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Key factors affecting performance of biogas latrines in urban informal areas: Case of Kampala and Nairobi, East Africa

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Large scale application of biogas latrine technology in developing countries faces technical, socio-economic and financial challenges. As a result, harnessing its full potential has not been realized. This study examined variables describing the design, construction, operation and maintenance of nineteen biogas latrines in relation to their performance in Kampala and Nairobi, based on survey and field observations. Pre-tested questionnaires were administered to users, owners and construction technicians/masons of the biogas latrines. Field observations were also undertaken to assess physical conditions of the biogas latrines. Principal component analysis was then used to establish correlation between variables of design, construction, operation and maintenance in relation to the performance of biogas latrines in terms of burning hours in a day. The design types of all the studied biogas latrine digesters were found to be of fixed dome. Co-digestion of human excreta and cow dung increased the number of biogas burning hours in a day from 0.5 to 1.1. The findings also show that the performance of the biogas latrines was influenced by six of the variables examined describing construction, operation and maintenance: skills of masons, use of standards in construction, training of users on operation and maintenance aspects, number of users/owners and their motivation for installation of biogas plants and physical conditions of the biogas latrines. This implies that the use of skilled masons, comprehensive training of users on operation and maintenance aspects and use of co-substrates are key variables for optimal performance of biogas latrines.

Key words: Biogas latrines, Kampala, Nairobi, performance.

INTRODUCTION

The sub-Saharan Africa (SSA) region is experiencing unplanned rapid urban population growth arising mainly from rural-urban migrations. Consequently, urban settlements in many SSA cities and towns are informal and occurring in slums. Incidentally, the high rate of urban population growth is not marching with existing energy sources and sanitation facilities due to higher demand from increasing population. Therefore, provision of safe and affordable sanitation in poor urban areas is one of the challenges for rapidly growing cities in low income countries (Reis et al., 2008). Urban sanitation improvements in developing countries have occurred in formal settlements whereas in densely populated parts of urban areas, sanitation provision is inadequate and is with least progress (Buttenheim, 2008; Hanchett et al., 2003). Inadequate sanitation has negative impacts on the environment and public health in urban areas of developing countries than in rural areas where simple and sustainable on-site sanitation solutions can be implemented (Bartlett, 2003; Genser et al., 2008). Therefore, innovative sanitation technologies including both on-site and off-site have been adopted in peri-urban and slum areas. Biogas latrine is one such technologies that can offer a sanitation solution in urban slums (Schouten and Mathenge, 2010) and has gained prominence in recent years (Bensah et al., 2010). However, inactivation of pathogens in resultant slurry from mesophilic anaerobic digestion in biogas latrines is not completely achieved (Mehl et al., 2011). This will have an impact on human health if slurry is used as manure in agricultural fields that has food crops and grazing livestock in that the pathogens which are disease causing could be transferred to humans through the food chain (Eamens et al., 2006). To minimize this impact on human health, slurry should be sanitized before it is used in agriculture and multi-barrier measures to risk reduction should be applied (WHO, 2006).

A biogas latrine is an integrated waste management system that provides a sanitation solution as well as energy in form of biogas (Buxton, 2010). It consists of a latrine structure, digester, displacement chamber, mixing chamber, slurry pit and biogas piping system (Sasse et al., 1991). The major designs and types of biogas latrine digesters used in developing countries are fixed dome and floating drum (Omer and Fadalla, 2003; Rajendran et al., 2012). These digester types operate with a seat on top of the digester either fixed or movable depending on the design type (Nijaguna, 2002). The performance of biogas latrines is indicated by their ability to provide sanitation solution to users and biogas production, which can be deduced from the number of gas burning hours, in instances where the gas line is not metered.

The performance of biogas latrines in relation to biogas production is mainly affected by temperature, organic loading rate, pH, moisture content, carbon to nitrogen ratio of substrates and hydraulic retention time (Deublein and Steinhauser, 2010). Other factors influencing performance are related to construction, operation and maintenance of the biogas plants (Day et al., 1990). A number of biogas latrines have in the past been abandoned due to poor feeding and irregular maintenance of the digesters (Arthur et al., 2011; Parawira, 2009). The lack of trained personnel responsible for construction of biogas latrines negatively affects their performance (Estoppey, 2010; Mwakaje, 2008). Additionally, biogas loss from latrines that were constructed by unskilled personnel in the slums of Nairobi has been documented (Umande, 2014). The operation and maintenance of the biogas latrines is dependent on the motivation of users to get sanitation and energy benefits from installed latrines. The sense of ownership by users of the biogas latrines is an important motivation in ensuring that they are properly operated and maintained (Ghimire, 2013).

Contrasting performance of biogas latrines have been reported in East Africa (Letema et al., 2012) varying even within the same city. In Kampala for example, biogas production is affected by the feeding and maintenance regimes (Lutaaya, 2013) whereas in Nairobi it is affected by operation and maintenance (Kithandi, 2014). There is currently limited information related to design, construction, operation and maintenance of biogas latrines. This is probably responsible for low adoption of the technology. Therefore, this study evaluated the effect of design, construction, operation and maintenance on performance of biogas latrines in East Africa with case studies in Kampala and Nairobi cities.

MATERIALS AND METHODS

Study areas

The study areas were cities of Kampala, Uganda (00° 18' 49'' N and 32° 34' 52'' E) and Nairobi, Kenya (1° 17' S 36° 49' E). Kampala has a population of 1.516 million people (UBOS, 2014) compared to 3.138 million people in Nairobi (KNBS, 2013). Kampala is the capital city of Uganda and has five administrative divisions of Makindye, Rubaga, Central, Kawempe, and Nakawa (Figure 1). In Kampala, the study was conducted in the four divisions of Makindye, Kawempe, Rubaga and Central. More than 60% of the population in Kampala live in slums characterized by high population density of more than 500 persons/hectare (Kulabako et al., 2010; UBOS, 2014). Nairobi is the capital city of Kenya and has eight administrative divisions, namely: Central, Dagoretti, Embakasi, Kibera, Makadara, Pumwani, Kasarani, and Westlands (Figure 2). In Nairobi, the study was conducted in four divisions of Kibera, Pumwani, Embakasi and Makadara with the highest number of slums. Nairobi city has about 60% of its population living in slums which are characterized by a high density of about 250 housing units/hectare with each housing unit having approximately 6 persons (Otiso, 2003; Ruhiu et al., 2009). Majority of the biogas latrines surveyed in Nairobi were in Kibera (a typical urban slum)

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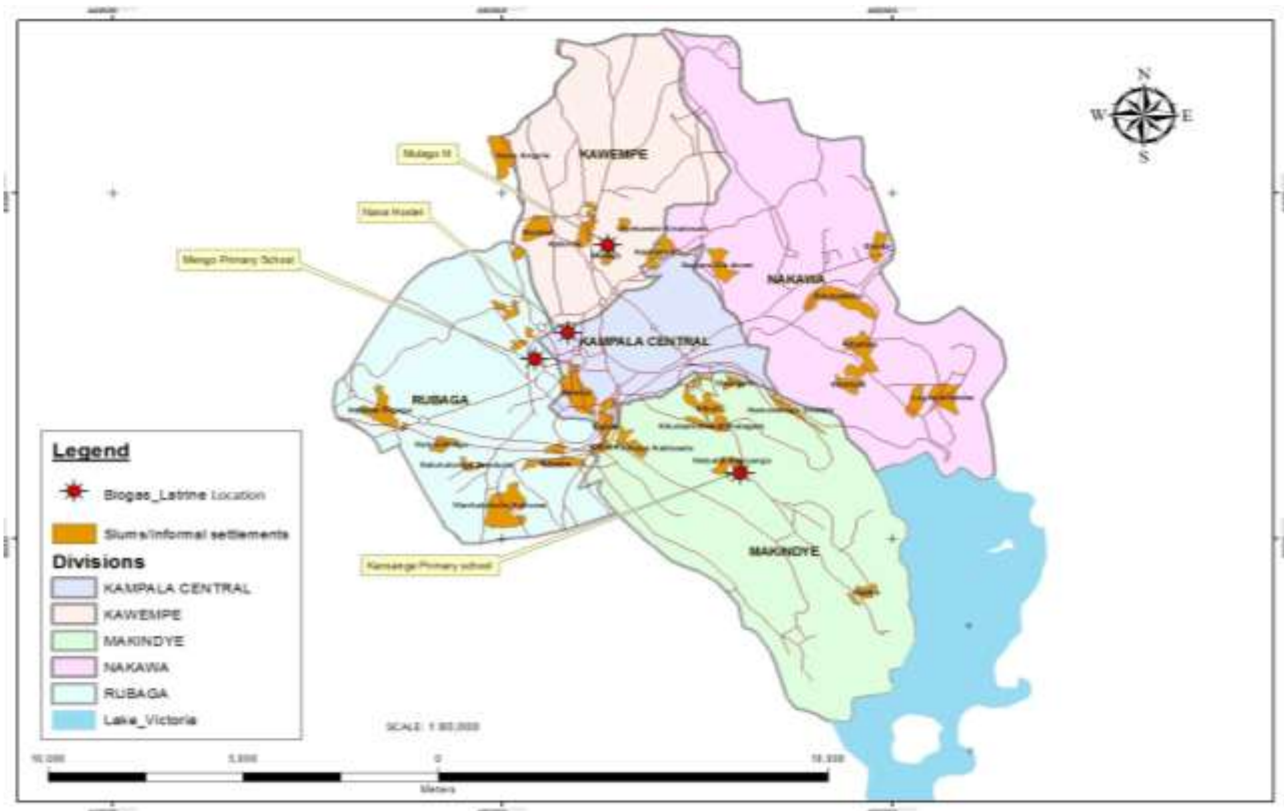

Figure 1. Map of Kampala showing location of the biogas latrines studied.

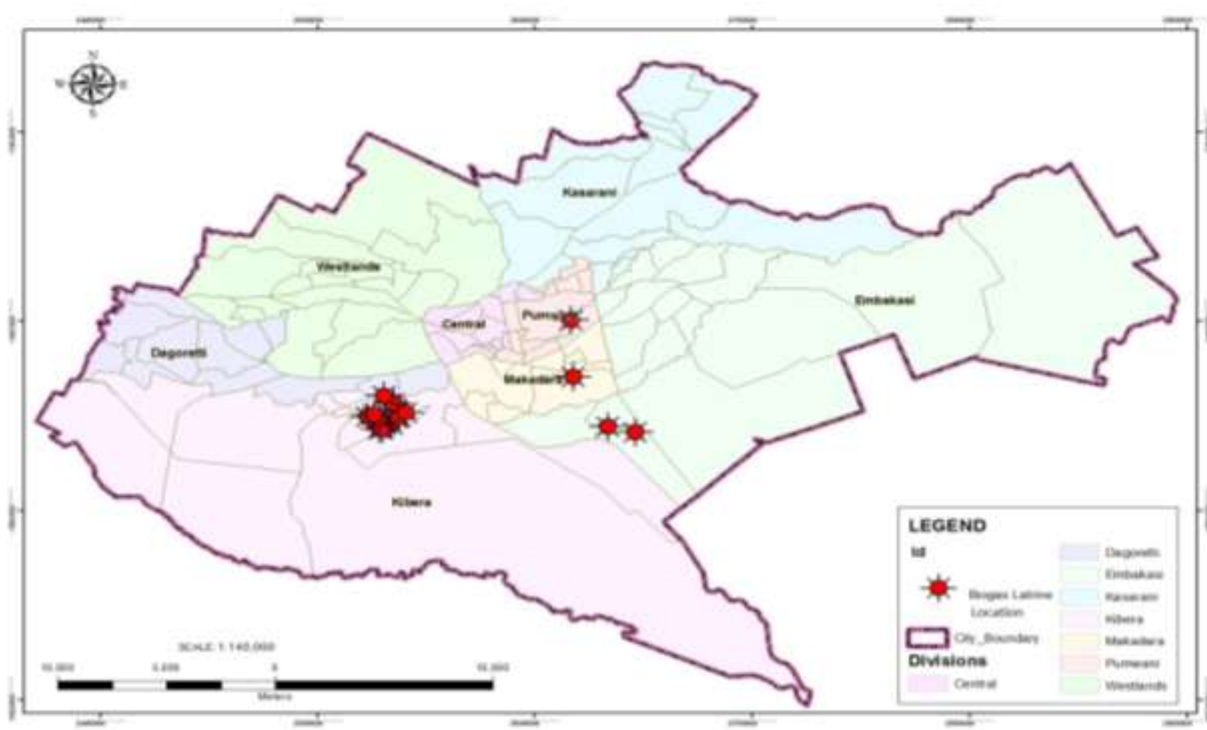

Figure 2. Map of Nairobi showing location of the biogas latrines studied.

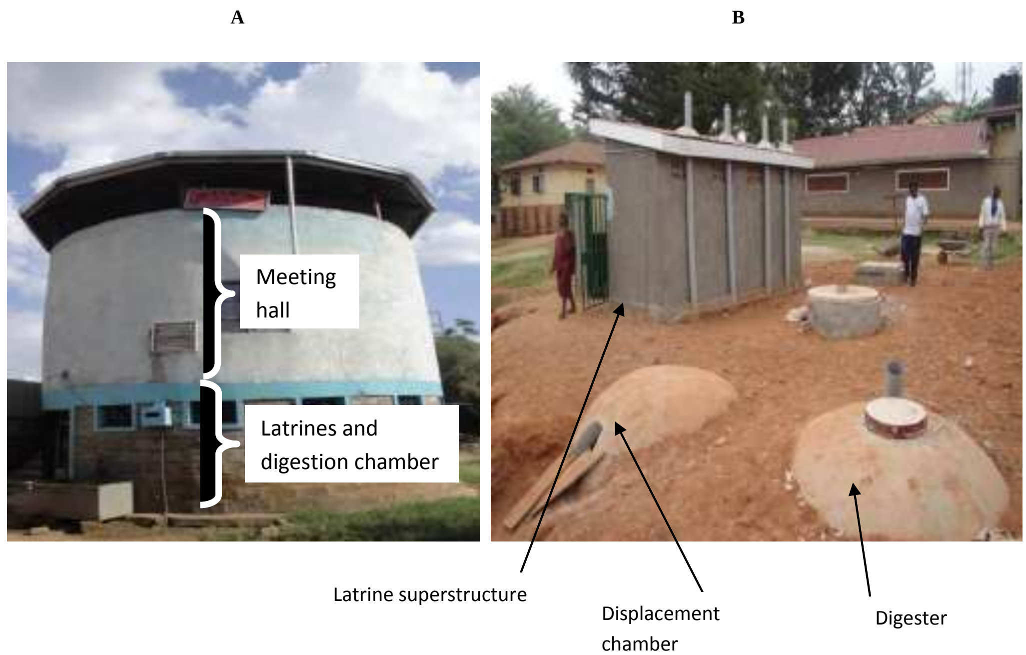

Figure 3. A typical biogas latrine in (A) Nairobi for Kibera slum community and (B) Kampala at Mengo Primary School.

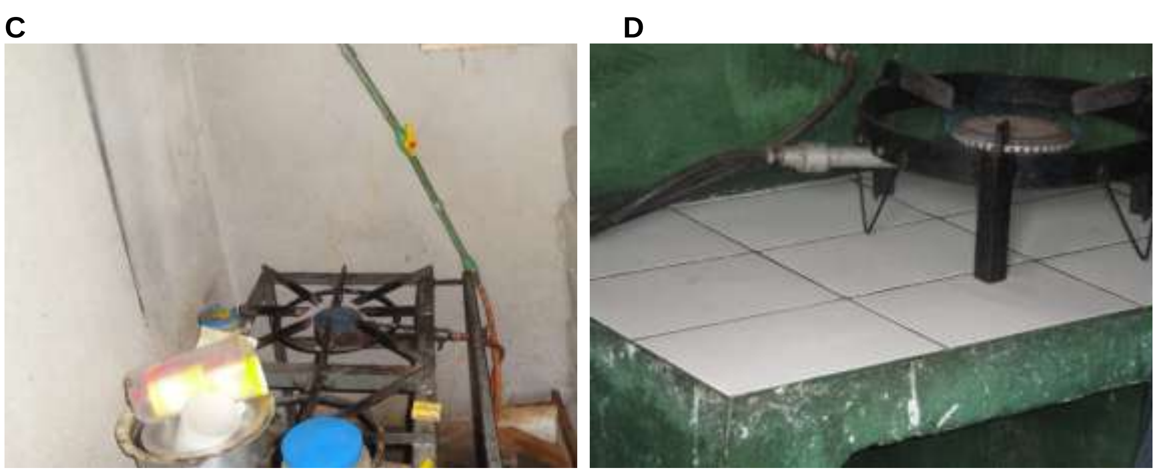

Figure 4. Typical gas stoves (which were similar) connected to biogas latrines in (C) Nairobi and (D) Kampala.

where most of them have been installed to address sanitation challenges therein.

The criteria for selection of Kampala and Nairobi is that both cities represented typical characteristics of urban areas in developing countries where the most prevalent form of sanitation technology is pit latrines, which can be connected to digesters to form biogas latrines. Secondly, the study targeted cities where biogas latrines existed in order to assess their performance. The biogas latrine technology was introduced in Nairobi by a non-governmental organization (NGO); Umande Trust where usage and management is mostly by the slum community. On the other hand in Kampala, the technology was introduced by Kampala Capital City Authority (KCCA) and Sustainable Sanitation and Water Renewal Systems (SSWARS), a local NGO. In Kampala, the biogas latrine technology is slowly picking up and currently available in institutions and communities following installation mainly by KCCA and SSWARS. All the surveyed biogas latrines in Kampala and Nairobi were built for communal or institutional use (Figure 3). The sizes and types of stoves connected to biogas latrines were similar enough in both Kampala and Nairobi (Figure 4).

Table 1. Parameters and variables assessed for the biogas latrines.

Parameters	Variable under the parameter
Design	Type of a digester Volume of a digester (from technical drawing plans)
Construction	Motivation of owners/users in installation of the biogas latrines* Skills of masons (by training and experience) Standards on construction material Physical conditions of the biogas latrines (1=poor, 2= fair, 3= good)
Operation and maintenance	Number of users Use of co-substrate(s) Frequency in maintaining of main valve, checking leakage, draining of condensate water, cleaning of overflow, oiling of gas tap and cleaning of stove Training of users on operation and maintenance activities/aspects in biogas latrines
Performance	Number of biogas burning hours in a day coming from similar gas stoves Users' satisfaction (full, partial, none)

*Motivation of owners/users in installation of biogas latrines meant the derived benefits from biogas latrine use that made the owners or users to construct the biogas latrine.

Sample size and selection

Selection of biogas latrines was based on them having been constructed and commissioned at least two months prior to the survey to ensure that the users had experienced some effects in terms of biogas and slurry use. In Kampala, there were four existing biogas latrines that satisfied the selection criterion, the sample size was the same as the population (n = N). In Nairobi, there were thirty existing biogas latrines at the time of the survey and fifteen were taken as a sample (n = 0.5 N) having satisfied the selection criterion. The groups of people interviewed during the survey included users, technicians or masons responsible for construction and owners or owners' representatives of the biogas latrines. The questions asked were guided by parameters and variables outlined in Table 1.

Questionnaires and field observations

Pre-tested structured questionnaires were used to collect information on parameters of design, construction, operation, maintenance and performance of biogas latrines. They were administered to four biogas latrines in Kampala located in Kansanga Primary School (Makindye Division), Mengo Primary School (Rubaga Division), Nana Hostel (Central Division) and Mulago III area (Kawempe Division). The 15 biogas latrines surveyed in Nairobi were located in Gatwekera Tosha, Tosha II, Nicofeli, Muvi, Jasho Letu, Stara, Kidyot, Rurii, Nyaharwa and Kibera Girls Primary School in Kibera Division, Twaweza and St. Hellena in Pumwani Division, Top I and Top II in Embakasi Division and Heshima Disabled in Makadara Division. The variables considered for each of the parameters studied are presented in Table 1. In addition, field observations of biogas latrines components (digester, displacement chamber, latrine superstructure, gas piping system and slurry pit) guided by a check list were undertaken to ascertain the conditions of the components. These were graded for performance on a scale of 1 to 3; where 1 was poor, 2 was fair and 3 was good.

Data analysis

Data collected using questionnaires were entered manually and cross checked to ensure the entries were correct. Data from the questionnaires on parameters of design, construction, operation and maintenance were analyzed using statistical package, SPSS Version 21. Data were normalized through square root transformation to enable analysis by principal component analysis (PCA). PCA was used to establish the correlation between variables of performance of biogas latrines and design, construction, operation and maintenance. PCA was applied to 15 variables (Table 1); motivation of owners/users, skills of masons, standards in construction materials, digester volume, physical conditions of the biogas latrines, users of the biogas latrines, use of co-substrate(s), maintenance of valve, checking leakage, draining of condensate water, cleaning of overflow, oiling of gas tap, cleaning of stove, burning hours/day and users' satisfaction. The number of principal components (PCs) extracted was based on criterion by Kaiser (1960) where the PC(s) with Eigen values greater than 1 were considered. The PCs were used to identify the most important variables affecting the performance of biogas latrines. PCA results were presented as component scores and loadings. A varimax rotation was applied to the PCs to minimize the contribution of variables with low loadings and maximize the contribution of variables with high loadings. Performance of biogas latrines (indicated by average number of burning hours/day which was coming from similar gas stoves) was plotted against each variable for the parameters of design, construction, operation and maintenance.

RESULTS

Characteristics and status of biogas latrines

All the digesters in Kampala and Nairobi were of fixed dome type and their volumes ranged from 18 to 54 m^3. The main materials for construction of the biogas latrines in Kampala and Nairobi were bricks and quarry stones, respectively. The average estimated number of users of biogas latrines in Kampala and Nairobi was 200 and 223, respectively.

Masons used for construction of the biogas latrines were all skilled in Kampala. However, the level of skills of masons in Nairobi was reported as very skilled (7%), skilled (80%) and non-skilled (13%). The categorization of the masons' skills was done based on their reported experience and training in construction of biogas latrines. The very skilled masons had long term experience (more than 5 years) and training in construction of the biogas latrines while the skilled ones were also experienced and trained in construction of biogas latrines, but not on a long term basis (less than 3 years). The non-skilled ones had neither experience nor training in construction of the biogas latrines.

All the users of biogas latrines except for two latrines in Nairobi were trained on various aspects of operation and maintenance (O&M), covered: proper feeding of the digester, optimal use of biogas, avoidance of using non-biodegradable matter, regular maintenance of biogas latrine components (pit latrine, digester, mixing chamber, displacement chamber, biogas pipeline and slurry pit) and proper handling of gas stoves. The training of users was on spot (13%), short term (54%), comprehensive (20%) and no training (13%) in Nairobi, while in Kampala it was on spot (50%) and short term (50%). On spot training entailed giving brief instructions on O&M to users of biogas latrines for a day by masons responsible for their construction. Short term training involved giving detailed instructions on O&M to users of biogas latrines for two or three days by the masons. Comprehensive training was done by qualified personnel from the local authority or service provider by means of detailed instructions on O&M for a period of one week or more. Frequency of cleaning of latrines and gas stoves was carried out either daily or as and when needed. There was daily cleaning (53%), weekly (16%), bi-weekly (21%) and those latrines which were cleaned as need arises (10%). Incidentally, the bi-weekly cleaned latrines had the highest mean number of users (210 people), with a mode of 300.

Owners or users of biogas latrines were motivated by the benefits attained from their use. The benefits were social, environmental and health related. Social benefits were the prestige and decency that the users could get from the use of biogas latrines. Environmental benefits were the advantages the users could get from having a clean environment as a result of their use of biogas latrines while health benefits were reduction in the water borne or respiratory diseases in the users' population as a result of using biogas latrines in cooking compared to use of fire wood. Majority of the biogas latrines (75%) in Kampala had their users' motivated to install the facilities due to social benefits, while most of the biogas latrines in Nairobi (80%) had their users motivated to construct the facilities due to health benefits. In this study, the number of burning hours per day of gas stoves connected to the digesters was used as an indicator for performance of biogas latrines in Kampala and Nairobi. The average number of burning hours/day for biogas latrines in Kampala and Nairobi was 1.3 and 1.7, respectively.

Effect of digester volume on performance of biogas latrines in Kampala and Nairobi

The digesters had volumes ranging from 18 to 54 m^3 for Kampala and 30 to 54 m^3 for Nairobi with differences in performance as depicted in Figure 5. The average number of burning hours in a day for the smallest volume of the digester (18 m^3) was fewer (0.8) compared to the largest digester (54 m^3) with 1.5 and 2.5 in Kampala and Nairobi, respectively. Performance of the biogas latrines increased with increasing volume of the digester, irrespective of the location and the assumption is that other factors that could have affected their performance were constant.

Construction of biogas latrines

Construction of biogas latrines in Kampala and Nairobi was done by masons with different skills. The average number of burning hours/day of the gas stoves of the biogas latrines (performance) varied with the different skills of masons (Figure 6). The biogas latrines constructed by very (highly) skilled masons in Nairobi produced biogas with longer average number of burning hours in a day (3) compared to those constructed by skilled masons in Kampala and Nairobi that had daily average number of burning hours of 1.1 and 1.6, respectively. There was no biogas latrines constructed by non-skilled and very skilled masons in Kampala. The performance of biogas latrines seemed to be influenced by the skills of the masons.

Use of standards in construction entailed ensuring that the masons took prescribed ratios of building materials. The biogas latrines in Nairobi where standards in construction were used had a higher number of burning hours in a day (2.7) compared to those in both Kampala and Nairobi (1.1 and 1.6, respectively) where standards were not used (Figure 6). There was no use of standards in construction of all biogas latrines in Kampala.

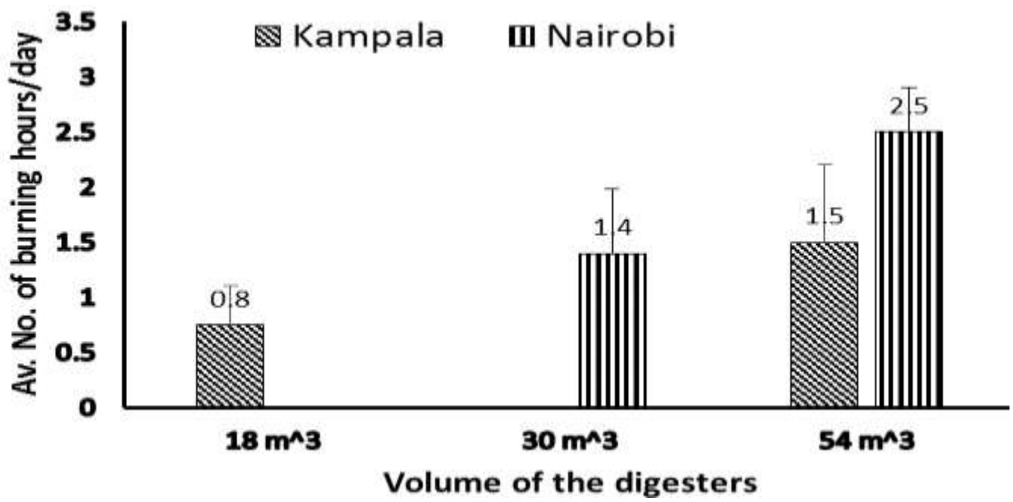

Figure 5. Average burning hours/day of gas stoves for different digester volumes of biogas latrines in Kampala and Nairobi (m^3 refers to m^3).

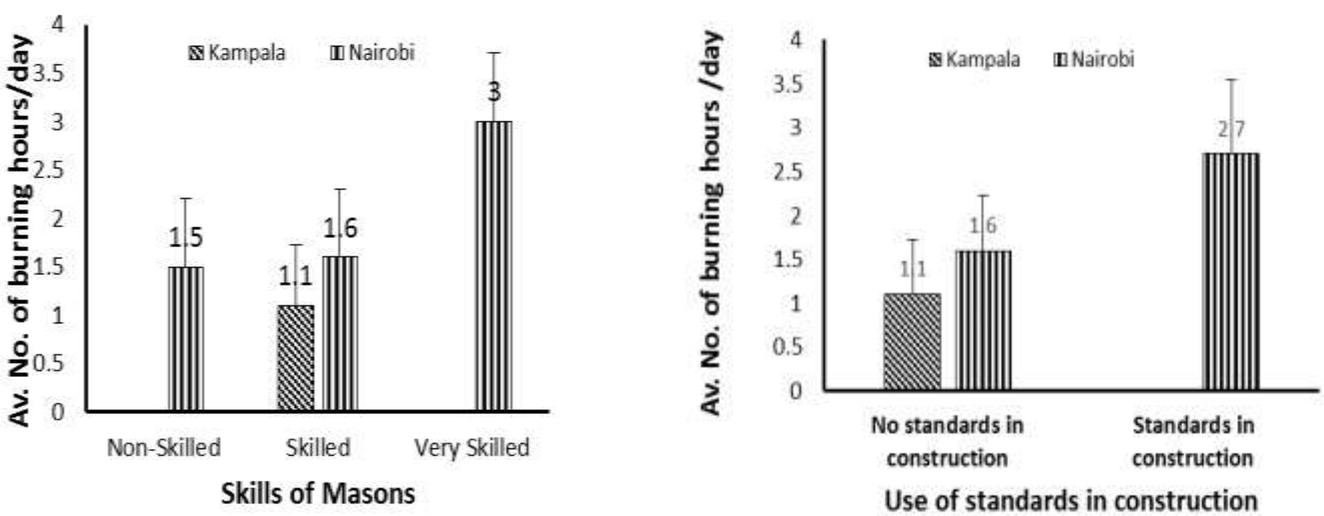

Figure 6. Average burning hours/day of gas stoves of biogas latrines constructed with different skills of masons and uses of standards in construction in Kampala and Nairobi.

Therefore, the use of standards in construction of biogas latrines influenced their performance.

Motivation factors for biogas latrine installation

The owners and users of biogas latrines were motivated by different benefits to construct or install them. The benefits included social, environmental and health. As shown in Table 2, motivation of owners/users affected performance of biogas latrines. The biogas latrines in Nairobi, where the owners were motivated to install them due to environmental benefits produced more gas in a day (2.5 h) compared to those installed due to social and health benefits. The biogas latrines installed due to health benefits also registered a fair performance with the average number of burning hours in a day being 1.7. In Kampala, where social benefits were the main motivation factor, the biogas latrines gave more biogas in a day (1.2 h) compared to those whose construction was motivated by environmental benefits (1 h). Biogas latrines installed due to environmental benefits as a motivation factor exhibited better performance which could have been as a result of the users operating and maintaining the facilities

Table 2. Performance of biogas latrines attributed to motivation factors (mean ± standard deviation).

Performance attribute	Attribute character	Average number of burning hours/day	
		Kampala	Nairobi
Motivation factors for biogas latrines installation	Social benefits	1.2 ± 0.763	0.5±0.000
	Health benefits	-	1.7±0.615
	Environmental benefits	1±0.000	2.5±0.707

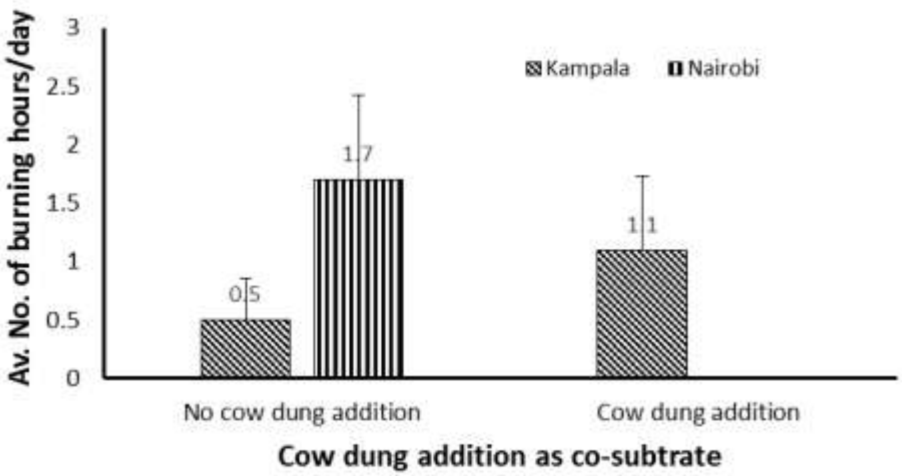

Figure 7. Average number of burning hours of gas stoves of biogas latrines with cow dung addition as co-substrate in Kampala and Nairobi.

well.

Operation and maintenance of biogas latrines

Use of co-substrate for digester feedstock

All the biogas latrines in Nairobi had human excreta without cow dung (co-substrate) fed into the digesters, while all the biogas latrines in Kampala had co-digestion of human excreta and cow dung. Cow dung was fed once per week for each of the surveyed units in Kampala with an average amount of 150 kg per feeding. The owners/users of the biogas latrines in Kampala reported that they were motivated to use cow dung as co-substrate after failing to get adequate gas for their use. Addition of cow dung as a co-substrate to human excreta increased the average number of burning hours per day of gas stoves of biogas latrines in Kampala from 0.5 to 1.1 (Figure 7). However, without the addition of cow dung as was the case with biogas latrines in Nairobi, the average number of burning hours in a day was 1.7, which was relatively high. This better performance of biogas latrines in Nairobi without addition of cow dung could be attributed to other factors other than co-digestion which may be use of standards in construction as reported in construction of biogas latrines.

Frequency of operational and maintenance (O&M) activities

One of the aspects of operation and maintenance of biogas latrines was water availability in the digester. Water was applied daily in all the biogas latrines in Kampala and Nairobi. On average, 11 L/m^3 of digester/day was used in biogas latrines in Kampala whose average digester volume was 18 m^3, while 23 L/m^3 of digester/day were used in digesters in Nairobi, that had an average digester volume of 30 m^3. The average water usage was higher in Nairobi than Kampala which may have been due to the different sizes of the digester and different training levels of users on O&M aspects. It was observed that majority of those who managed/used the biogas latrines had limited knowledge on different operational and maintenance activities like: maintenance of main valves, checking leakages, draining of condensate water, cleaning of overflow, oiling of gas tap and cleaning of

Table 3. Number of biogas latrines with different frequency of operation and maintenance (O&M) of biogas latrine components in Kampala (K) and Nairobi (N).

O & M activities	Number of biogas latrines with different frequency of operation and maintenance*									
	Daily		Weekly		Bi-weekly		Based on need		Never	
	K	N	K	N	K	N	K	N	K	N
Maintenance of main valves	-	-	-	-	-	-	3	14	1	1
Checking leakages	-	-	-	-	-	2	4	13	-	-
Draining of condensate water	-	-	-	-	-	-	-	1	4	14
Cleaning of overflow	-	-	-	-	-	-	4	15	-	-
Oiling of gas tap	-	-	-	-	-	-	2	2	2	13
Cleaning gas stoves	1	7	3	7	-	-	-	1	-	-

*Total number of biogas latrines was 4 in Kampala and 15 in Nairobi.

gas stoves. However, those who received comprehensive training were well versed with regular operation and maintenance of the facilities.

It was further observed that the operation and maintenance cost of each biogas latrines on average per year was US$ 250 and 1500 in Kampala and Nairobi, respectively. The higher operation and maintenance costs of biogas latrines in Nairobi could be attributed to the bigger sizes of the facilities. Most of the operational and maintenance activities in biogas latrines were carried out on a need basis (as and when required) except the cleaning of the gas stove which was done either daily or weekly (Table 3). The other aspect of maintenance that deserved attention was the frequent usage of the water trap to release condensate water build up within the gas pipeline system, but it was rarely done in both locations. The frequency of carrying out the O&M activities ranged from daily to never (none occurrence of the activity). In general, Nairobi had more regularly maintained biogas latrines compared to Kampala.

Training of users on operation and maintenance aspects of the biogas latrines

Another important factor that influenced biogas latrine performance was training of users of the biogas latrines. The users were trained on proper feeding of the digester, optimal use of biogas, avoidance of use of non-biodegradable matter, regular maintenance of biogas latrine components and effective application of slurry. The training session were on spot at the biogas latrine locality, short term duration off-site and comprehensive which included both on-site and off-site sessions. The biogas latrines where users had comprehensive training in Nairobi recorded the highest number of burning hours in a day (2.5). Users in Kampala were not given any comprehensive training on O&M. Biogas latrines whose users were given on spot training in Kampala and no training in Nairobi recorded the least number of average burning hours in a day of 0.8 and 1.3, respectively (Figure 8). Hence, training of users on O&M aspects is an important factor affecting performance of biogas latrines.

Users' satisfaction on the functioning of the biogas latrines

Users of biogas latrines were assessed on their level of satisfaction in using of the biogas. The level of satisfaction was taken as a variable that gave an indication of the performance of the biogas latrines. It was noted that indeed the satisfied users experienced longer burning hours (Figure 9). Therefore, it can be considered that the full satisfaction was as a result of the biogas being enough for the users' energy needs which were mainly cooking. Partial satisfaction implied the users could use the biogas in a day, but it could not satisfy all their cooking energy needs. The users whose biogas latrines experienced the least number of burning hours in a day were not satisfied as shown in biogas latrines in Kampala which generated biogas for a half an hour/day which was inadequate for any of their cooking energy needs.

Overall performance of biogas latrines using PCA

Performance of biogas latrines was indicated by the number of burning hours in a day and users' satisfaction. This was done by comparing the contribution referred to as loading in PCA on the items (variables) within each principal component (PC). The variables produced unrelated components with Eigen values greater than 1, all cumulatively accounting for 81% of the variance of the data set (Table 4). PCA indicated that the main attributes to the performance of biogas latrines were using standards during construction, checking of gas leakage and training of users on operation and maintenance

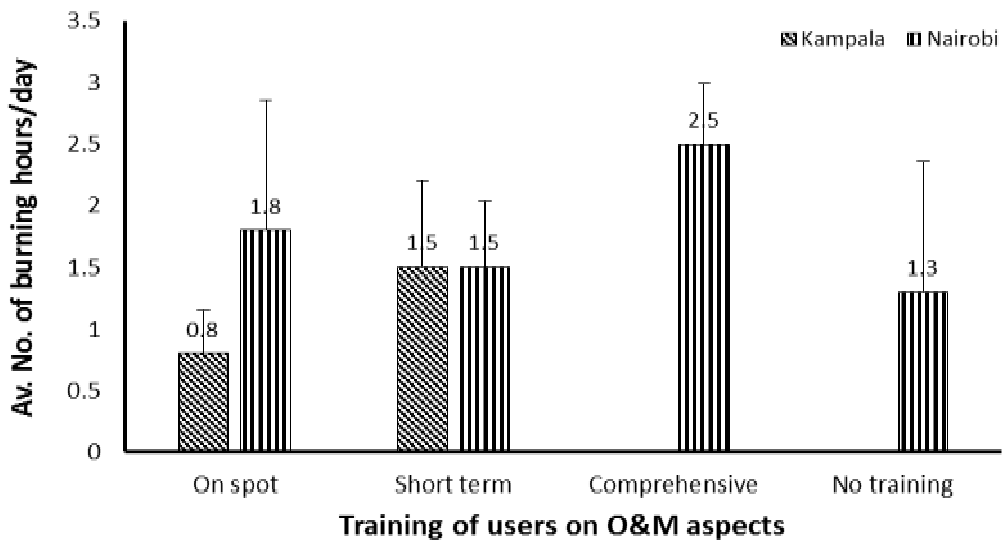

Figure 8. Average number of burning hours/day of gas stoves in Kampala and Nairobi with different training of users on O&M aspects of biogas latrines.

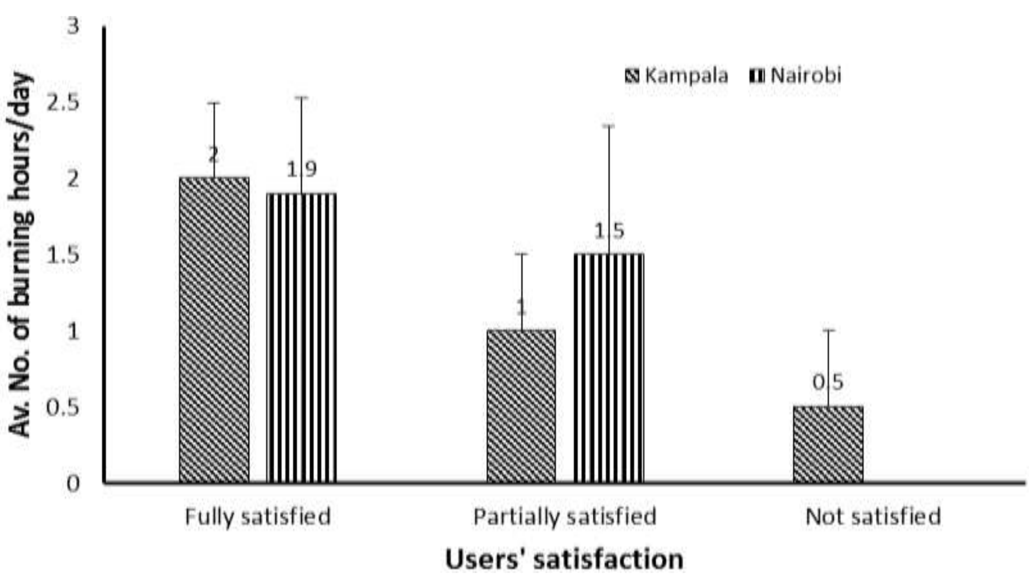

Figure 9. Users' satisfaction on the average number of burning hours/day of gas stoves of biogas latrines in Kampala and Nairobi.

aspects which were dominant in PC1. It was noted that the physical conditions of biogas latrines reduced their performance, which is linked to the operations and maintenance activities. In this study, PCA indicates that biogas latrine performance increased with the number of users which is associated with feeding of the digester. The effect of skills of masons and volume of digesters was reflected in PC 5 and 6, respectively.

The first principal component (PC1) explained up to 20% of the variance of the analyzed data set (variables) and was characterized by high PCA loadings of variables under construction, operation and maintenance of the biogas latrines which were: use of standards in construction, training of users on O&M, maintenance of main valve and checking of leakages. The second principal component (PC2) that accounted for 15.6% of the variance, explained cumulatively 36% of the variance and was characterized by high PCA loadings for variables

Table 4. Principal component loadings and explained variance of six components with varimax normalized rotation.

Variable	Principal component					
	PC1	PC2	PC3	PC4	PC5	PC6
Motivation of owners/Users	-0.300	-0.136	0.343	0.744*	-0.131	0.237
Skills of masons	-0.124	0.047	0.067	0.156	0.910*	-0.035
Use of standards in construction	0.839*	0.294	0.109	-0.099	-0.097	-0.115
Digester volume	-0.266	0.122	0.105	0.133	0.075	0.813*
Physical conditions of biogas latrines	-0.015	-0.633*	-0.195	0.051	-0.152	0.589*
Users of biogas latrines	0.058	0.907*	-0.159	0.180	0.083	0.066
Training of users on O&M	0.794*	0.031	0.063	-0.152	-0.199	-0.225
Maintenance of main valve	0.601*	0.270	-0.213	-0.015	0.512*	0.349
Checking leakage	0.863*	-0.048	0.091	0.060	0.106	-0.075
Draining of condensate water	-0.028	0.358	0.862*	-0.240	0.098	0.102
Cleaning of overflow	0.149	-0.203	0.825*	0.133	-0.125	-0.108
Oiling of gas tap	0.479	0.375	-0.101	0.589*	0.140	-0.242
Cleaning of stove	-0.146	0.418	-0.625	-0.066	-0.442	-0.140
Burning hours/day	-0.051	0.187	-0.183	0.819*	0.280	0.107
Users' Satisfaction	0.410	0.629*	0.023	0.047	-0.059	0.119
Eigen value	3.1	2.3	2.1	1.8	1.5	1.4
Explained variance (%)	20.4	15.6	14.2	11.8	10.2	9.2
Cumulative variance (%)	20.4	36.0	50.2	61.9	72.1	81.4

The values with * are loadings that are significant in a principal component (>0.5).

of performance, construction, operation and maintenance which were: users' satisfaction, physical conditions of biogas latrines, and users of biogas latrines.

The third principal component (PC3) that accounted for 14.2% of the variance, explained cumulatively up to 50% of the variance of the analyzed data set and had high loadings for variables under operation and maintenance which were: draining of condensate water and cleaning of overflow. PC4 accounted for 11.8% of the variance, explained cumulatively up to 62% of the variance in the data set and was characterized by high loadings of variables for construction, operation, maintenance and performance which were: motivation of users, oiling of gas tap and number of burning hours/day. This was an important principal component in explaining the effect of some of the variables for construction, operation and maintenance (motivation of owners/users in installing biogas latrines and oiling of gas tap; O&M activity) on the performance of the biogas latrines (indicated by the number of burning hours of biogas in a day). PC 5 accounted for 10.2% of the variance, explained cumulatively 72% of the variance in the data set and had high loadings of variables for construction, operation and maintenance which were: skills of masons and maintenance of main valve. Lastly, PC 6 accounted for 9.2% of the variance, explained cumulatively 81% of the variance of the data set and exhibited high loads for variables under design and construction which were: digester volume and physical conditions of the biogas latrines.

DISCUSSION

Design of digesters of biogas latrines in this study focused on two variables; digester type and volume. The reason why all the digester types in both Kampala and Nairobi are fixed dome, could be attributed to the following: (a) they are easy to construct with locally available materials, (b) they are less costly, and (c) they are easy to insulate by constructing below ground as stated by (Santerre and Smith, 1982). Additionally, Nijaguna (2002) reported that fixed dome type digester is the most common digester design used in developing countries. Fixed dome digesters require high structural strength during construction coupled with high quality workmanship to make them gas tight (Bensah et al., 2011; Kishore et al., 1987; Nijaguna, 2002). The requirement of high quality workmanship to achieve gas tightness implies that for poor construction of fixed dome digesters in Kampala and Nairobi gas leakage would occur and hence reduced number of burning hours of the gas stoves.

The findings of this study showed that skills of masons responsible for construction of biogas latrines affected the performance of biogas latrines as the number of burning hours increased with increase in the skills of masons from non-skilled to the very skilled (1.5 to 3 h/day, respectively) (Figure 5). The use of standards during construction was undertaken in the majority of biogas latrines of Nairobi resulting in the number of burning hours/day being relatively higher (2.7) implying better performance. Schaart (2010) reported that using skilled masons to construct biogas plants requires that standards in construction be observed and hence performance of the biogas plants enhanced. This is comparable with our results (Figures 5) whereby increase in skills of masons and use of standards in construction resulted in increased number of burning hours per day.

The materials used for construction in Kampala and Nairobi were bricks and quarry stones respectively, which according to Datong (1989) and Jash and Basu (1999) are less costly to acquire and maintain compared to other materials. However, Rajendran et al. (2012) stated that use of non- elastic material like bricks or stones in construction of biogas digesters as it was the case in Kampala and Nairobi may result in gas escape through pores when pressure in the digester increases. This is however countered by a weak ring which according to Sasse (1991) prevents vertical cracks in the digester due to increase in gas pressure. The gas pressure also results into discharge of the slurry through the displacement chamber. The other disadvantage is that they also need more space compared to elastic construction materials of polyvinyl chloride (PVC), polyethylene, neoprene and rubber mainly used in plug flow digesters (Kalia, 1988).

Organizations or persons responsible for installation of the biogas latrines in Kampala and Nairobi were motivated by different factors to adopt the biogas latrine technology. These factors were social, health and environmental benefits. This study showed that in Kampala and Nairobi social and health benefits were the major factors considered respectively to have motivated the owners or users in installing the biogas latrines, one of the factors (health benefits) is related to public health and sanitation. According to Arthur (2011), adoption of biogas plants for communal use is primarily a result of a sanitation and public health benefits and production of biogas is secondary. However, in this study, the owners and users of biogas latrines also took into account other benefits (social) apart from those that were related to sanitation and public health (environmental and health benefits) (Table 2), where the use of biogas was considered prestigious (social benefit) and a major factor in installation of the biogas latrines. Although, our study suggests that motivation for using biogas latrines was due to health benefits, handling and use of human excreta and slurry have a disadvantage of human interaction with disease causing pathogens (total coliforms, *Escherichia coli,* helminths and protozoa) as the anaerobic digestion processes and retention times in the biogas latrines may not allow for complete inactivation of pathogens (Manser et al., 2015; Mehl et al., 2011). There is need therefore for further sanitization of slurry.

Adoption of biogas technology where the production of biogas through anaerobic digestion process is energy-efficient and environmentally beneficial was reported by Garfi et al. (2012) and Mwirigi et al. (2009) as a motivation in the uptake and sustainability of the technology. This is in agreement with our findings where users or owners of biogas latrines were also motivated by environmental benefits of the facilities in both Kampala and Nairobi. Hence, it can be stated that motivation of users/owners of biogas latrines by environmental, social and health benefits may have improved the uptake of the technology and therefore its performance. Indeed, results from PCA (Table 4) showed that motivation of users/owners in installation of the biogas latrines was significantly (PCA loading of 0.744) related to the number of biogas burning hours in day.

Feeding of the digester using human excreta was enhanced by introducing cow dung as co-substrate in all biogas latrines in Kampala with the number of burning hours increasing from 0.5 to 1.1. Co-digestion improves biogas yield due to improvement of nutrient balance and optimization of flow qualities (Ağdağ and Sponza, 2007; Mata-Alvarez et al., 2000). Additionally, Khalid et al. (2011) reported multiple benefits of co-digestion which are: facilitation of a stable and reliable anaerobic digestion performance and production of slurry of good quality plus an increase in biogas yield. However, the biogas latrines in Nairobi performed better than those in Kampala without co-digestion of human excreta and cow dung. This could be attributed to other factors influencing their performance other than co-digestion like carrying out frequent and regular operation and maintenance activities (Table 3). There is also a possibility that co-digestion of human excreta and cow dung in the biogas latrines of Nairobi could lead to increased biogas production.

The frequency of operational and maintenance activities in biogas latrines of Kampala and Nairobi was done mainly on need basis, this meant that not until problems were evident, the operators or users of the biogas latrines had limited knowledge of what could have been going wrong. PCA (Table 4) revealed that one of the operation and maintenance activity; oiling of gas tap was significantly (PCA loading of 0.589) related to the number of biogas burning hours in a day. According to Day et al. (1990) and Ghimire (2005), frequent maintenance of biogas plants ensures that there is improved performance of biogas production. The causes of failure of biogas plants as reported by Bhat et al. (2001) are technology and skill related. Limited knowledge or skills on operation techniques and maintenance by users and those managing biogas latrines affected their performance negatively. Biogas leakage due to damage of biogas pipelines and improper maintenance of the biogas latrines may be a potential source of greenhouse gas emissions, hence contributing to global warming and climate change (Yu et al., 2008). On the other hand with properly maintained biogas latrines, greenhouse gases such as methane will be well controlled (Jicong et al., 2006).

Training of users on operation and maintenance aspects of the biogas latrines had an effect on their performance. There was increase in the number of burning hours in a day of gas stoves of biogas latrines with increase in training from none at all to comprehensive. With comprehensive training of users our results showed that the biogas latrines produced a higher number of burning hours in a day (2.5) than those whose users were subjected to no training (1.3) (Figure 7). This case is in line with observations made by Ghimire (2005) who reported that training of users and follow up services, thereafter, is one of the factors that contributes to failure or success of biogas plants.

Conclusions

This study assessed the effect of design, construction, operation and maintenance on performance of biogas latrines in Kampala and Nairobi and the following key conclusions can be drawn.

(1) Some variables of parameters of design, construction, operation and maintenance affected performance of the biogas latrines indicated by the number of biogas burning hours in a day. These variables were digester volumes, skills of masons, use of standards in construction, motivation of users/owners in installation of biogas latrines, training of users on O&M aspects, use of co-substrates, O&M activity-oiling of gas tap, number of users and physical conditions of the biogas latrines.

(2) Biogas latrines, which were constructed following building standards achieved good performance. Furthermore, there was incremental performance of biogas latrines with increase in skills of masons from non-skilled to very skilled.

(3) High scale (comprehensive) training of users on the O&M aspects gave corresponding increase in performance of the biogas latrines.

(4) The use of cow dung as co-substrate to human excreta increased the performance of the biogas latrines in Kampala and when cow dung was absent, biogas production was not sustained. The non-application of cow dung in the biogas latrines in Nairobi did not result into biogas shortages.

Conflict of interests

The authors have not declared any conflict of interest.

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REFERENCES

Ağdağ ON, Sponza DT (2007). Co-digestion of mixed industrial sludge with municipal solid wastes in anaerobic simulated landfilling bioreactors. J. Hazard. Mater. 140(1):75-85.

Arthur R, Baidoo MF, Antwi E (2011). Biogas as a potential renewable energy source: A Ghanaian case study. Renew. Energy 36(5):1510-1516.

Bartlett S (2003). Water, sanitation and urban children: the need to go beyond “improved” provision. Environ. Urban. 1 (2):57-70.

Bensah EC, Mensah M, Antwi E (2011). Status and prospects for household biogas plants in Ghana–lessons, barriers, potential, and way forward. Int. J. Energy Environ. 2(5):887-898.

Bensah EJ, Antwi E, Ahiekpor (2010). Improving Sanitation in Ghana-Role of Sanitary Biogas Plants. J. Eng. Appl. Sci. 5(2):125-133.

Bhat P, Chanakya H, Ravindranath N (2001). Biogas plant dissemination: success story of Sirsi, India. Energy Sustain. Dev. 5(1):39-46.

Buttenheim AM (2008). The sanitation environment in urban slums: implications for child health. Popul. Environ. 30(1-2):26-47.

Buxton D (2010). Disposal of latrine waste: Is biogas the answer? A review of literature. In. Loughborough University, Leicestershire, UK.

Datong Z (1989) An analysis of domestic biogas storage installations in China. Biomass 20(1):61-67.

Day DL, Chen TH, Anderson JC, Steinberg MP (1990). Biogas plants for small farms in Kenya. Biomass 21(2):83-99.

Deublein D, Steinhauser A (2010). Front Matter. Biogas from Waste and Renewable Resources: An Introduction, Second Edition:I-XXVIII.

Eamens G, Waldron A, Nicholls P (2006). Survival of pathogenic and indicator bacteria in biosolids applied to agricultural land. Soil Res. 44(7):647-659.

Estoppey N (2010). Evaluation of small-scale biogas systems for the treatment of faeces and kitchen waste. Eawag-SANDEC publications.

Garfi M, Ferrer-Marti L, Velo E, Ferrer I (2012). Evaluating benefits of low-cost household digesters for rural Andean communities. Renew. Sustain. Energy Rev. 16(1):575-581.

Genser B , Strina A, dos Santos LA, Teles CA, Prado MS, Cairncross S, Barreto ML (2008). Impact of a city-wide sanitation intervention in a large urban centre on social, environmental and behavioural determinants of childhood diarrhoea: analysis of two cohort studies. Int. J. Epidemiol. 37(4):831-840.

Ghimire P (2005). Technical study of Biogas plants in Bangladesh. In, IDCOL/SNV, Dhaka.

Ghimire PC (2013). SNV supported domestic biogas programmes in Asia and Africa. Renew. Energy 49:90-94.

Hanchett S, Akhter S, Khan MH, Mezulianik S, Blagbrough V (2003). Water, sanitation and hygiene in Bangladeshi slums: an evaluation of the WaterAid–Bangladesh urban programme. Environ. Urban. 15(2):43-56.

Jash T, Basu S (1999). Development of a mini-biogas digester for lighting in India. Energy 24(5):409-411.

Jicong H, Yanhua X, Fengde W, Renjie D (2006). Greenhouse gas emissions from livestock waste: China evaluation. In, International Congress Series. Elsevier. pp. 29-32.

Kaiser HF (1960). The application of electronic computers to factor analysis. Educ. Psychol. Meas. 20:141-151.

Kalia AK (1988). Development and evaluation of a fixed dome plug flow anaerobic digester. Biomass 16(4):225-235.

Khalid A, Arshad M, Anjum M, Mahmood T, Dawson L (2011). The anaerobic digestion of solid organic waste. Waste Manage. 31(8):1737-1744.

Kishore V, Raman P, Rao VR (1987). Fixed dome biogas plants. A design, construction and operation manual. Fixed dome biogas

plants. A design, construction and operation manual.
Kithandi RM (2014). Utilisation and Sustainability of Bio-centres in Kibera Slums, Nairobi County. Msc Thesis Unpublished MSc Thesis, Kenyatta.
KNBS (2013). Statistical Abstract In. Kenya National Bureau of Statisitcs, Nairobi, Kenya.
Kulabako RN, Nalubega M, Wozei E, Thunvik R (2010). Environmental health practices, constraints and possible interventions in peri-urban settlements in developing countries–a review of Kampala, Uganda. Int. J. Environ. Health Res. 20(4):231-257.
Letema S, Van Vliet B, Van Lier J (2012). Innovations in sanitation for sustainable urban growth; modernized mixtures in an east african context. In, On the water front: selections from the 2011 world water week in Stockholm, Stockholm, Sweden. 3:1-6. Lutaaya F (2013). Quality and Usage of Biogas Digesters in Uganda. unpublished MSc Thesis Unpublished MSc Thesis, Royal Institute of Technology.
Manser ND, Wald I, Ergas SJ, Izurieta R, Mihelcic JR (2015). Assessing the fate of Ascaris suum ova during mesophilic anaerobic digestion. Environ. Sci. Technol. 49(5):3128-3135.
Mata-Alvarez J, Mace S, Llabres P (2000). Anaerobic digestion of organic solid wastes. An overview of research achievements and perspectives. Bioresour. Technol. 74(1):3-16.
Mehl J, Kaiser J, Hurtado D, Gibson DA, Izurieta R, Mihelcic JR (2011). Pathogen destruction and solids decomposition in composting latrines: study of fundamental mechanisms and user operation in rural Panama. J. Water Health 9(1):187-199.
Mwakaje AG (2008). Dairy farming and biogas use in Rungwe district, South-west Tanzania: A study of opportunities and constraints. Renew. Sustain. Energy Rev. 12(8):2240-2252.
Mwirigi JW, Makenzi PM, Ochola WO (2009). Socio-economic constraints to adoption and sustainability of biogas technology by farmers in Nakuru Districts, Kenya. Energy Sustain. Dev. 13(2):106-115.
Nijaguna B (2002). Biogas technology. New Age International, New Delhi, India.
Omer AM, Fadalla Y (2003). Biogas energy technology in Sudan. Renew. Energy 28(3):499-507.
Otiso KM (2003). State, voluntary and private sector partnerships for slum upgrading and basic service delivery in Nairobi City, Kenya. Cities 20(4):221-229.
Parawira W (2009). Biogas technology in sub-Saharan Africa: status, prospects and constraints. Rev. Environ. Sci. Biotechnol. 8(2):187-200.
Rajendran K, Aslanzadeh S, Taherzadeh MJ (2012). Household biogas digesters - A Review. Energies 5(8):2911-2942.
Reis RB, Ribeiro GS, Felzemburgh RD, Santana FS, Mohr S, Melendez AX, Queiroz A, Santos AC, Ravines RR, Tassinari WS (2008). Impact of environment and social gradient on Leptospira infection in urban slums. PLoS Neglected Trop. Dis. 2(4):e228.
Ruhiu J, Ogendo M, Kamundi E, Kaseve C, Owuocha K, Mbachia S (2009). Strategic guidelines for improving water and sanitation services in Nairobi's informal settlements. In., Nairobi, Kenya.
Santerre MT, Smith KR (1982). Measures of appropriateness: the resource requirements of anaerobic digestion (biogas) systems. World Dev. 10(3):239-261.
Sasse L, Kellner C, Kimaro A (1991). Improved biogas unit for developing countries. In, Deutsche Gesellschaft fur Technische Zusammenarbeit (GTZ) GmbH, Vieweg & Sohn Verlagsgesellschaft Braunschweig.
Schaart IG (2010). Mason and Enterprise Development under the Biogas Program in Vietnam. In., Hanoi, Vietnam.
Schouten M, Mathenge R (2010). Communal sanitation alternatives for slums: A case study of Kibera, Kenya. Phys. Chem. Earth Parts A/B/C 35(13):815-822.
UBOS (2014). National Population and Housing Census Provisional Results. In. Uganda Bureau of Statistics, Kampala, Uganda.
Umande (2014). Engendering Positive Change in Slums-Role of Biocentres in the Supply of Affordable and Sustainable Water and Sanitation Services in Informal Settlements. In. Umande Trust, Nairobi, Kenya.
WHO (2006) Guidelines for the Safe Use of Wastewater, Excreta and Grey Water. World Health Organization Press, Geneva, Switzerland.
Yu L, Yaoqiu K, Ningsheng H, Zhifeng W, Lianzhong X (2008). Popularizing household-scale biogas digesters for rural sustainable energy development and greenhouse gas mitigation. Renew. Energy 33(9):2027-2035.