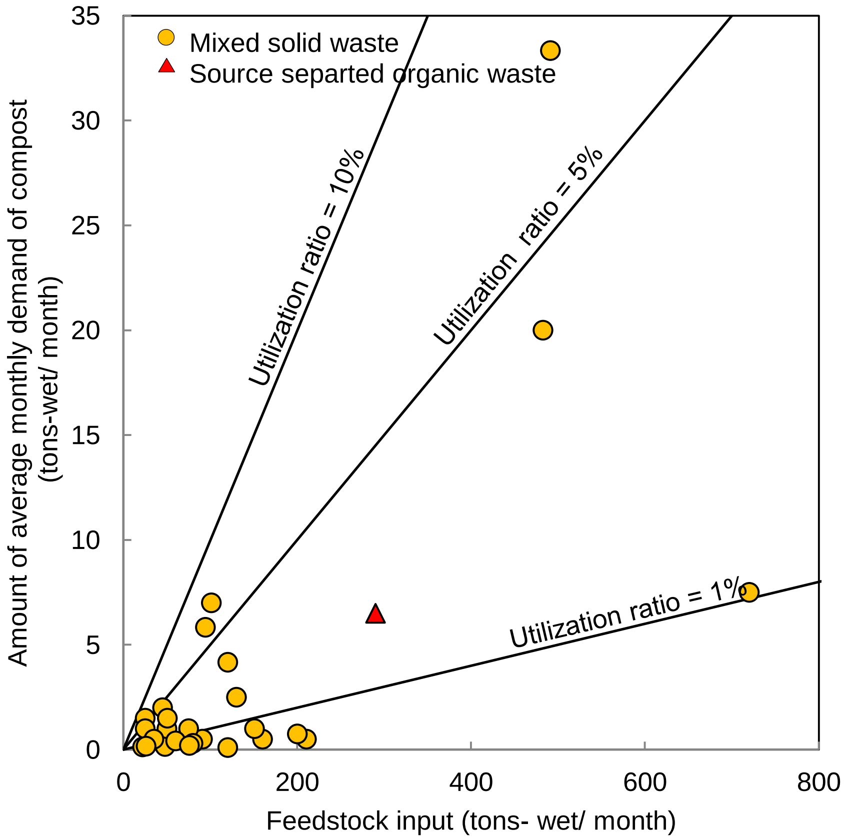

Figure 2- 22 Monthly utilization ratios in replied facilities, n=27, three facilities were excluded because selling of compost did not start yet

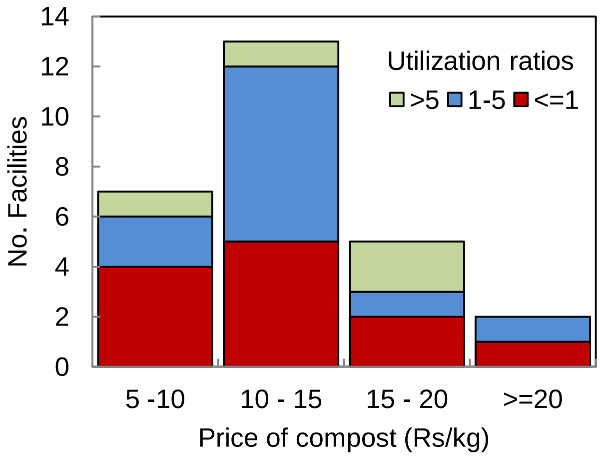

Figure 2- 23 Variation of retail price of compost with monthly utilization ratios in replied facilities, n=27, three facilities were excluded because selling of compost did not start yet

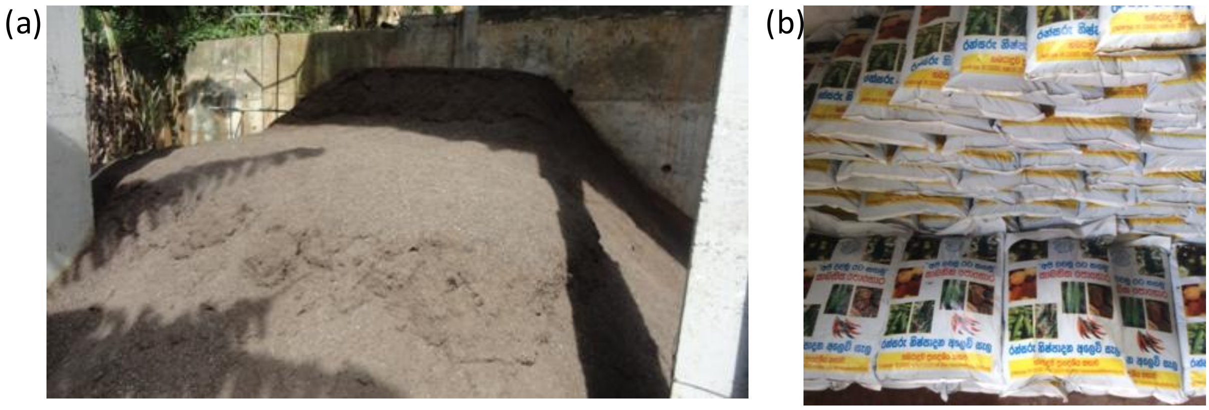

Figure 2- 24 Produced compost at visited facilities (a) before packing, (b) after packing

2. 5 Cost of the composting processes

2.5.1 Construction cost

Figure 2-25 illustrates the construction cost per unit of treatment capacity (C/V) vs. treatment capacity of the facilities plotted in log–log scale. The costs were not normalized using cost indices, as during field visits it was found that the constructions were not completed immediately. Even after the composting process was initiated, some of the construction proceeded.

Figure 2-25 shows some economy of scale, in other words, the values of C/V decreased as the treatment capacity increased. However, a significant difference in construction cost per unit treatment capacity was not visible between the roofed and open composting facilities. This is because the composting area was roughly 50% of the total area in open composting facilities, and maturation and screening proceeded under a roof as explained previously. Some deviations of the C/V values may occur as the values were not normalized using location factors due to the unavailability of these factors.

Due to small differences in the treatment capacities, estimation of the magnitude of the scale indices was not performed.

2.5.2 Operational costs

The operational costs of the composting process comprised costs for the utilities and salaries. Cost for the utilities included those of electricity, water, and fuel.

As stated in the questionnaire replies, only 77% of the facilities consumed electricity, and over the whole composting process, this consumption was only during post-treatment (screening). In addition, nine of these facilities consumed electricity for water pumping from wells. In addition, during field visits, it was observed that 50% of the visited facilities used electricity for the packaging of compost.

As indicated in the replies, 40% of the facilities used the public water supply, whereas others supplied water either by pumping or manually obtaining water from wells due to the remoteness of the location. Water was used mainly in cleaning activities and also partially for moisture addition.

Fuel was consumed by only 30% (9/30) of the facilities. As noted on site, seven facilities consumed fuel for operating machines whereas the remaining two consumed fuel for generating the power required for screening.

Two facilities did not consume any of the above utilities. In addition, one facility has been excluded from this operational cost analysis due to the unavailability of the required data.

Figure 2-26a shows the cost of the utilities per unit of input material on a wet basis. There is an economy of scale in turning both mechanically and manually. Mechanical turning has a higher cost for utilities per unit input than that of annual turning. This difference resulted from fuel consumption of turning machines, and it accounted for >75% of the utility costs per unit input. Among other facilities, electricity was the main contributor to the cost of utilities, with a contribution range of 48%–100% of the total utility cost.

Figure 2-26b shows the cost for salaries per unit input on a wet basis according to the replies. No difference was evident between manual and mechanical turning, as mechanical turning requires additional personnel for sorting.

As cost for salaries is 10 times higher than cost for utilities, the most effective way to reduce the operational cost is having source separated waste for composting.

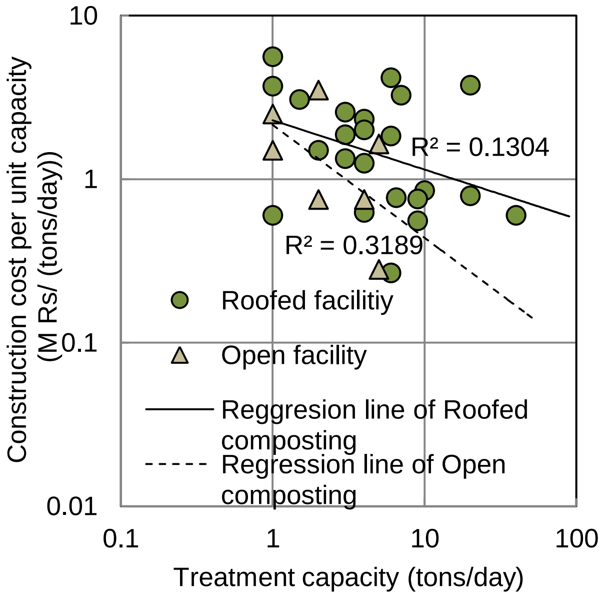

Figure 2- 25 Construction cost per unit treatment capacity (C/V) in all replied facilities

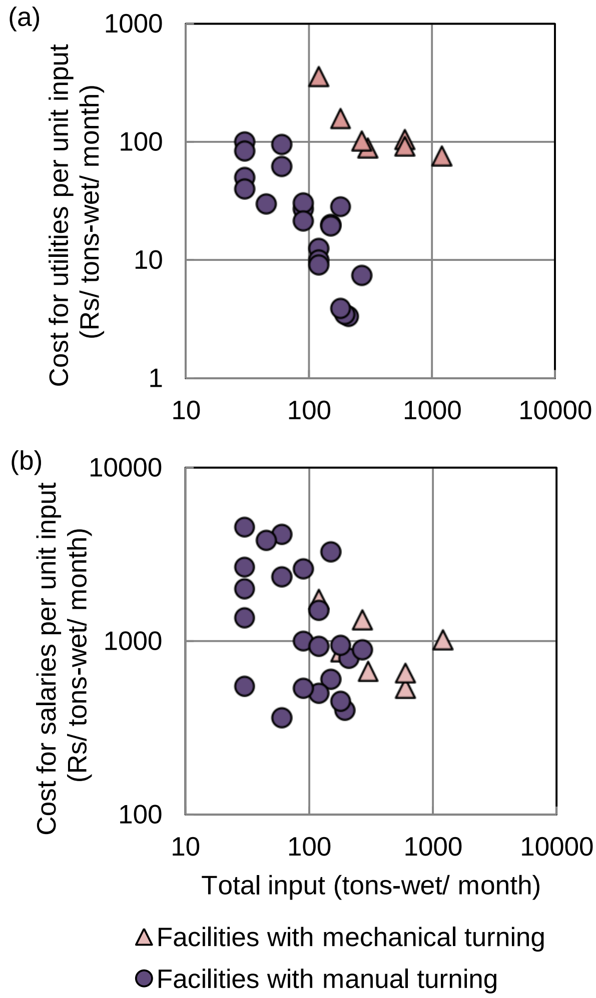

Figure 2- 26 Cost for utilities and salaries per unit input in replied facilities (a) Cost for utilities (include electricity, water and fuel), (b) cost for salaries

2. 6 Recommendations

In Sri Lanka, even though collected solid waste composting is identified and implemented as a solution for upgrading the existing solid waste management, the demand for compost remains at a low level according to the research outcomes of the current study. One possible reason is the low quality of the produced compost. To sustain the collected solid waste composting process, more demand for composting could be stimulated by improving the quality of the compost and by marketing the usage of the compost among farmers.

To improve the quality of the compost, the source-separated waste collection system is required to reduce the amount of contaminated feedstock for composting. However, the implementation of source-separation waste collection is not an easy task, as experienced during the current study. Source separation requires strong commitments from both the waste generators and the respective authorities. To facilitate source separated waste collection, residents should be aware of the initiative to separate waste and the respective authorities should strengthen and enforce laws to compel residents to carry out waste separation. Source-separation waste collection systems would reduce the manpower required for sorting and may lead to a reducing of the cost spent on wages. In addition, the recovery rate of recyclable material could be increased by implementing source-separated waste collection systems.

Temperature monitoring should be introduced within the composting process. By monitoring the temperature during the composting stage, the stability of the composting could be ensured. In addition, the monitoring of temperature could help to identify malfunctioning stages of composting, such as a sudden drop of temperature during the initial stage of decomposition, and corrective steps (such as applying turning or moisture addition) could be taken to overcome these situations. Furthermore, temperature monitoring would facilitate the regulation of the moisture addition and lead to the control of excessive leachate generation because in the facilities that lack moisture regulation, difficulties in leachate management are encountered and often the generated leachate are discharged into nearby areas.

During the constructions of windrow piles, the feedstock should be loosely arranged. In addition, to ensure the maturity of the compost, the duration of maturation should be increased and the shape of the maturing heaps should be kept to smaller sizes to enable passive aeration.

To engage with these suggestions, the workers should be suitably trained. Generally, the available labor force associated with the waste management sector is less educated. Therefore, to transform unskilled workers into skilled workers, training programs are essential. Currently, one facility conducts such a program for workers at newly built composting facilities. This training program includes sorting, constructing piles, turning, and moisture addition. However, these training programs still do not address temperature monitoring and how to take precautions according to temperature profiles. Therefore, this program should be revised with those points in mind (e.g., temperature and moisture monitoring and workers' awareness of the importance of good maturation (longer durations)). An additional problem faced by the composting facilities is retaining skilled workers. Generally, recruitment in waste management sectors has a low reputation amongst society. As a result, workers intend to search for another job, even after they become skilled. As a solution, it can be suggested that workers should be hired as permanent staff as the majority of workers remain recruited on a temporary basis.

To increase demand for compost, the usage of the compost should be promoted among the farmers. One option to achieve this is to undertake organic farming attractively at the facility premises. This will assist to obtain more attention of the buyers. As noted onsite, every facility has an area dedicated to organic farming on the facility premises. However, some facilities did not maintain the farmed space attractively. It is also important to routinely assess the quality of the compost (once per month) by sending the samples to the appropriate institution, such as an agricultural department.

Advertising is an additional option available to market compost amongst potential buyers. Conducting seminars on the advantages of using organic fertilizers is one method of advertising. In addition, small leaflets could be distributed and large advertising notice boards could be erected in places such as city centers.

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CHAPTER 3
Household scale anaerobic digestion for on-site waste management

3. 1 Introduction

For the non-collected waste which is treated at on-site in households, anaerobic digestion (AD) 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 [1]; 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 implementations of AD systems 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 household-scale AD was then included in implementation initiatives by 2000. According to several resources, around 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 [2-3]. However, recent interest in domestic anaerobic digestion is steadily increasing. The Sri Lankan biogas program has been initiated to promote anaerobic digestion. This program subsidizes the construction of AD 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 household-scale AD systems were not well evaluated by going through their input, output, operational steps, their effectiveness in waste management, their use in supplying energy and fertilizers, and cost.

In light of these issues, this research aims to study the process flow, material flow, management of biogas and bio-slurry, changes in waste disposal, and cost of existing AD systems.

3. 2 Methodology

3.2.1 Existing household scale AD in Sri Lanka

Figures 3-1 and 3-2 show the classification of various household AD processes in Sri Lanka and basic designs of AD digesters, respectively, and these are summarized in the following text.

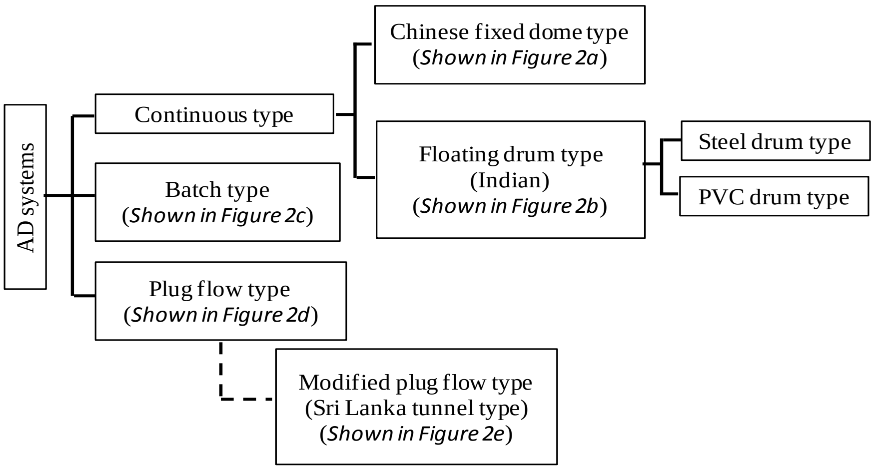

Figure 3- 1 Classification of AD processes found in Sri Lanka

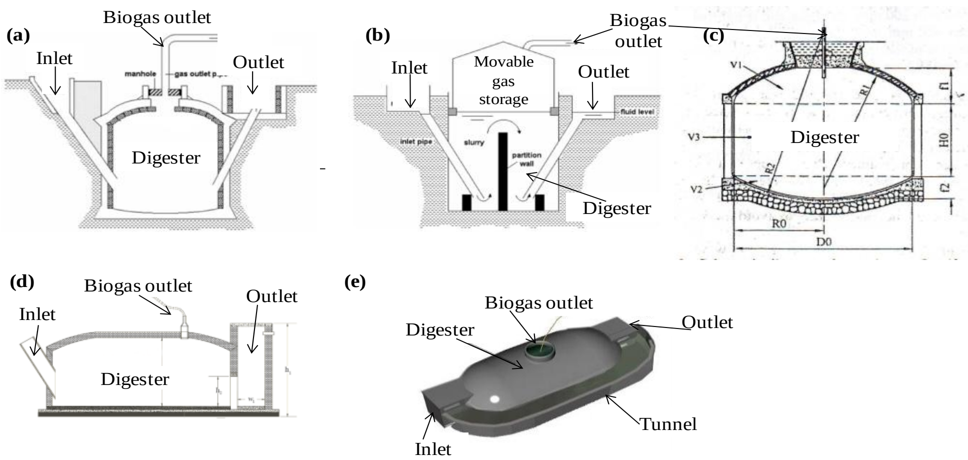

Figure 3- 2 Basic designs of AD digesters: (a) Chinese fixed dome type, (b) Floating drum type (Indian), (c) Batch type, (d) Plug flow type, (e) Sri Lanka tunnel type

Source: [2,4]

The Chinese fixed dome type (Figure 3-2a) and the floating drum type (Indian) (Figure 3-2b) are typical continuous-type structures. In these types, organic waste is fed in from the inlet and the digested mixture (full or part) flows out at the outlet. The inlet, outlet, and digester of both types are made of concrete. The gas storage section in the floating type is made from steel. In the Chinese type, the upper part of the digester is used for gas storage. For both systems, at the start of gas production, the slurry inside the digester is displaced into the outlet tank due to the hydraulic pressure created by the gas. The displaced slurry then moves again into the digester when the gas pressure decreases in accordance with its utilization. Floating drum (steel type) reactors are not currently used due to the frequent occurrence of corrosion in the drum, and a floating type reactor made entirely with PVC has now been introduced instead.

Batch-type digesters (Figure 3-2c) are made with concrete and an outside storage area for biogas. The digester is designed to be emptied completely after a fixed retention time of six months. This type was designed to locally target fermentation of rice straw in rural areas of Sri Lanka, but they are no longer being implemented.

Plug flow digesters (Figure 3-2d) are designed to have a length that is five times that of the width. These types are made of concrete, fiberglass, or PVC. It is theoretically assumed that the fed materials inside plug flow reactors do not mix in a vertical direction and that digested materials are pushed forward whenever fresh materials are introduced into the digester. However, the actual operation is rather more complex and differs from this perception. In addition, gas generally accumulates inside the tubular type digester.

The Sri Lankan tunnel-type reactor (Figure 3-2e) is a locally modified plug flow reactor. It has a closed tunnel for recycling slurry through the outlet into and then into the digester through the inlet.

According to available records [2], 90% of the 7500 AD systems currently installed in Sri Lanka are Chinese fixed dome reactors.

3.2.2 Questionnaire survey

An on-site questionnaire survey was used to collect information on household AD, and Table 3-1 briefs the content..

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

The second section determines the digester's details (type, capacity, operation started year, and current condition), the operation steps (stirring, removal of condensed water, cleaning of cookers and lamps), monitoring steps (monitoring of gas pressure and gas leaks) followed by users and problems encountered. Additionally, user training and orientation is requested.

The third part inquires input details. Amount of Kitchen Waste (KW) and Livestock Waste (LW) are requested as a feeding ratio (input: total), and approximate input amounts are requested for other waste (yard waste, straw, water hyacinth etc.). The input amount of human waste (HW) is not requested as HW is fed using a direct connection between toilets and ADs. The amount of water added for KW, LW, and other waste-types are requested as a volume ratio. For cases of HW, the questionnaire determines whether the water amount used for toilet flushing is adjusted in the digestion process. The detergents types used in toilets are also requested. Furthermore, previous disposal methods for the respective input types are also determined. Furthermore, previous disposals for the respective input types are requested.

The product and cost savings section (output) asks about the use of biogas and bio-slurry, including the current reduction in the amount of previous fuel used and fertilizer consumed in relation to the use of biogas and bio-slurry as a percentage, respectively. Finally, the resulting cost savings are asked for.

Under the cost section, the construction cost (including any subsidy received) and maintenance costs are requested.

The final section determines user satisfaction (satisfied or not, willingness to recommend technology to others) and ideas for future modifications (any desire to use the output for other purposes and willingness to deal with other inputs such as night soil).

The aim of including the main income/occupation and ownership of crops and livestock is to realize user's living conditions and educational background. The number of family members and amount of livestock is requested to estimate the total amount of waste generated (KW, HW, LW), and the reason for asking whether the water volume used for flushing toilets is adjusted for the ADs is to simplify estimations (if not, then general toilet water consumption is used in calculations).

Table 3- 1 The content of the questionnaire

Category	Items	Content
(1) Background of users	Household details Electricity supply Cultivation and Livestock Motivations to have a biogas unit	No. of members, Main income source/ occupation Type and size
(2) Process	AD digester Operation and maintenance Problems encountered during operations Monitoring Training and orientation	Type, Capacity, Started year, Working or not (reasons) String, Removing condensed water in gas pipes (methods and frequency), Frequency of cleaning of biogas utilizing apparatus Gas pressure, Gas leaks
(3) Input & Previous disposal methods of input	Kitchen waste, Livestock waste Other waste Human waste Disposals of input before AD process	Input ratio to AD (%), Water addition (waste volume: water volume) Amount, Water addition (waste volume: water volume) Water usage in flushing (adjusted or not, if adjusted amount per flushing), Type of detergent Methods
(4) Products and Cost savings	Usage of biogas Usage of bio-slurry	Type & percentage of biogas for each use (ex:- cooking, lighting) Replaced fuel and its reduction , cost saving Type & percentage of slurry for each use Replaced items and its reduction, cost saving
(5) Cost	Construction and Maintenance	Amount (Rs/-)
6) User's perception	Satisfaction Future Modifications	 Extend input types, Extend use of products

3.2.3 Selection of users for the survey

Although household AD systems have been implemented in all Sri Lankan provinces, there is no centralized database that holds associated information. 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 technology and requested the users' names, addresses, contact numbers (telephone), reactor information (type, year started and capacity). However, only the names and addresses of anaerobic digestion users in five provinces (out of 9) were available. Those were obtained via email from the first two institutions while the latter three institutions provided data after being visited.

The surveyed AD users were selected as covering all five provinces and easiness to reach those (in terms of distance and travelling cost). 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 the districts after consideration of traveling distance. Finally, 100 users were selected and the questionnaire survey was conducted during a visit between July 10 and August 16, 2016. Table 3-2 shows the number of AD users surveyed within the selected districts.

Table 3- 2 Locations of surveyed AD users

Province	District	Selected ADs
Southern	Galle	38
	Hambantota	4
Western	Colombo	6
	Gampaha	2
North western	Kurunegala	20
	Puttalam	2
Cental	Matale	11
Uva	Badulla	14
	Monaragala	3

3. 3 General outline of the surveyed AD systems

3.3.1 Background of the interviewees

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

According to the answers received for main income/occupation, most people in second group had a lower educational and income back ground because being farmers compare to first group which mostly comprised of people with good education and income (doctors, engineers, lawyers, government officers, and teachers) as shown in Table 3-3.

All five groups were connected to the electricity grid. Water was provided from either public connections or wells; the latter were widely encountered in the first, third, and fourth groups. In addition, 18 AD systems from all groups (14 households, all in the commercial group, and 1 temple) were located in areas with LA waste collection services.

Table 3- 3 Occupation/main income of surveyed systems in the 1st & 2nd groups

Group	Occupation/ main income									
	Farmers (Agriculture)	Farmers (Livestock)	Doctor	Engineer	Lawyers	Government officials	Teachers	Businessmen	Army services	Labors
Group 1 (17 users)	12%	-	18%	6%	-	47%	6%	29%	-	-
Group 2 (74 users)	58%	99%	-	-	1%	12%	-	12%	5%	4%

3.3.2 Reasons behind using AD

The reasons/motivations of respondents for using AD are presented in Table 3-4.

Table 3- 4 Reasons/motivations of users for using AD

		Reasons/motivations				Total
		Ability to produce energy	Ability to produce fertilizer	Ability to treat waste	Availability of subsides	
Groups	1. Households	53%	18%	88%		17
	2. Households with livestock	86%	30%	54%	5%	74
	3. Commercial settings	67%		100%		3
	4. Temple	50%		75%		4
	5. Swine farms			100%		2

Waste treatment and energy production were the main reasons for owning an AD system (Table 3-4). The reasons for using AD for waste treatment were as follows: escaping the inconvenience of irregular waste collections for household solid waste (for the first, third, and fourth groups), and decreasing odor problems arise from previous livestock dung management (for the second and fifth groups). The use of energy from the AD was considered beneficial as it avoided difficulties in collecting firewood (for the second and fourth groups) and reduced the cost of LP gas (for the first, third, and fourth groups). People interested in organic farming only considered the benefits of slurry production. Interestingly subsidization for AD construction was the least motivational factor even though most users (except 11) received subsidies (around 50% of construction cost). Sometime the lower responses may be related to the respondents' attitudes as they desire to highlight only the benefits motivated them.

Table 3-5 presents the method by which people were informed about AD. Group 1 was mostly informed by friends and service providers, while Group 2 was informed by the government (veterinary officers). This could be related to the difference of respondents' educational background Government guidance is essential for popularizing AD technology among less educated less income people.

Table 3- 5 Method of being informed about the AD

Group	Informed by		
	Government officials	A friend (user of AD system)	Service providers
Group 1	2	10	5
Group 2	71	1	2
Group 3		3	
Group 4	3	1	1
Group 5	1		1
Total	76	15	9

3.3.3 Type, capacity and input type of AD systems

The types of surveyed AD systems were as follows: 94 Chinese fixed domes, 4 Plug flows, 1 floating drum (PVC compact model), and 1 Sri Lanka tunnel type. The type of system used was related to the preference of the installer.

Table 3-6 shows the capacity and input type of the all AD systems. LW was the main waste input for Groups 2 and 5, and KW or KW plus HW were used in other groups.

No clear relation was seen between waste type and system capacity. Similarly, no clear correlation was found between waste amount and capacity (discussed later). Possible reason may be the capacity of the AD digester was not selected considering the waste's type and amount.

Table 3- 6 The capacity and input waste of the AD systems

Group	Input waste	Capacity, m3							Total
		<8	8	10	12	15	20	>20	
1. Household	KW	1	1						17
	KW & HW		4		2		8		
	KW & WH		1						
2. Household with livestock	LW	1	32	14	5	7	1		74
	LW & KW		13						
	LW & KW & HW			1					
3. Commercial settings	KW							1	3
	KW & HW						2		
4. Temples	KW	1	1						4
	KW & HW						2		
5. Swine farms	LW					2			2

KW: Kitchen waste, HW: Human waste, LW: Livestock waste, WH: Water hyacinth

3.3.4 Current conditions of surveyed AD systems

As Figure 3-3 shows, 91% of surveyed systems were found to be operational because around 60% of those had been implemented within the past three years.

Nine including newly built as well as older (≥10 years) systems were non-operational. The reason for three AD systems was the lack of LW to feed in (where the only input was LW) because livestock were sold recently due to economic difficulties. Two AD systems were not being fed because they were to be removed to provide space for a house extension. One AD system was not currently operations as it was just constructed.

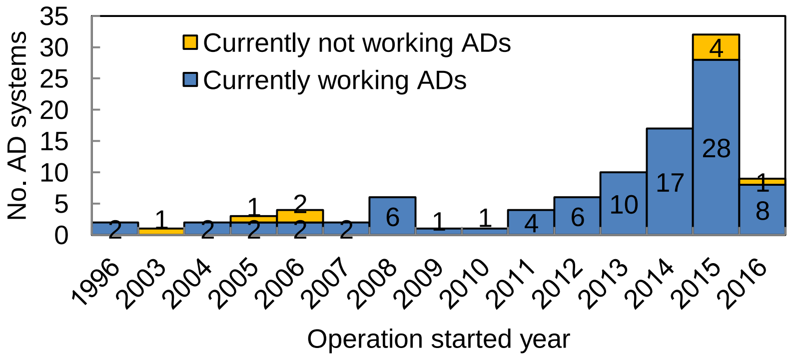

Figure 3- 3 Year of start and current condition of AD systems

Biogas leaks detected from the digester top of one digester prevented the operation. The leaks probably occurred due to the excessive gas pressure inside the digester and/or weak digester construction. Two systems were not yet producing gas, even though feeding had occurred during the preceding three months. This could be the result of a lack of microbial activity inside the digester due to incomplete initial feeding (initial feeding introduced microbes). The users of the AD with leaks and AD systems not producing biogas had already informed their service providers several times, requesting visits and repairs, but not yet been provided. This suggests that the aftercare services are inadequate.

3.3.5 Operations and maintenance

System feeding

Waste, except for HW, was mixed with water at the inlet of the AD system, and only LW accumulated inside livestock stable and organic fraction of KW and chopped WH was used. After mixing LW with water, floating grass and straw particles were removed. HW was fed by directly connecting the toilet with the digester, and users were aware not to use chemical detergent for toilet cleaning. Users decided the water volume (roughly equal to LW volume) employed in LW mixing by experience and not by measuring. For KW and WH, the added water volume was equal to the waste volume. None of the HW feeders had adjusted water volume during toilet flushing.

Stirring

Stirring will hinders scum formation, but was practiced by only 4 (of the second group) users using a rod (see Figure 3-4) that was inserted in a different position from the inlet. However, stirring was rarely practiced, although the recommended frequency was every 15 days.

Monitoring (gas pressure and gas leaks)

Monitoring gas pressure is important for protecting the reactors against high gas pressure. High pressure inside the reactors can result in cracks in the reactor's walls, which ultimately cause leaks. Out of 100 ADs surveyed, gas pressure had been monitored in only 62 ADs using manometers (42 users), or pressure meter (10 users), or both manometer and pressure meter (9 users). If a pressure increase over the recommended pressure was observed, users released gas into the environment or via a flame on the cooking stove.

Maintenance

Condensed water in the gas outlet pipe can be problematic, but water can flow back into the reactor due to the pipe slope or to the manometer. Although ten systems were equipped with manual water traps (Figure 3-5) to remove condensed water in the gas outlet pipe, these were not used.

Only 32 systems were equipped with H_2S filters, but these were not regularly cleaned. All users used biogas for cooking, and stoves were corroded (3 users changed stoves) due to corrosive gas or non-durable cooking stoves.

Seven users of LW feeding removed scum layers because it disturbs the recovery of gas by forming a lid in the digesters. The possible reason for scum formation could be the improper mixing of LW with water. However, scum had been removed on average only 2–4 times in 10 years, and it had then been applied to crops. The scum formation can be controlled by applying stirring.

Figure 3- 4 Stirring practiced in one AD system

Figure 3- 5 Manual condensed water removal traps

3. 4 Analysis of the AD processes

In this section, 87 Chinese fixed-dome AD systems (mostly encountered type), consisting of 15 in the first and 72 in the second groups, were analyzed (including nonoperational ADs). ADs 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.

3.4.1 Input amounts and composition

The amounts of KW, HW, and LW were estimated using the generation values in Table 3-7. The value for KW relates to Sri Lanka and the HW (night soil: urine and feces) generation value is a typical figure used for developing countries in a tropical climate. LW generation values are the most commonly used values when designing AD processes in Sri Lanka.

KW and HW were estimated by multiplying the waste generation values with the number of people in respective 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 dung 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 into the AD and considered it in estimations. The value used for WH input was provided by each user. The composition was then calculated following the input estimation.

Table 3- 7 The values used to estimate waste and biogas generation

Type	Generation		Biogas production	
	Assumed values	References	Assumed value, (l/kg-wet)	Reference
Kitchen waste	0.36 kg/capita/day	[5]	160	[8]
Human waste	1.3 kg/capita/day	[6]	28	[6]
Cattle dung	10 kg/animal/day	[4]	35	[4]
Buffalo dung	15 kg/animal/day	[4]	37	[4]
Swine dung	2.25 kg/animal/day	[4]	80	[4]
Goat dung	2.1 kg/animal/day	[7]	35	[9]
Water hyacinth			45	[10]

According to the estimations, AD systems in first group with KW+ HW consisted 80% of HW in input. One system was fed with KW+WH and comprised 90% WH.

In the second group, 12 users used LW + KW and LW composition in input was varied 80%–95%. Only one user used LW, KW, and HW at 55%, 10%, and 35% respectively, while others only used LW.

The relation between daily feeding quantities (Q-input + water) and the working capacities of the digesters is shown in Figure 3-6(a) and Figure 3-6(b) for the first and the second groups, respectively.

The feeding quantities (Q) of LW, KW, and WH were estimated by assuming the waste/water volume ratio to be 1: 1, as the users claimed, and that is the optimum ratio [11]. The average water usage for toilet flushing in Sri Lanka of 20 L/capita/day [12] was used for HW. The working capacity (V′) was 90% of the actual capacity (V) for Chinese fixed domes according to Sri Lankan standards [4].

As both figures show, the capacities were not selected considering the feeding amount, and thus the hydraulic retention time (HRT -V′/Q) varied widely. The anaerobic digestion occurred in mesophilic conditions (25–45°C) as digesters were at ambient temperature, averagely around 27°C. The recommended HRT for mesophilic conditions ranges between 10 and 60 days [11, 13]. As shown in Figure 3-6(a) and 3-6(b), the HRTs were mostly longer than the recommended values. Although a longer HRT ensures complete digestion, an extended HRT is the result of the oversized digesters and is uneconomical. However, AD systems with a low feeding ratio have higher HRTs (>90 days), and thus users can increase the feeding ratios.

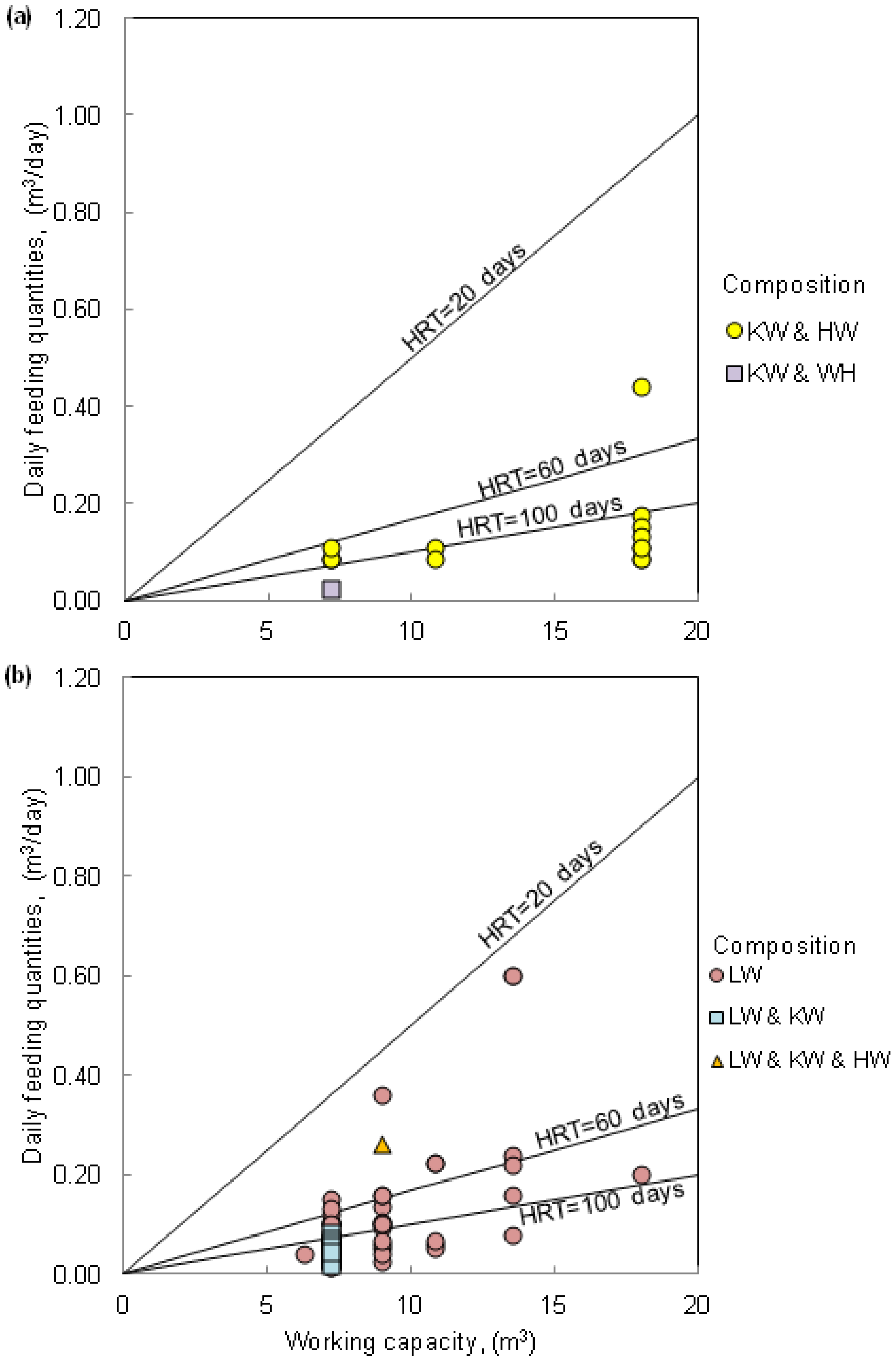

Figure 3- 6 The relation between the daily feeding quantities and working capacities (a) in the 1st group and (b) in the 2nd group

3.4.2 Changes in waste disposal methods

Merits

Table 3-8 shows the waste disposal methods used prior to having AD processes. Waste was mostly disposed of in open dumping, but even when collected, its final destination was also an open dump. When KW is fed into the AD, source-separated inorganics such as PET bottles, plastics, and glass bottles can be sold to recyclers. Livestock owners receive reduced complaints from neighbors about the odor (arising from dung open dumping and the frequent overflowing of swine dung in closed pits). Improved indoor air quality (in relation to not burning wood) and time saving (in relation to not collecting wood) are also other benefits.

Reasons for limiting use of waste

59 users in the 2nd 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 AD systems (4 users). The other 20 users had not been informed of feeding KW into the AD systems.

HW was rarely put into AD systems 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, it was difficult to connect toilets with AD digesters to feed HW in the second group.

Users of low feeding LW implemented composting (5 users) or open dumping (19 users) to handle the remaining amounts of LW.

Table 3- 8 The waste disposals prior to having AD systems

		1st group (14*)		2nd group (72)		
		KW	HW	KW	HW	LW
Previous waste disposal methods	Dumped openly	2		11		61[a]
	Disposed into collection services	11				
	Used to make compost	1		2		6[b]
	Discharged into a closed pit [d]					5[c]
	Discharged into a toilet pit [d]		13		1	
Total		14	13	13	1	72

**One house exclude as it had AD from very beginning*

[a] Only cattle/buffalo/goat dung, and sometime part of dung used for cultivations

[b] Only cattle /buffalo dung

[c] Only swine dung

[d] Cess pits

3.4.3 Biogas and uses

Most households used biogas only for cooking but additional uses were boiling dairy milk (7) and preparing swine food (4). All users said that the biogas flame was blue and odor-free. Initially, 17 users (in the second group) had wanted to use gas for lighting to reduce electricity bills but had given up as essential accessories (such as lamps and generators) were not available in the local area.

Biogas production, demand, and fuel reduction

Biogas production was estimated by multiplying the estimated input by the biogas potentials (normally considered values for AD processes in countries like Sri Lanka) in Table 3-7.

As per Sri Lankan standards [4], the biogas demand for cooking is 300 L/capita/day; with this in mind, the production-to-demand (P/D) ratio was calculated and compared with fuel reduction percentages given by users in Table 3-9

The P/D ratio was 0.3 for most of Group 1, and it ranged from 0.2 to 8.0 for Group 2. The consistency of the P/D value for Group 1 is due to the fact that P and D vary only with the number of people. Regardless of the P/D ratio, however, the reduction in fuel was mostly higher than 75%, which suggests that the estimated demand is overestimated when the P/D ratio is small. A high fuel reduction rate is reasonable with a high P/D ratio.

Table 3- 9 Percentages of fuel reductions by using biogas

Group	Fuel reductions	Fuel type		Number of users with low feeding
		LP gas	Wood	
1st	>=75%	7(3)	2(2)	-
	75-50%	5		
	<50%	1		
2nd	>=75%	7(6)	53(48)	22
	75-50%		7	2
	<50%	1	1	-

**3 units were excluded as no biogas yet*

( ) - No. of units with 100% reductions

No uses other than cooking mostly resulted in wasting gas abundances. Users with higher P/D ratios used to burn extra amounts of gas in cooking stoves or release these extra amounts into the environment by opening the valve at the digester's top when they observe a high pressure (above the recommended pressure) on the pressure meters. In several ADs, the high pressure (due to no pressure monitoring) created by the accumulation of gas abundance inside the gas storage caused small cracks in the digester's wall and resulted in gas leaks. On the other hand, 24 users used lower feeding of LW to cut off gas abundances.

The reduction in fuel consumption enabled cost savings for all LP gas users and five wood users in Group 2 because others obtained wood from nearby areas freely. 93% of the users in both groups were satisfied (as biogas is clean and comfortable to use and has a low cost) with using biogas and encouraged others to use AD systems.

3.4.4 Slurry and uses

48 users of technology used slurry for crops, whereas 32 got rid of it. The remaining AD systems were to emit slurry because operations have recently started.

Slurry application

The slurry was used in crops directly or after making the compost. According to users, the slurry was free of bad odors 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 or composting 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 [10], 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.

Disposal of slurry without use

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 (9 users in the 1st 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.

3.4.5 Cost assessment

Construction cost

Figure 3-7 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.

No significant correlation was found in Figure 3-7. The difference in the price of the construction material by area and labor costs may be the reason. According to the questionnaire survey, the cost of the material included the transportation cost. In addition, labor cost was decreased by the users themselves supporting construction works. On the other hand, 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 46,000 Rs. The construction costs shown in Figure 3-7 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.

Cost savings

Figure 3-8 shows the cost savings when using biogas and slurry. Of 87 users, 26 and 9 had saved the cost associated with fuel and fertilizer, respectively.

In Figure 3-8(a), a higher cost saving was obtained for LP gas users than for wood users. The low fuel reduction rates suggest that there is room to save fuel costs by increasing gas production. In addition, increasing the biogas production can reduce the electricity cost for lighting and electrical appliances.

As Figure 3-8(b) shows, there was better saving of cost in the main crop due to the larger dose of chemical fertilizers applied compared with the secondary crop. The low reduction rates of chemical fertilizers in Figure 3-8(b) suggest further possible uses of slurry and higher cost saving, but people believe that the more moderate use of chemical fertilizers hurts the harvest of main crops, which means an appropriate instruction to people is necessary.

Recovery of costs

Figure 3-9 shows the construction cost versus the annual cost savings in Groups 1 and 2, respectively, with the years needed to recover the initial cost (construction cost/annual cost saving). Two symbols were used for the construction cost and construction cost minus subsidization except for the six nonsubsidized AD systems.

Both figures indicated that it took mostly over ten 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 by correct sizing.

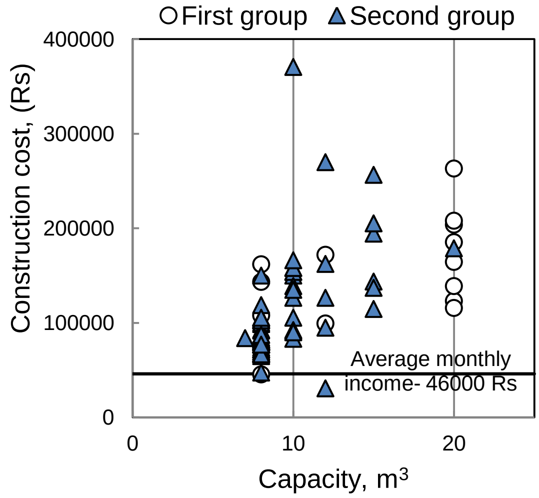

Figure 3- 7 Construction cost for AD systems

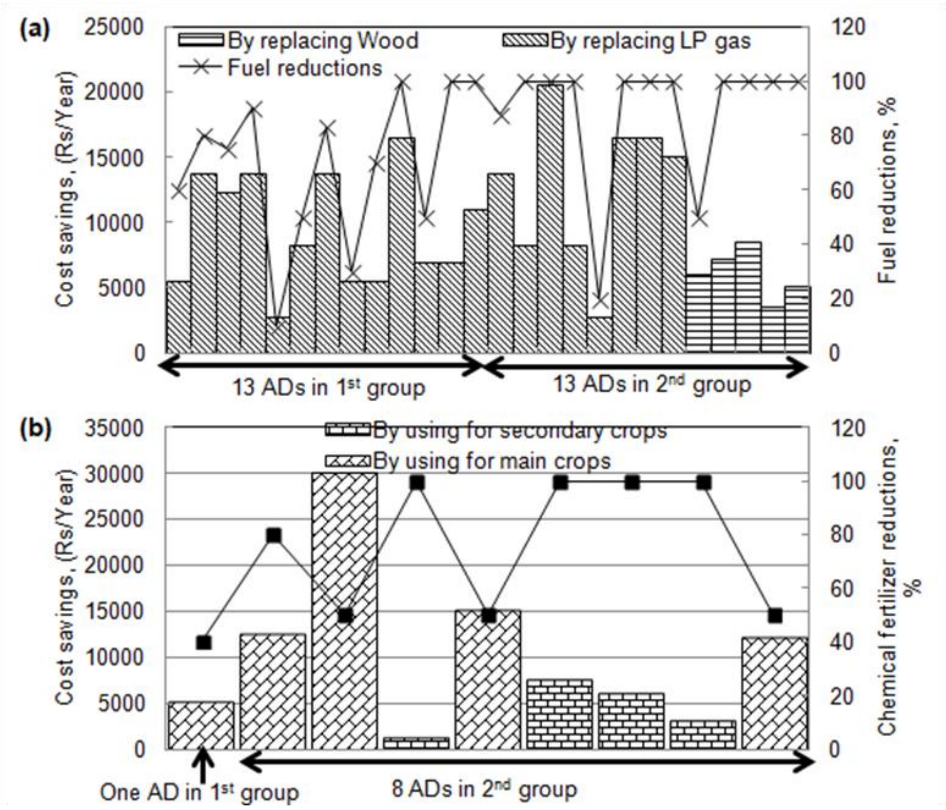

Figure 3- 8 Cost savings: (a) using biogas, (b) using bio-slurry

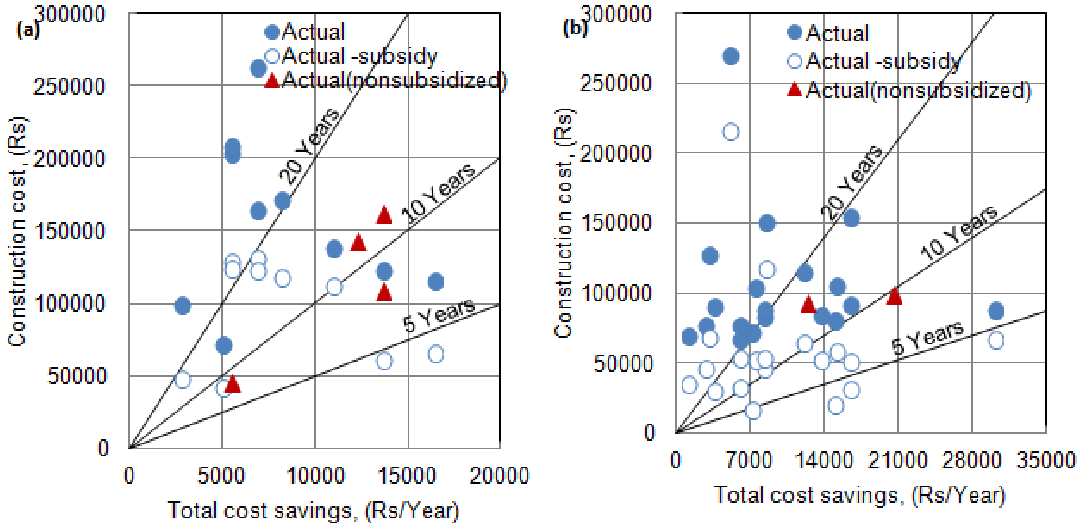

Figure 3- 9 Construction cost vs. cost savings (a) in Group 1 (b) in Group 2

3. 5 Recommendations

This study was conducted to know the current situation of Household-scale AD, which is 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.

The encountered AD systems are not appropriately selected for feeding waste amounts. Most AD systems are oversized and is not fully utilized. Several users did not feed the full amount of available LW, even though it was possible to do so, and most users did not use KW with LW. All types and amounts of waste that can be disposed of into AD processes should be the critical information for installers to design the AD processes (appropriate digester sizing). This practice reduces the construction cost thus duration of cost recovery.

All users used biogas for cooking only, and gas production was exceeded demand for several households with livestock. The extra gas could be used for lighting (lighting by burning gas in a filament lamp or generating electricity using a biogas-driven generator). The designers should consider the potential biogas production using available waste & then the uses of biogas should be decided. The accessories required for the each use should be provided. However, the accessories required are not readily available, so it is necessary to increase their supply into market.

Prior to using slurry on crops, it was mostly exposed to sunlight and loss quantity and quality. Thus it is necessary to be used a cover (a lid) at the outlet/slurry tank. In addition, slurry leaching out from earth trenches can stop by replacing earth trenches with PVC pipes. Slurry use in cultivation also contributes to cost saving, if the correct combination of slurry and chemical fertilizers is used. In addition, slurry disposed of into surrounding areas was resulting in unclean surroundings and provoking neighbors to complain. The use of slurry in composting is one option if there is adequate space; otherwise, disposal into soakage pits through rubble sand layers is a possible option.

H_2S filters should be used and regularly cleaned to reduce corrosion in gas cookers, but most users did not have a filter or those who had, did not cleaned it frequently. Although the absence of water traps appears to be non-problematic, it would be preferable to include traps and pressure meters in systems. Hence after implementing the AD systems, support for maintenance is necessary, which includes correct initial feeding, proper mixing of the input with correct amounts of water, regular gas pressure monitoring and water removal from dehydrators, and maintenance of H_2S filters.

To widen the use of AD, people's awareness regarding anaerobic digestion has to be increased. For that, the benefits of AD use should be advertised (using posters and media advertisements in national language) on the basis of quantitative data, such as cost saving by the use of gas and slurry, available subsidy, and loan facilities to construct AD systems. Users have to be informed of the types of waste that can be disposed of by AD systems, by describing the importance of that (e.g., feeding HW will improve sanitary conditions).

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CHAPTER 4
Future possibility of extending compost and anaerobic digestion

4. 1 Introduction

In Sri Lanka, still, a large part of the generated solid waste is being managed improperly. Figure 1-1 in the Chapter1 shows that 28% (out of 35%) of the collected waste by LAs is being disposed of into open dumps while around 55% of the waste being disposed improperly at on-site. These figures emphasize neediness of expanding the centralized composting for collected waste and the anaerobic digestion for the household solid waste management. To fulfill that requirement effectively, the possible countrywide use of both composting and anaerobic digestion are studied in this chapter while addressing the issues mentioned in chapter 2 and chapter 3.

4. 2 Future possible use of centralized composting for collected waste

According to the National solid waste management supporting center (NSWMSC), 122 out of 335 of total LAs owned the composting facilities in which majority were simple windrow composting during 2014. To reduce the organic waste being disposed of in open dumps, remaining 213 LAs need composting processes. In this study the required implementations of windrow composting facilities and cost needed for implementations and operations are determined.

4.2.1 Methodology

Considering the amount of waste collected per day by candidate LAs, the required number of composting facilities and capacities are determined. Then suitable windrow composting process flow is decided to obtain good quality production by considering the issues identified in Chapter 2. Next, the required area and equipment for each size of windrow composting is estimated referring the literature, and both implementation cost and operational cost are calculated.

4.2.2 Determining the required windrow composting facilities

Daily waste collections

Out of 335 LAs in Sri Lanka, more than 200 of LAs practice open dumping for waste collected by collection services by 2014 according to the NSWMSC. Figure 4-1 shows the variation of daily waste collection amounts along with the respective population of those LAs. The daily waste collection amounts vary between 0.5 and 700 ton/day. The 81% of the LAs have equal or less than 10 ton/day of waste collection. Regarding population, 86% of the LAs have less than 10000 of the population. Figure 4-1 shows that the waste collection amounts do not correlate with population because the collection services are enabled only for the main city areas (not for entire area) of the respective LAs.

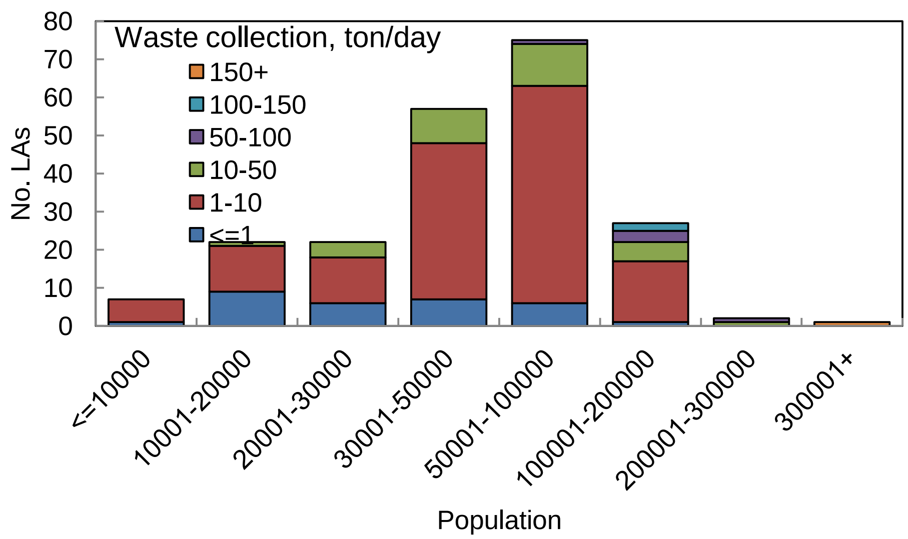

Figure 4- 1 Variation of the waste collections LAs (without composting) with respective population of the LAs (n=213 LAs)

Implementation of composting facilities

When the implementation of composting facilities for these LAs is concerned, it is not economically feasible to construct individual composting facilities for each LA. This is because; most of the LAs need small sized facilities (below 10 ton/day) according to the waste collection amounts. Also, the LAs with the largest waste collection demand larger footprint for windrow composting but may be unable to find suitable space within own ruling area because of being highly populated.

To overcome the above issues, the joint facilities (one facility for several nearby LAs) have been concerned. The joint composting facility locates in one LA and surrounding LAs transport the collected waste daily into it. The selection of the number of LAs per one composting facility is decided by the waste transporting distance (from the main city center to the main city center of respective LAs) which is below 40km. Figure 4-2 shows the resulted requirements of composting facilities with the required sizes. According to the Figure 4-2, 59 of composting facilities are needed for all the 213 LAs. The average sizes of the composting facilities are 10, 20, 30, 80 and 140 ton/day (after rounding up the average values to closest 10) in which 20 ton/day is the widely needed capacity.

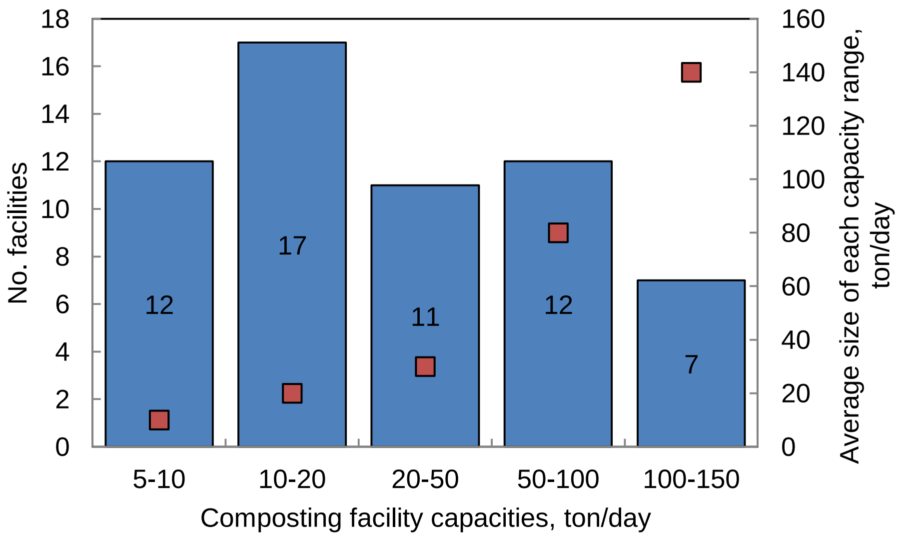

Figure 4- 2 Requirements of the composting facilities with capacities

4.2.3 Designing the composting process flow

According to the chapter 2, the quality of the final compost product is not good and caused lower demand. Hence the process flow has to consist with steps to gain good quality compost.

The considered process flow for composting facilities

Figure 4-3 shows the selected process flow for a properly functioning composting facility. Weighting, shredding, mixing with bulking materials, temperature and moisture monitoring during composting, and monitoring the maturation are the newly added steps.

It is assumed that every facility will receive source separated waste collections for composting.

Using a weighbridge is vital to maintaining records of composting facilities to calculate the efficiency of the composting process. This is important to take necessary modifications in future such as how waste amounts are being increased, what are the actions needed to be taken.

To speed up the composting process by reducing the particle size, shredding is concerned. As the shredding machines, low-speed high torque dual shaft shredders are selected. The low-speed high torque shredders have advantages like lower power consumption, can produce more even particle distribution, provide room to quickly turn off the shredding if non-shreddable objects are fed (mistakenly) and remove it by reversing the rotors [1].

Mixing shredded feedstock with bulking materials (coarse residue of compost because providing woodchips, rice husks is not reliable for all the facilities) is considered to control the moisture content.

To ensure the adequate decomposition of feedstock, monitoring the temperature of composting piles are included. Before adding moisture into the windrow piles, moisture content has to be monitored.

The generation of leachate is collecting into a leachate pond using a drainage system with a slope toward the pond. To control the leachate, the entire facility is roofed to cutoff the rainwater infiltration into the windrow piles. The strength of the collected leachate (by reducing the BOD content) is to be decreased by introducing aeration using submersible pumps in leachate ponds (The treatment facilities for leachate is not considered because it is quite expensive) as recommended by [2]. To obtain good quality compost product, 28 days of maturation is concerned as recommended by [2-3]. The final product has to be safely stored until it is sold out.

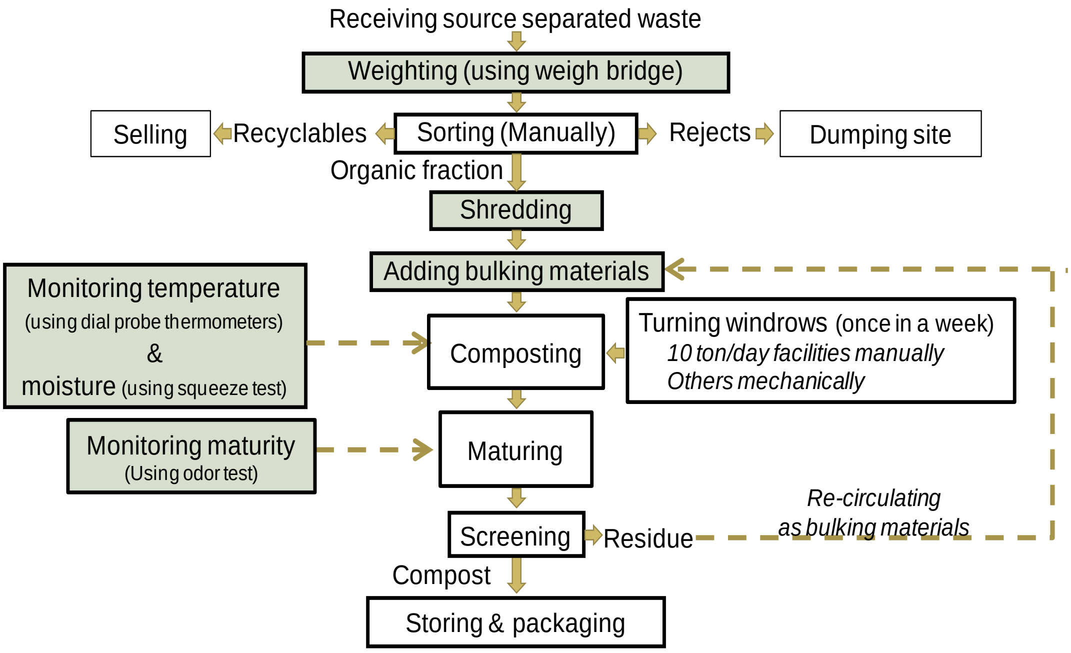

Figure 4- 3 Desirable process flow (colored steps are newly added)

The temperature monitoring of the windrow piles are going to be determined using 1m temperature probes, and measurements should be done daily for each decomposing piles.

Measuring the moisture condition of the windrow piles can be done using simple hand squeeze test [2, 4]. For this test, a handful of compost material from a pile after each turning had to be picked up and squeezed for 10 seconds. If the moisture level is ok, then the picked materials leave wetness on the palm, and it would retain the shape. If the moisture level is low, the compost material expands (without holding shape), and no wetness would retain on the palm and demand moisture addition.

The maturation is going to be ensured using a simple odor test as recommended by [2]. In this test, the compost which completes the maturation duration is placed in a plastic bag after correctly moistened. Then the bag has to be kept for two days after tightening the mouth of it at room temperature. If the material is correctly decomposed, no odor should release from the bag when it is opened.

4.2.4 Sizing the composting facilities

Based on the parameters in Table 4-1, the area needed for windrow composting process for selected five capacities was calculated.

It is expected to receive source separated solid waste to the composting facilities. The composition of the incoming waste in wet basis is assumed. The bulk density of the sorted feedstock (contain only mainly food waste) after shredding is taken from [6]. The moisture content of the feedstock is assumed as 70% [7]. Already produced compost is used as bulking materials because other materials (wood chips, rice husks) are not readily available for all regions. The amount of compost requirement to mix with feedstock is assumed as 10% of the volume of shredded feedstock according to the [8]. This will help to reduce the odor nuisance too. According to the [9] 20% of volume shrinking is assumed for blending feedstock with bulking material.

The windrow pile dimensions are assumed, and 33% of a shrinking of cross section area [9] is expected because of own weight of the feedstock. Based on cross-section dimensions the length of a pile is calculated. 35 days composting phase is assumed for one windrow pile with once in a week turning. Manual and mechanical (using bobcat-S100) turning are considered for small (10 ton/day) and large facilities, respectively. The distance between the two piles is assumed according to the turning method. The 28 days is allocated for maturation. Assuming 20% of production rate (production/feedstock input) in the wet basis final production of compost is calculated. 800 kg/m3 of bulk density and 25% of moisture content for final compost is assumed for calculation of area needed for storing based on [10].

Table 4- 1 Parameters used to determine the area needed for constructing windrows

Item	Value	Reference
Composition of incoming waste Feedstock for composting Readily recyclable materials Pre-rejects	 70% 20% 10%	 [5]
Bulk density of feedstock (after shredding)	600 kg/m^3	[6]
Moisture condition of feedstock	70%	[7]
Bulking material addition (as % of feedstock volume)	10%	[8]
Shrinking factors after blending with bulking materials	20%	[9]
Cross section of a windrow pile Height Width	 1.5m 2m	 Assumed Assumed
Shrinking factor during construction of piles	33%	[9]
Duration of composting	35 days	[2]
Turning method For 10 ton/day For >10 ton/day	 Manual turning Mechanical turning	 [10] [10]
Distance between two windrow piles For manually turning windrows For mechanically turning windrows	 1m 2m	 [2]
Turning frequency	Once per week	[2]
Duration of maturation	28 days	[2-3]
Efficiency of composting process (in wet basis)	20%	[2]
Moisture condition of final compost	25%	[11]
Density of the compost	800 kg/m^3	[10]

Area required for composting process

Table 4-2 shows the required area for each capacity. The area for unloading and sorting, storing recyclables is taken from the design manual for small-scale composting process published by NSWMSC [10]. For the 10, 20, 30 ton/day capacity facilities, both unloading and sorting and storing recyclables are done in the same space according to the same reference. The area for composting, maturation and sieving and storing the final product of compost are determined using values in Table 4-1.

Table 4- 2 Area required for each phase

Designated for	Capacities, ton/day				
	10	20	30	80	140
Unloading and sorting, m^2	60	120	120	480	840
Storing sorted recyclables (for 10 days), m^2				60	60
Composting, m^2	467	1048	1392	3112	5175
Maturation, m^2	117	262	348	778	1294
Sieving and storing (for 3 days) the compost, m^2	3	5	8	21	36

4.2.5 Equipment needed

Table 4-3 illustrated the requirement of equipment according to the capacity of the facilities. Required number of skid steer loaders (for turning), shredding machines, screening machines (rotary trammels), and sealing machines (for packing the final product) are decided according to the guidance given by design manual for small-scale composting facilities [10]. Each weight scale (for packing), weighbridge (for measuring incoming waste), and a submerged pump (installed at leachate ponds) are accounted for each size. The number of thermometers is decided by considering each thermometer is for a 5m length of the one windrow pile according to the [4].

Table 4- 3 Required equipments for each size of composting facilities

Equipment	Capacities, ton/day				
	10	20	30	80	140
Skid steer loader, (one for 30 tons)		1	1	2	3
Shredding machines, (one for 30 tons)	1	1	1	2	3
Screening machines, (one for 30 tons)	1	1	1	2	4
Sealing machines, (one for 30 tons)	1	1	1	1	1
Weight scale	1	1	1	1	1
Weigh bridges	1	1	1	1	1
Submerge pumps to aerate the leachate	1	1	1	1	1
Composting thermometers, (1 for 5m of the windrow)	1	1	1	3	6

4.2.6 Cost assessment of implementing composting process

Implementation cost

The implementation cost consists of construction and equipment purchasing costs. Construction cost includes the cost for facility building construction and cost for leachate collection tank, power & water supplying related works, constructing an administrative building, and other works.

Cost for construction is calculated using the 2017 building standard rates published by the building department of Sri Lanka & reference [12]. Using the values in Table 4-4 (which shows the market prices of equipment as of May 2018) the cost of the required equipment is determined. Then 10% (as per [5]) of the equipment cost is added as expenditures for tools like mamoties.

Table 4-5 shows the breakdown of implementation costs of five capacities. Construction cost is as high as over 80% in all facilities while the cost of turning machines is the most significant cost item of equipment cost for mechanically turning facilities. The 10 ton/day facility has to spend a higher amount for a shredding machine.

Figure 4-4 shows the construction cost/capacity (C/V) graphed as a function of considered capacities in log-log scale. Figure 4-4 shows some economy of scale (Value of C/V decreased as treatment capacity increased) as the implementation cost varied between 1.4 M Rs/ton to 0.8 M Rs/ton for the smallest capacity to the largest capacity, respectively.

Table 4- 4 Cost of equipment (as of May 2018)

Equipment	Price, Rs/unit	Power consumption
Skid steer loader (bobcat S100)	3000000	8 l-diesel/hr
Shredding machine (Huanchuang HC-DS40100)	932200	60 kW
Screening machines (rotary)(FR engimech)	210000	2.2 kW
Sealing machine (Darley CH)	33000	1.5 kW
Weigh scale(Budry BES-Z72)	30000	0.01 kW
Submersible pump (Singer WP-CHSUB-2)	20000	0.75 kW
Weigh bridge (Mansil Instruments, India)	820000	0.012kW
Thermometers (Pooja 800-120)	3300	
(Model numbers)		

Table 4- 5 Breakdown of implementation cost

Capacity, (ton/day)	10	20	30	80	140
Total implementation cost, (M Rs)	12.7	28.4	35.2	66.7	109.1
Breakdown of implementation cost, %					
Construction cost	82.3%	80.4%	84.3%	84.8%	86.3%
Equipment cost					
Turning	0%	10.6%	8.5%	9.0%	8.2%
Shredding	7.3%	3.3%	2.6%	2.8%	2.6%
Screening	1.7%	0.7%	0.6%	0.6%	0.8%
Weighbridge	6.4%	2.9%	2.3%	1.2%	0.8%
Other	2.3%	2.1%	1.7%	1.6%	1.3%

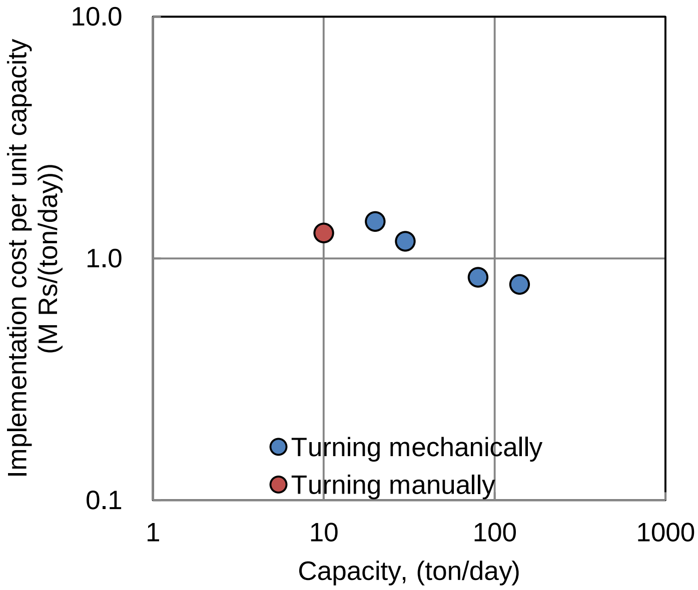

Figure 4- 4 Construction cost per treatment capacity

Figure 4-5 shows the comparison of total implementation cost of all 59 facilities with the annual allocations for the several main expenditures of the country in 2018 according to the ministry of finance. The total cost is several times higher than the annual allocations mentioned in the Figure 4-5. This means, the all the implementations cannot be commenced at once. For that, the 59 facilities have to be constructed in several phases (like 15 facilities per year) or have to take financial support (loans or aids) from foreign countries.

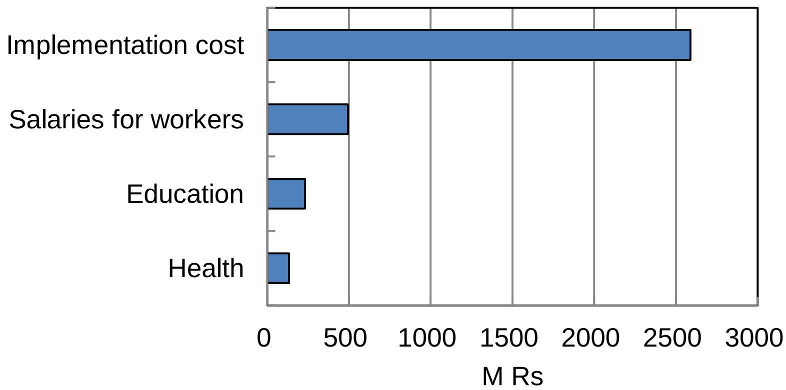

Figure 4- 5 Comparison of implementation cost with important several allocations annually

Operational cost

Operational cost includes the cost for utilities and cost for maintenance. Utility cost includes the cost of fuel, electricity & water.

Cost for fuel (used for turning machines) and electricity (for equipment) per annum (30*12 days) are calculated based on operational hours of each equipment mentioned in Table 4-6, power consumption (in Table 4-4) and current unit price of electricity and diesel as of May 2018. The operational hours for shredding machines, screening machines considered based on their working capacities per hour. Others are assumed values (for Weigh Bridge, weigh scale, pumps). The water consumptions for each sized facility is estimated using water consumptions values in several windrow composting facilities estimated in reference [12]. The cost for water is calculated as of the current unit price of water in May 2018.

Table 4- 6 Operating hours of each equipment per day

Equipment	Capacity, ton/day				
	10	20	30	80	140
Weigh bridge, hr	1	1	1	2	2
Skid steer loaders, hr		4	4	4	4
Shredding machine, hr	1	1	1	2	3
Screening machines, hr	1	1	1	3	4
Weigh scale, hr	1	1	1	2	2
Submersible pumps, hr	1	1	1	2	2

Maintenance cost consisted of salaries for workers and repairing. Cost for salaries per annum (30*12 days) is calculated by referring to the Table 4-7 in which workers required for each capacity is mentioned. The manpower demand is decided based on a manual for designing small-scale composting plants in Sri Lanka [10]. As the monthly salary per person, 25000 Rs/month/person is considered. As the cost for the repairing equipment, 12.5 % of the equipment purchasing cost is assumed as per [4].

Table 4-8 shows the estimated operational cost and its breakdown. In each sized facility, the cost of workers salary is the highest cost category which ranges from 65-84% of the total operational cost. The cost for salaries per unit input would be doubled if facilities received mixed waste collections (according to the chapter 2, the average cost for the unit input- around 1400 Rs/ton-wet whereas the same value for these five capacities is around 700 Rs/ton-wet).

Table 4- 7 Workers required for each capacity

Task	Capacity, ton/day				
	10	20	30	80	150
Supervisors, people	1	1	1	1	1
Sorting (4ton/person), people	2	5	7	20	35
All other works, people (1 ton/ people for manual turning and 2 ton/people for mechanical turning)	10	10	15	40	70

Table 4- 8 Operational cost and breakdown

Capacity, (ton/day)	10	20	30	80	140
Total Operational cost, (M Rs/ year)	4.6	7.4	10.2	25.6	43.4
Breakdown, %					
Electricity	6.3%	3.9%	8%	8.6%	7.7%
Fuel	0%	17%	12.4%	9.8%	8.7%
Water	3.5%	4.4%	4.8%	5%	6.1%
Salary	84.2%	65.2%	68%	71.6%	73.2%
Maintenance	6.1%	9.4%	6.8%	5%	4.3%

Table 4-9 shows the comparison of estimated operational costs of all facilities with the current average waste management cost of LAs with same size waste collections. As Table 4-9 shows, the operational cost of composting is around 20% of the existing waste management cost. This means, composting cost would be manageable for LAs who is responsible for the composting facilities.

Table 4- 9 Operational cost and breakdown

Waste collection, (ton/day)	Cost of waste management *, (M Rs/ Yr)	% of composting operations cost
<=10	25	18% (4.6/25)
10-100	92	15% (14.3**/92)
>100	281	15% (43.4/281)

* Reference [13]
** Average of 20, 30 and 80 ton/day facilities

4.2.7 Cost recovery years

Table 4-10 shows the years needed to recover the cost of composting through income received from selling compost and recyclables. It is assumed that the average price of compost is 15 Rs/kg (as per chapter 2) and the average price of recyclables is 1 Rs/kg [14]. According to [5], the cost for packaging 50kg of compost is 35 Rs, and it is used to calculate packaging cost. The recovery years are calculated by dividing implementation cost with income by selling products (compost+ recyclables) minus operational cost. As Table 4-10 shows, the initial cost can be recovered within 4 years for all the capacities. This means it is feasible to take foreign loans for implementations if all the productions are sold out.

Table 4- 10 Years needed to recover the cost by selling compost & recyclables

% of demand (selling/production)	Capacity, ton/day				
	10	20	30	80	140
100%	4 Yr	3 Yr	3 Yr	2 Yr	2 Yr
50%	Impossible	22 Yr	13 Yr	7 Yr	6YR

4.2.8 Possible ways to maximize the use of compost

Figure 4-6 shows the distribution of compost production according to the provinces of Sri Lanka when all the composting facilities (existing and new) commenced operations. As it shows, 50% comes from the western province which is densely populated. When the agricultural use of compost is considered, most of the agricultural fields are located in other provinces (especially in the Northwestern, Eastern and North-central provinces). Hence there should be a distribution system for compost to reach the compost to the agricultural lands. The co-distribution of compost with chemical fertilizers as suggested by [2] is one possible option. All the chemical fertilizer companies are located at their hubs in the western province. So they can easily access the composting facilities in the western province. To become this reality, the government should suggest for the chemical fertilizer companies to deliver compost with chemical fertilizers with a predefined ratio.

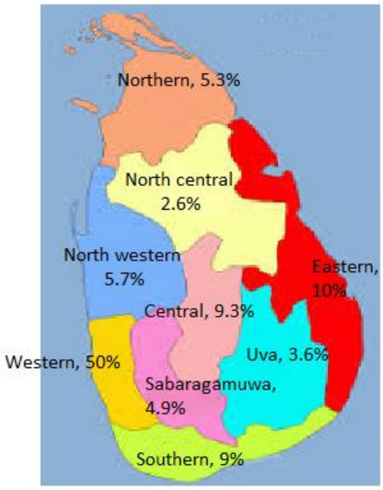

Figure 4- 6 Possible compost production from collected waste in each province (Based on waste collection amounts)

4. 3 Future possible use of anaerobic digestion for households

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 the Groups 1 (households only) and the Group 2 (households with livestock) mentioned in the Chapter 3, respectively. In this section, the possibility of using the anaerobic digestion (AD) in future is discussed for these households with considering the benefits.

4.3.1 Methodology

Firstly, all the possible scenarios to maximize the use of AD by increasing biogas production and biogas demand are considered. Then cost assessment is performed for the all scenarios to check the feasibility.

4.3.2 Increasing biogas production and demand

Table 4-11 shows the daily biogas demand (including the need for other 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 [15]). 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 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-1.5kW, 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. The amount of each waste generation and biogas generation from each waste is determined using respective values considered in the Chapter 3.

Figure 4-7 shows the expected changes of biogas amount by increasing the production and demand for the considered cases of both the first and the second groups.

Cases for the first group (See Figure 4-7)

Group 1 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.

Cases for the second group (See Figure 4-7)

Since possible improvement varies by livestock size, 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).

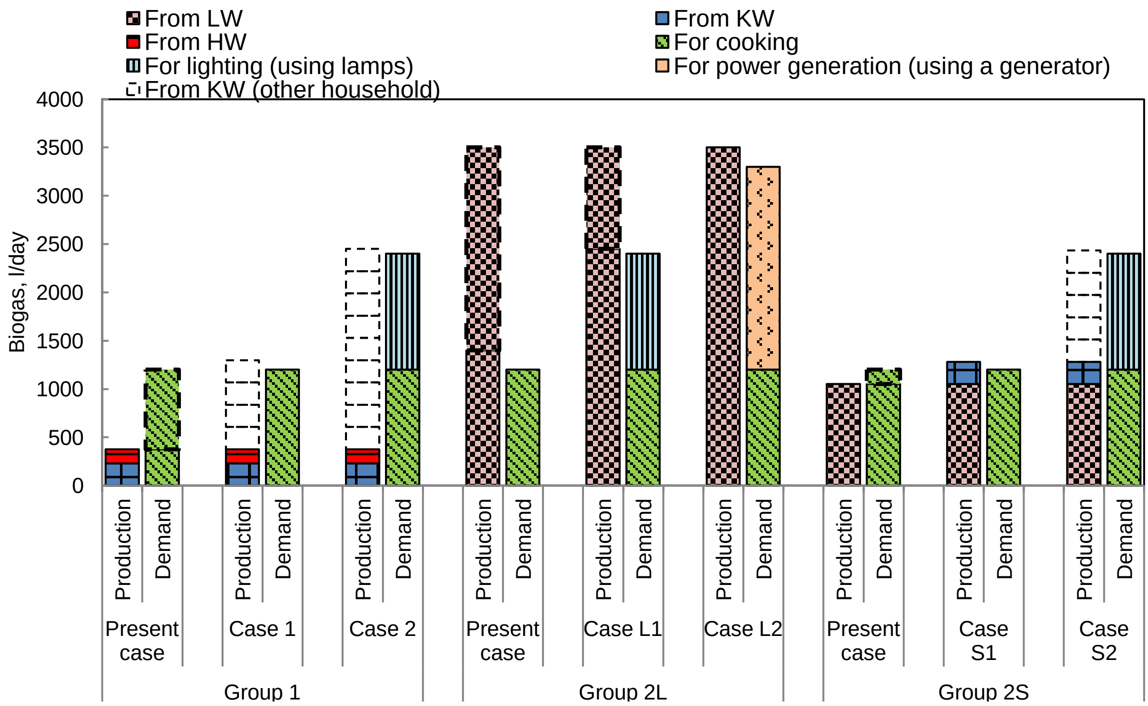

Figure 4- 7 Expected changes of biogas amount by increasing the production and demand for the considered cases of both groups

Table 4- 11 Daily demands of fuels for each use for a four member household

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

a- Reference [16]

b- Reference [17]

c- Assumed four 60W light bulbs for 4hrs (=0.06 kW * 4 * 4 hrs)

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

Table 4- 12 Values used to estimate nutrient (N, P, K) supplying by using slurry for cultivations

	Contents of NPK in each waste			Utilization rate of each nutrient, % [20]
	KW [18]	HW [19]	LW [19]	
TS, %	19	13	20	
Total N, (% in TS)	1.6	4.0	2.5	50% (KW) 25% (HW and 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%

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

4.3.4 Benefits evaluation

Cost savings

As shown in Table 4-11, 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 percentages of each nutrient available for crops (shown in Table 4-12) and the amount of input waste.

Figure 4-8 summarizes the annual cost savings based on prices in Table 4-13. As Figure 4-8 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. The smallest saving is resulting in by occupying biogas lamps.

Cost recovery

Table 4-14 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 [21]. In order to prevent corrosion, the use of desulfurizers is considered for lamps and generators. The cost recovery years are less than 10 years, except for the present case of Group 1. Subsidizing for the construction cost of ADs will further reduce the recovery years.

The considered improvements (case 1 & case 2) for the group 1 reduce the cost recovery as acceptable as 6 years. This means, instead of subsidies loans can be provided for the most of future implementations (as group 1 is the largest group) and it is economically advantageous for the government. Same situation is for group 2S. However, group 2L type households need subsidies for implementation of AD systems as cost recovery closes to 10 years.

Table 4- 13 Market prices of LP gas, Electricity and fertilizers (N, P, K supplying)

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 (46% N contain) Triple supper phosphate (43% P_2O_5 contain) Muriate of potash (60% K_2O contain)	50 Rs/kg 50 Rs/kg 50 Rs/kg

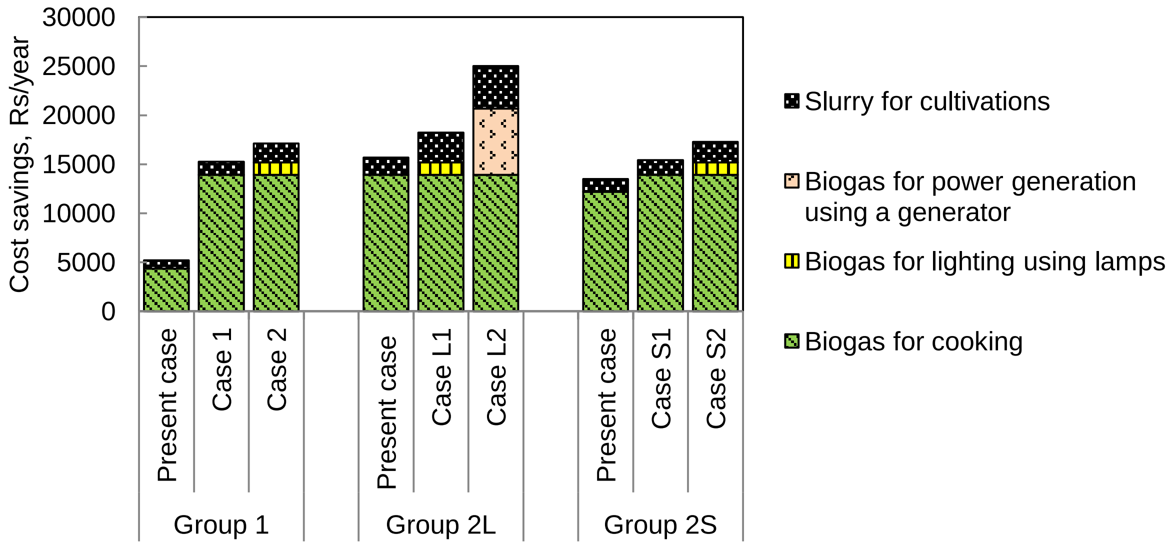

Figure 4- 8 Annual cost savings of the considered cases of each group

Table 4- 14 Cost of implementation and maintenance, cost savings, and cost recovery years

	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 desulfurization unit			
Group 1 (6m^3)	Present case	90000				900	5219	21
	Case 1	90000				900	15256	6
	Case 2	90000	4280		1560	900	17106	6
Group 2L (10m^3)	Present case	130000				1300	15669	9
	Case L1	130000	4280		1560	1300	18233	8
	Case L2	130000		73500	1560	1300	25009	9
Group 2S (6m^3)	Present case	90000				900	13494	7
	Case S1	90000				900	15417	6
	Case S2	90000	4280		1560	900	17267	6

( ) Appropriate sizes of the ADs according to correct HRTs

**Implementation cost are as of October 2017*

***Includes cost for dehydrators and pressure gauges*

4.3.5 Possible ways to maximize the use of AD

People's awareness regarding AD has to be increased. For that, the benefits of AD processes use should be advertised (using posters and media advertisements in national language) on the basis of quantitative data, such as cost saving by the use of gas and slurry, available subsidy, and loan facilities to construct AD systems.

Users have to be informed of the types of waste that can be disposed of by AD systems, by describing the importance of that (e.g., feeding HW will improve sanitary conditions). To collect KW from neighbors, as shown in Figure 7, both parties (owner and others) may need encouraging by highlighting the advantages (e.g., the owner has increased uses and others have a treatment for KW).

4.3.6 Summary

In future implementations of composting facilities, it is needed to have good demand for the compost. As the estimations shows, under high demands, it is feasible to implement composting facilities by taking loans as loans can be recovered within considerable time limits.

On the other hand, future implementation of household scale anaerobic digestion shows, it is economically feasible to construct one AD for several households. Under such a circumstance, instead of subsidies, loans can be provided. To make this suggestion real, the LAs have to follow the selection criteria to select the owner of the AD and donor of KW. Mostly it is preferable to select owner as the household who pays for cooking fuels. Then the nearby households should be encouraged to give KW for the AD.

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CHAPTER 5
Conclusions

5. 1 Summary of the thesis

The main outcomes and conclusions of this thesis are briefed as follows.

Chapter 1 described the importance of using centralized composting and household scale anaerobic digesting for better waste management in Sri Lanka. As the generated solid waste contains a significant portion of organic waste, biological treatment methods are the most opted waste disposal methods for Sri Lanka. In this thesis, centralized composting for the waste collected by collection services of local authorities and anaerobic digestion for household waste at on-site was concerned.

Chapter 2 studied centralized composting facilities by questionnaire and on-site surveys to evaluate the composting process and identify the essential improvements. One problem identified by the study was producing low-quality compost because of no source separation at the origin and no monitoring for temperature, moisture, stability, or maturity during composting. The material flow showed, because of waste in the mixed state, the recovery of organic feedstock for composting and recyclables for selling was decreased. The demand for produced compost was not good due to low quality plus lack of informing or advertising about the use of compost among potential users. Construction cost showed, constructing open composting yards (without roofs) did not result in a significant economic benefit compared to the cost of roofed composting yards. Operational cost confirmed that salary for workers could be reduced if there is source separation for collected waste.

In chapter 3 evaluated the existing use of household-scale anaerobic digestion for on-site management of household waste to recognize current situations. The study was conducted using an on-site questionnaire survey for current users. The primary 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 anaerobic digesters with appropriate size were not being provided. The total amount of potential waste was not fed in into anaerobic digesters. Maintenance is poor, especially lack of desulfurizer will reduce the lifetime of gas utilization equipment.

Also, condensed water removals, monitoring the pressure inside digester were missing. The imbalance between supply and demand for biogas is also a problem. The example of low supply includes a case when a limited part of livestock waste is only fed into the AD, and it is necessary to supply accessories for lightning or electricity generations to users. The slurry was inadequately used (quality and quantity of the slurry were subjected to be degraded). The analysis of the cost shows due to being oversized and underused of outputs, the time spent to recover the initial cost was long.

In chapter 4 investigated the future possibility of using both composting and anaerobic digestion for the entire country. For remaining 213 of LAs needed 59 joint composting facilities according to waste collection amounts. The average sizes were 10, 20, 30, 80, and 140 ton/day in which 20 ton/day is the widely needed size. The process flow of the compost was modified to obtain quality compost by including receiving source separated waste, weighting, shredding, adding bulking materials, monitoring temperature, moisture, and maturity of the compost. The sizing the facility was appropriately done as the piles can be constructed appropriately by referring to the related literature. The estimated cost of operations showed the worker's salary is the highest cost item. However, workers salary would be doubled if the mixed waste is received (by comparing with reported workers salaries in chapter 2). The cost recovery shows, if there is good demand (100%) for compost it is feasible to pay back loans taken to implement composting facilities. Otherwise, the facilities have to be constructed in several phases because the total implementation cost cannot be spent at once by the government. On the other hand, the possible use of household anaerobic digestion was considered for two groups of households as households only (group 1) and households with livestock (group 2). First of all, for both two groups, the strategies needed to increase the biogas production were considered. For the Group 1, the production of biogas is increased by increasing the feeding of KW by collecting neighbors KW. The demand also increased by using lighting by burning biogas at lamps. For the group 2 with a higher number of animals, the demand for the biogas was increased by considering power generation. In the same group with a small number of animals, the strategy was as same as group 1, i.e. increasing the input. The sizing of the reactor for anaerobic digestion was done according to the input. The cost assessments showed the maximum use of outputs & correct sizing of the AD resulted in the recovery of cost within 6 years period the most cases (as group 1 which represents 93% of the households with non-collected waste). Short cost recovery years means the government can support implementing household scale AD by giving loans instead of subsidies and it would be more economically feasible for the government.

5. 2 Overall conclusions

The existing practices of the centralized composting for collected waste and the household scale anaerobic digestion for the non-collected waste are being progressed with poor designs and poor operations as mentioned in chapter 2 and chapter 3.

To get the maximum use of both methods in terms of waste management, proper technical guidelines, regulations, and assistance by the government are necessary. For the composting requirements are appropriately designed process flow with necessary equipment for monitoring, training for workers, guidance for local authorities and people to have source separated waste collections. Similarly, the household scale AD needs guidance for installers to proper designing, instructions (through installers and local governments) for users regard to feeding, maintenance, and use of slurry, supplying necessary accessories to use biogas, informing and encouraging people to construct AD systems (through local governments and installers). Also, the country wide trend towards organic fertilizers is necessary to sustain the future implementations of these processes. The government should initiate programs to inform people about organic farming by highlighting its advantages quantitatively and qualitatively. As cost assessments of future implementations shows, the burden on the government in terms of financial requirements can be ease by having proper design and proper operations for each process.

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