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Small- and medium-scale biogas plants in Sri Lanka: Case study on flue gas analysis of biogas cookers

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Abstract. Biogas technology has received attention in Sri Lanka already from the initial days of the energy crisis in 1973. Biogas production by anaerobic fermentation is a promising method of producing energy while achieving multiple environmental benefits. The study was carried out in the different areas of Sri Lanka at the level of biogas plants owners (n = 51) and local consultants (n = 4) in August 2014. Methods of data collection included semi-structured personal interviews and questionnaire survey. Further, at 51 biogas plants flue gas analysis was done through the portable device TESTO 330-2, which is capable of capturing the gas concentration of CO and NO; consequently by recalculating the concentration of CO_2 and NO_2. Surprisingly, the quite high concentration of CO was detected c(CO) = 1,008.92 mg m^{-3}, which might be caused by one and/or various combinations of the following factors such as insufficient burning, inappropriate biogas cookers and inappropriate maintenance. The concentration of NO is under the value of 0.046 mg m^{-3}, which is under the permissible exposure limit of nitric oxide. Average temperature of flue gas is within the typical flue gas exit temperature for burning in biogas cookers (TS = 449.16 °C) and flue gas excess air (4.0%), however the air/gas efficiency (54.0%) was recognized at lower value than the optimal one for small- and medium-scale biogas plants. Easy energy access is a trigger for development, especially in terms of human, social and economic development and biogas plants represents a boon for farmers and rural people to meet their energy needs. However, further factors must be also examined and evaluated, such as exploration of gas composition and its microbiological content, emission analysis exploring particle size distribution, emission rates and potential harmful exposures.

Key words: biogas technology, biogas cookers, Sri Lanka, flue gas analysis.

INTRODUCTION

Sri Lanka (officially the Democratic Socialist Republic of Sri Lanka) is an island country with abundant sun-light year-round in the northern Indian Ocean off the southern coast of the Indian subcontinent in South Asia (Kolhe et al., 2015). It has a total land area of 65.610 km^2 and an estimated population of 20.33 million (Department of Census and Statistics, 2013). There have been large increases in fossil fuels emissions (Mattsson et al., 2012), so further emission reduction potential should be considered.

In 2002 energy consumption was 4 GJ annual per capita showing a low level of industrial development in Sri Lanka. Biomass provided about 52% of total energy used, petroleum accounted for about 40% and electricity only for around 8%. The household energy consumption accounted for about 65% of total energy consumption and industry for about 13%, transportation for further 13% and the rest for other purposes (de Alwis, 2002). These days Sri Lanka is still very reliant on the agricultural sector. Currently, the electricity generation system comprises 40.5% of hydropower, 49.0% of thermal power and 10.5% of renewable energy. However, in dry seasons the thermal power stations based on fossil fuels increase their share up to the 70% (Kolhe et al., 2015). Furthermore, Sri Lanka is currently dependent on imported fossil fuels, making the country vulnerable to the disruptions. The energy sector of Sri Lanka is expected to show further rapid growth in the coming decades, leading to higher CO_2 emissions (Selvakkumaran & Limmeechokchai, 2015). Therefore the low carbon activities and activities with beneficial impact in reducing the CO_2 emissions have to be designed and implemented.

The biogas technology was first introduced to Sri Lanka in 1970s (mainly on the research basis). In 2011 it was believed to be up to 5,000 biogas plants in use (de Alwis, 2002; Bond & Templeton, 2011); however, only one third of these BGPs functioned properly. Through the Sri Lanka Domestic Biogas Programme it was built further 3,150 biogas plants from 2011 to 2014[2]; however, the exact number of biogas plants in Sri Lanka remains unknown as well as information about distribution of different BGPs models. However, the most common types in Sri Lanka are the following: BGPs based on the Chinese fixed dome model (various sizes) and currently rising up model of Arpico based on floating drum models (1 m^3 and 5 m^3) and SiriLak Umaga model.

The small-scale BGPs are predominant in the target area where input material is commonly composited from one or various combinations of kitchen organic waste, kitchen waste water, market organic waste, and human waste without chemicals. The most common size of these small-scale BGPs is 8 m^3 with expected feedstock load of 25 kg of organic materials producing around 30 m^3 of biogas monthly. Medium-scale BGPs are mainly connected with the developing industrial sector (such as hotels, factories, farms, hospitals, religious places, training centres and prisons and force camps) in Sri Lanka.

Furthermore, community scale biogas plants are rising as well. Majority of above mentioned BGPs use standard two-flame biogas cookers from various manufacturers.

The Ministry proposal also highlights the objective of increasing the share of nonconventional renewable energy from 4.1% in 2007 to 20% in 2020 including BGPs (Anonymous, 2013a). To promote the expansion of feasible biogas production, optimisation of the whole process chain is essential (Mann et al., 2009). Biogas technology has already received attention in Sri Lanka from the initial days of the energy crisis in 1973, including 'Colombo Declaration', which was calling for regional development of biogas technology (de Alwis, 2002). The penetration of cleaner and energy efficient technologies in small power systems such as the case of Sri Lanka has encountered many problems, such as: high initial costs, unclear government policy, lack of financing instruments, lack of awareness about the usable technology and others (Priyantha et al., 2006).

The use of renewable energy sources is often suggested as a possible solution to reduce a nation´s contribution to climate change and its dependency on fossil fuels (Liu et al., 2010), but there is need for further evaluation (Zhang et al., 2013). Global

[2]Currently there is running The SWITCH-Asia joint partnership Project called Sri Lankan Renewable Energy focused on up-scaling of biogas technology in Sri Lanka.

warming, caused by increasing emissions of CO_2 and other greenhouse gases (GHGs) as a result of human activities, is one of the major threats currently confronting the environment (Fan et al., 2007). CO_2 accounts for the largest share of GHGs globally (Fan et al., 2007), for agricultural activities it is estimated to account for about 13.5% of the total GHG emissions (Phan et al., 2012) and if emissions are allowed to increase without limits, the greenhouse effect can possibly destroy the environment for humans and other living creatures, even threatening the existence of humankind (Fan et al., 2007).

Biogas production by anaerobic fermentation is a promising method of producing energy while achieving multiple environmental benefit e.g. fossil energy substitution, carbon emission reduction, pollution abatement, welfare improvement (Contreas et al., 2009; Zhang et al., 2013) and it was evaluated as one of the most energy-efficient and environmentally friendly forms and technologies for renewable energy production (Weiland, 2010). According to Pehme & Veroman (2015) technology of biogas production shows great environmental benefit in comparison with conventional technologies in terms of global warming potential. However, there are still some unscrutinised factors of biogas technology (Roubik et al., 2016) waiting for examination. One of such is a flue gas analysis of biogas cookers, as it can show the quality of combustion (Skanderová et al., 2015) having direct effect on service life of such a device (Roubik et al., 2016).

Household biogas cookers, although individually small in size, are numerous and thus have the potential to contribute significantly to inventories of GHGs (Obada et al., 2014). Biogas cookers are common in use in developing countries, where biogas technology is exploited. However, these biogas cookers do not achieve high and stabile combustion efficiency (SNV, 2001; Obada et al., 2014). Thereby, emitting a substantial amount of fuel carbon as product of incomplete combustion (such as carbon monoxide, methane and total non-methane organic compounds as well as carbon dioxide) can be expected (Ramana, 1991).

The major objective of this paper is to fill in the gap around flue gas of biogas cookers, to find out the quality and efficiency of combustion, because the inefficient combustion process can lead to the high emissions of carbon monoxide and nitrogen oxides (Skanderová et al., 2015). Therefore the flue gas analysis was conducted. This survey intends to provide in-depth understanding about the issue with taking into accounts possible risks. Investigating such a topic is within continuing concern about biogas technology in rural areas of developing countries.

MATERIALS AND METHODS

Target area, data collection methods and statistical analysis

The survey was carried out in the different areas of Sri Lanka: Ampara, Anuradhapura, Akkaraipathu, Arugambay, Batticaloa, Colombo, Galle, Kandy, Kegalle, Karuwalagaswewa, Galle, Puttlam, Nochchiyagama (Fig. 1), at the level of BGPs and BGP owners ($n = 51$) and local consultants ($n = 4$), in August 2014. Methods of data collection included semi-structured personal interviews, questionnaire survey at the level of BGP owners and local consultants and observation; and flue gas analyses at the level of biogas technology.

A semi-structured personal interviews and questionnaire survey were used to obtain information about biogas technology owners, time spent on maintenance of biogas technology, funding and economic aspects of the technology, and types of inputs, hours of cooking, digestate practices and information about biogas cookers. Small- and medium-scale biogas plants were chosen according to the list of the Czech NGO People in Need implementing the project: '*Promoting Renewable Energy as a Driver for Sustainable Development and Mitigation of Climate Change in Sri Lanka*' and local project partners from Janathakshan (GTE) Limited. Collected data were categorized, coded and analysed in a statistical programme Statistica 10. Due to the nature of data Spearmen's correlation coefficient (ρ) was used to detect possible relations between time spent on maintenance of biogas technology and its recalculated concentration of CO_2 from flue gas analysis and age of biogas cooker and recalculated amounts of CO_2 from flue gas analysis. Student´s *t*-test was used to determine if there are variances among flue gas analysis through categories of biogas plants.

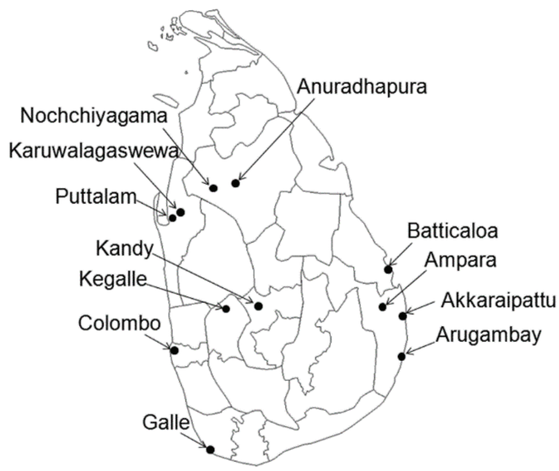

Figure 1. Map of visited areas (Sri Lanka).

Biogas yield calculations

Minimal biogas yield from various biodegradable wastes (resulting from survey results of the most common input material) was calculated for an average biogas plant according to the typical yields in mesophilic conditions (*i.e.* 20–45 °C) according to IAEA (2008).

Biogas plants categorization

For purposes of data representation, the categorization of biogas plants according to their size was chosen (Table 1).

Table 1. BGPs categorization

	No of analysed BGPs	Size of BGPs (m^3)*
Community scale biogas plant	4	More than 60
Medium-scale biogas plants	16	12–60
Small-scale biogas plants	31	Less than 12

*The size is showing the total volume of the biogas plant digester

The flue gas analysis

The flue gas analysis was done through the portable device TESTO 330-2 (Testo AG, Germany), which is capable of capturing the gas concentration of CO and NO; consequently by recalculating concentrations of CO_2 and NO_2. As specified by the manufacturer (Testo AG, Germany), the recommended minimum measurement time for obtaining accurate values covers 3 minutes for 90% response. After every measurement, the flushing of the device was done, according to recommended flushing times (automatically set up by the device according to the ppm concentrations).

Principle of recalculation of the mass concentration of CO_2 is following:

$$CO_2 \left[\frac{mg}{m^3}\right] = \frac{\left[CO_{2max} \cdot \left(O_{2ref} - O_2\right)\right]}{O_{2ref}} \quad (1)$$

where: CO_{2max} – maximal concentration of CO_2; O_{2ref} – referential oxygen value (21%); O_2 – measured concentration in %.

Principle of recalculation of the mass concentration of CO is following:

$$CO \left[\frac{mg}{m^3}\right] = \left[\frac{O_2 - O_{2refer}}{O_{2ref} - O_2}\right] \cdot CO_{ppm} \cdot 1.25 \quad (2)$$

where: O_{2refer} – cross-referential oxygen value (3%, according to the manual-Testo AG, Germany).

Principle of recalculation of the mass concentration of NOx is following:

$$NO_x \left[\frac{mg}{m^3}\right] = \left[\frac{O_2 - O_{2refer}}{O_{2ref} - O_2}\right] \cdot CO_{ppm} \cdot 2.05 \quad (3)$$

The conversion factors (1.25 and 2.05 for the concentrations of CO and NO_x, respectively) are applied in above formulas 2 and 3 corresponding to the standard density in mg m^{-3} of the gas concerned. For NO_x the standard density of NO_2 is used, because only NO_2 is a stabile compound and NO reacts very fast with oxygen to NO_2 (Testo, 2011).

RESULTS AND DISCUSSION

With relatively stable thermal efficiency, biogas might be of a high heat value and is also convenient to use, making it appropriate for technological economy. Although, the structure of rural energy consumption has changed in Sri Lanka, cooking still plays the leading role in energy consumption in rural household and examined BGPs.

From the examined BGPs majority were fixed dome models (72.55%), followed by SiriLak Dahara models (21.57%) and Arpico models (5.88%). Majority of surveyed BGPs use standard two-flame biogas cookers (in case of larger BGPs multiple two-flame biogas cookers were in use) from various manufacturers. Commonly, biogas cookers were initially set within the implementation of BGP and fixed. For the small-scale BGPs various feedstock materials and their mixtures are used. Most common input material was kitchen waste (74.19%), followed by toilet waste (22.58%), pig manure (12.90%), cow dong (6.45%) and quail manure (3.22%). In case of medium-scale biogas plants, major input material was also kitchen waste (68.75%), followed by wastewater (37.5%) and pig manure (12.50%). In case of community scale BGPs majority of input material were market leftovers (vegetable mainly) in 50% and wastewater (also 50%), followed by rice starch in 25%.

If considered almost 20 m^3 as the average size of surveyed BGPs and average time of biogas cookers on active use: 6.03 hours/day (+/-3.98), with minimum 1 hour/day up to 12 hours/day – cooking during the full day without cease (counting with stabile feedstock), 600–700 m^3 of biogas generation per year can be expected (considering the fact that users use biogas until its end).

Table 2 shows average values of flue gas analysis calculated for all 51 BGPs. Interesting results are related to the high concentration of CO (mg m^{-3}) detected. This might be caused by the one and/or various combinations of the following factors such as insufficient burning, inappropriate biogas cookers and inappropriate maintenance. Table 2 shows also measured difference from concentration of CO in its diluted and undiluted form (37.59% in diluted form). The concentration of unavoidable produced NO equals $c(NO) = 0.05$ mg m^{-3}, which is showing still acceptable value for transformation of biodegradable wastes into biogas and its consequent burning. According to the Occupational Safety and Health Administration (OSHA) the permissible exposure limit for nitric oxide (NO) exposure is as (30 mg m^{-3}) over an 8-hour workday (NIOSH, 2015). As the typical flue gas exit temperature is in the range from 440 °C to 500 °C (Anonymous, 2013b). Average temperature of flue gas (TS) with almost 450 °C seems to be appropriate for average use of biogas cooker. However, the respondents reported occasional use of high temperatures to accelerate the process (*i.e.* cooking, water boiling). Such a practice can lead to the malfunction of biogas cooker (Roubík et al., 2016).

As the optimal air/gas efficiency is expected to be over 55% and if considered measured air/gas efficiency 54%, the further potential of a cooker could be maximised by improving air/gas regulation systems (KEBS, 2013) and maintenance habits of the users (Roubík & Mazancová, 2014).

If the biogas flame has too much fuel, then it will burn incompletely, giving unwanted CO, carbon particles and is less efficient (Fulford, 1996). Biogas cookers should run with a small excess of air to avoid the danger of flame have too much fuel (Fulford, 1996), however when the excess of air is too high it cools the flame resulting also into lowering the efficiency. Our results of excess air (4%) in average, if compared with results of Obada et al. (2014) (1% among two types of biogas cookers), show slightly different values which might be caused also by the higher amount of inlet air jets.

Table 2. Average values from flue gas analysis (N = 51)

O_2 (%)	CO_2 (%)	CO_2 max (%)	CO (mg m^{-3})	CO (undiluted/ (mg m^{-3}))	NO (mg m^{-3})	TS* (°C)	Efficiency of flow (%)	Excess air (%)	Flow (l min^{-1})
13.30	4.95	13.6	1,008.92	2,683.99	0.046	449.16	53.96	3.99	0.66

*Average temperature of flue gas measured from biogas cooker outlet

The recalculated average concentrations of CO_2, CO and NO_X s for all examined BGPs are shown in Table 3. A quite high dispersion of values of CO is obvious, which we assume are caused by the combination of several factors: variability of burning of biogas cookers during flue gas analysis, various input materials for BGPs and divergent maintenance of biogas cookers. These values are in accordance with values described in Obada et al. (2014) for similar biogas systems. However, interesting results were found out in following biogas systems: lower flue gas analysis results of the hotel medium-scale biogas plants (N = 6), which is expected to be caused by proper maintenance and proper BGP feeding. Similar results were found out in the case of tea farms (medium scale BGPs with higher reported time spent on maintenance of technology; N = 2). On the other hand, rice mills BGPs and pig farm BGPs (medium scale biogas plants, N = 6) showed higher flue gas analysis. In case of rice mill BGPs, we assume poor maintenance and composition of biogas feedstock can be main reasons.

Table 3. Recalculated values of essential compound from flue gas analysis (N = 51)

	CO_2 (mg m^{-3})	CO (mg m^{-3})	NOx (mg m^{-3})
Average	4.98	2,9495.60	0.02
Min	0.78	59.34	0
max	12.69	19,3500	0.65

There were no significant differences (using *t*-test) in results of flue gas analysis among size categories of biogas plants; as also mentioned in the study by Obada et al. (2014); showing so that the size of BGPs is not a crucial factor influencing the amount of flue gas of the biogas cookers. The factors *time spent on maintenance of biogas technology* and its *recalculated concentration of CO_2 from flue gas* analysis were analysed using Spearmen´s correlation. The results show that with higher time assigned to the maintenance, the flue gas analysis of CO_2 was slightly lower (Table 4). This implies the importance of proper maintenance and adequate time which need to be stipulated for the technology maintenance (Roubík & Mazancová, 2014). Furthermore, the age of biogas cookers and recalculated concentrations of CO_2 from flue gas analysis were contrasted by Spearmen's correlation coefficient. Results imply ($\rho = 0.286$, $\alpha = 0.05$) that with age of the biogas cookers the concentrations of CO_2 growth. This can be also caused by adherence of dirt on the biogas cookers, as well as the decreasing condition of the device.

Table 4. Relationship between maintenance of biogas technology and concentration of CO_2

Category of biogas plants	Spearmen´s correlation coefficient
Community biogas plants	$\rho = -0.102$, $\alpha = 0.05$
Medium-scale biogas plants	$\rho = -0.125$, $\alpha = 0.05$
Small-scale biogas plants	$\rho = -0.091$, $\alpha = 0.05$

Also further consideration should be given to exploration of gas itself and its microbiological content. For example Vinneras et al. (2006) were trying to identify microbiological community in biogas systems. Low risks of spreading disease via biogas system were evaluated; however, wide variety of fungi, spore-forming and non-spore-forming bacteria was recognized in biogas. According to our survey bad smell was identified in 28% of cases signalling the possible presence of H_2S. However, this can be easily removed by the use of a H_2S absorbent (Roubik et al., 2016). Further research should be done in characterization and analysis of emissions from biogas cookers, as similarly was done in study of Fan & Zhang (2001), with taking into account also particle size distribution, emission rates and potential exposures. Also further research focusing on effects of use of different biogas cookers on the flue gas during the time is needed.

CONCLUSIONS

The technology of biogas production has multiple advantages: to reduce waste and transform it into valuable energy. Biogas plants in Sri Lanka offer environmental, health and socio-economic benefits for local, regional and even national level. However, further factors must be also taken into account, such as combustion of biogas and its consequent effects. Due to this reason this study provided view into the flue gas analysis connected to the biogas cookers. Flue gas analysis was done through the portable device TESTO 330-2, which is capable of capturing the gas concentration of CO, NO; consequently by recalculating concentrations of CO_2 and NO_2. In our case reflecting almost 20 m^3 as the average size of surveyed BGPs and average time of biogas cookers on use: 6.03 hours/day (+/- 3.98), with minimum 1 hour/day up to 12 hours/day (counting with stabile feedstock), 600–700 m^3 of biogas generation per year can be expected. Quite high concentration of CO was detected c(CO) = 1,008.92 mg m^{-3}), which might be caused by combination of the following factors such as: burning, inappropriate biogas cookers and inappropriate maintenance. The concentration of NO was c(NO) = 0.046 mg m^{-3}. Average temperature of flue gas was within the typical flue gas exit temperature for burning in biogas cookers (TS = 450 °C). Air/gas efficiency was slightly under the adequate value of 55% (54%), therefore further potential should be maximised by improving of air/gas regulation systems and maintenance habits of the users. Furthermore, excess air (4%) was analysed. Also bad odour was identified in 28% of cases signalling the possible presence of H_2S.

Easy energy access is a trigger for development, especially in form of human, social and economic development and biogas plants represents a boon for farmers and rural people to meet their energy needs. This study implies that it is important to explore further factors such as exploration of gas itself and its microbiological content with its effects on flue gas analysis, as well as exploring particle size distribution, emission rates and potential human harmful exposures. It is essential to minimize the potential conflict among the environment, sustainable development and further use of biogas technology in rural areas of developing countries.

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