Ensuring Appropriateness of Biogas Sanitation Systems for Prisons - Analysis from Rwanda, Nepal and the Philippines

Martin Gauthier[1], Alain Oppliger[2], **Christian Lohri[3]**, Christian Zurbrügg[4]

[1,2] International Committee of the Red Cross, Geneva, Switzerland
[3,4] Eawag: Swiss Federal Institute of Aquatic Science and Technology, Dübendorf, Switzerland

Presenting author's email address: christian.lohri@eawag.ch
Abstract Record Number: 292
Presentation Theme: Theme 1

Keywords: Anaerobic digestion, prison sanitation, institutional waste management, biogas

Brief biography of presenting author: Christian Lohri has a background in Environmental Sciences and is working at Eawag in the department Sandec (Water and Sanitation in Developing Countries). His main research focus is on organic waste treatment in urban areas of developing countries. He has been involved in anaerobic digestion projects on household, institutional and municipal scale in Tanzania, Ghana, Nepal and Ethiopia.

Abstract
Biogas sanitation systems are seen as a promising technology for institutional settings of developing countries as they combine effective treatment of human excreta and kitchen waste, while at the same time generating a renewable fuel source for cooking and a nutrient-rich fertilizer. The Water and Habitat Unit of the International Committee of the Red Cross (ICRC) has been involved in the realization of biogas systems in prisons for the last 10 years to improve the poor sanitary conditions in detention facilities. In partnership with local organisations, ICRC has replaced the undersized and deteriorating septic tank systems in prisons of Rwanda, Nepal and the Philippines with fixed-dome biogas systems. After at least one year of operation, the 13 implemented systems were assessed in terms of their technical performance, economic viability, environmental impacts and social acceptance. For this purpose, on-site investigations were conducted (observations, interviews, measurement of gas production and composition, and analysis of process stability, reduction of organic load and pathogen content). 11 systems were in operation at the time of evaluation and displayed satisfactory process parameters with daily biogas production ranging between 26L/person and 62 L/person (obtained in prisons where kitchen waste was added to the digester). The vast majority of detainees perceived the biogas systems positively, mainly because it provides a smoke-free source of cooking fuel that contributes to money saving, and because it improved the hygienic conditions in and around the prison.
This paper synthesises the experiences from Rwanda, Nepal and the Philippines by grouping them into technical, operation & maintenance, economic, environmental and socio-cultural aspects. Based on these results, it highlights important issues such as criteria for site selection, dimensioning of digester, stakeholder's responsibilities, and health risks and mitigation measures, which all need to be considered in order to ensure the appropriateness of biogas sanitation systems as sustainable solution for prisons in developing countries.

1. Introduction and purpose

More than 2.6 billion people worldwide do not have access to basic sanitation. The poorest and most vulnerable fraction of the world's population is mostly affected by this dramatic situation, which severely threatens health wellbeing and livelihoods. Prisoners are among the most discriminated groups, often suffering from detrimental sanitary conditions. The International Committee of the Red Cross (ICRC) visits people deprived of freedom in numerous countries and assists prison authorities in their efforts to improve conditions of detention among which sanitation is one element. Within this scope of activities, the Water and Habitat Unit of ICRC has been involved in the realization of biogas systems in prisons of Rwanda, Nepal and the Philippines for the past ten years. Such biogas projects have been realized in partnership with local expertise and technical institutes[1]. Main reason was to substitute the undersized and deteriorating septic tanks with biogas systems and hereby improve the sanitary conditions, reduce the health risks of the detainees and provide a renewable and smoke-free source of cooking fuel.

This paper aims at identifying the key questions to address so that biogas systems are appropriate technologies for the prison context of developing countries from a sustainable development perspective. It relies on results from different field studies conducted by ICRC and partner organisation, which assessed the technical performance, economic viability, environmental impacts and social acceptance of the implemented systems after

[1] Partners included KIST and EREP (2009, Rwanda), BSP-N and Eawag/Sandec (2009, Nepal), Practical Action Consulting (2011, Philippines).

at least one year of operation. Key lessons, best practices and recommendations in terms of performance, impacts and acceptance of the biogas systems are highlighted.

2. Design and Methods

The main findings are derived from three studies conducted between 2009 and 2011, which involved on-field investigations on 13 biogas systems in 11 prisons of Rwanda (Muhanga, Gikongoro, Cyangugu), Nepal (Kaski, Chitwan, Kanchanpur) and the Philippines (Cagayan de Oro, Davao, Sultan Kuradat, Manila, Cradle). The results are synthetized by using a conceptual framework that groups the various issues according to the different sustainability aspects: Technical, operation & maintenance, economic, environmental and socio-cultural aspects. The methods used to assess these various issues are:

- Observations of the state of the biogas systems (functionality of complete system including inlet, digester, gas utilization devices, outlet) and operational procedures (handling and use of waste, water, gas and effluent, hygiene, and allocation of responsibilities).
- On-site measurements such as
    - Daily gas production and biogas composition (CH_4, CO_2 and rest gases)
    - Analysis of process stability and physico-chemical characterization of in- and outflow (pH, temperature, Redox potential, electrical conductivity, COD, NH_4-N, P)
    - Measurement of pathogen contamination of digested effluent (E.Coli as indicator).
- Sampling and laboratory analysis of TS/TSS, VS and helminth egg count
- Semi-structured interviews with a wide range of stakeholders at each prison site (prison staff, detainees, surrounding population, authorities, ICRC Water and Habitat staff) to find out
    - Acceptance and perceived impacts (incl. benefits and burdens) of the biogas systems in comparison with previous septic tank systems
    - Investment, operational and maintenance costs
    - Fuel or wood savings by using biogas for cooking

3. Results & Discussion

3.1 Technical aspects

3.1.1 General

Table 1 provides an overview of all 13 biogas systems studied. Results show that the anaerobic digestion (AD) systems in operation all have satisfactory process stability, i.e. favourable conditions for AD are prevailing: The range of pH (7.1-8.4), digester temperature (mesophilic range 22.2-36°C) and negative Redox potential all indicate a suitable environment for AD. The comparison of the hydraulic retention time needs to be interpreted with caution as calculations were not done in a coherent way. In Rwanda the total digester volume was used for the calculation (a) while, in Nepal only the active slurry volume in the digester was considered (b) and in the Philippines the combined volume of digester & compensation chamber (c) was used for calculation. Considering this, the HRT results of the Philippines are strikingly low, which means that either the daily inserted waste quantity (incl. flush water) is much higher than planned or that the plant is simply under-dimensioned. Such low HRT results in a low hygenization and methanization rate of organic matter and should thus be avoided.

Table 1: Overview of evaluated biogas sanitation systems in prisons (types, sizes, basic indicators for process stability)

	Location	*Number of detainees*	*Persons connected to biogas toilets*	*Type*	*Digester size [m^3]*	*Start of oper-ation*	*Oper ation ality*	*pH*	*Temp. [°C]*	*Redox Pot. [mV]*	*HRT [days]*
RW[1]	Muhanga	7604	n.a.	Serial UG[4] domes	500 (5*100)	2005	**Yes**	8.1	22.2	- 41	n.a.
	Gikongoro	3385	2600	Serial UG domes	300 (3*100)	2007	**Yes**	7.9	24.6	- 42	38
	Cyangugu	3499	2500	Serial UG domes	400 (4*100)	2002	**Yes**	8.4	22.5	- 64	49
NP[2]	Kaski	65	65	UG dome	10	2008	**Yes**	7.2	26.4	- 372	23.1
		135	135	UG dome	12	2008	**Yes**	7.1	25.6	- 401	20.4
	Chitwan	115	115	UG dome	10	2008	**Yes**	7.1	29.8	- 389	13.3
		155	155	UG dome	35	2008	**Yes**	7.4	28.8	- 391	31.6
	Kanchanpur	106	106	UG dome	10	2008	**Yes**	7.2	30	- 402	14.5
PH[3]	Cagayan de Oro	1112	800	Tunnel	25	2009	**Yes**	7-8	36	- 100	14.6
	Davao	1142	369	Tunnel	10	2008	**Yes**	7.5	35.5	- 64	12.7
	Sultan Kuradat	270	360	Tunnel	10	2009	**Yes**	7-8	36.5	- 80	17.4
	Manila	519	519	AG[5] dome	24	2007	**No**	n.a.	n.a.	n.a.	22.8
	Cradle	220	240	Tunnel	12	2008	**No**	n.a.	n.a.	n.a.	22.4

[1]RW: Rwanda; [2]NP: Nepal; [3]PH: Philippines; [4]UG: underground; [5]AG: above ground

3.1.2 Inputs

The studies revealed that the total amount of human waste input from sanitation facilities in the prisons can be anticipated in the range of 3.3 to 4.9 L/pers./day (human faeces per adult person and day between 0.25 and 0.4 kg and between 1 and 1.5 L of urine per person plus 2-3 L/pers./day water used for anal cleansing and flushing). This is the amount per person that flows into the biogas reactor. Generally it is advised to ensure that the digester is fed regularly with a homogeneous substrate input in terms of quantity and quality. Changes in quantities can hardly be prevented (see 3.1.3 for technical solutions to adapt to changes in input quantity). Due to the uniformity of daily diet observed in all prisons, relevant changes in excreta quality are not likely to occur. Kitchen waste (such as vegetable and fruit peelings, residuals in cooking pots, food leftovers) is a highly suitable additional feedstock and leads to considerable increase of biogas production (discussed in 3.1.4 & 3.3).

3.1.3 AD technology, design and site selection

External heating of the digester is hardly ever an option due to an unfavourable institutional setting as well as an unfavourable energy balance and associated financial issues. Suitable average local temperature is thus crucial and should not go below 15°C, as this would slow down microbial activity too much. When deciding about the site for the digester, the criteria should include suitable ground conditions for construction work, possibly an unshaded location as close as possible to the toilets and kitchen to minimize pipe lengths. In addition, the site needs to be inspected beforehand during rainy season to identify potential areas of stagnant water and to ensure sufficient gradient to enable discharge of the effluent by gravity. Fixed dome underground digesters which have been adapted to local circumstances, (e.g. the stone or brick masonry model GGC2047 for Nepal, see Figure 1) are considered to be most suitable for the prison context in developing countries as the technology is well known and widespread, cost-effective, and the required components locally available. Depending on the availability of materials, digester walls can either be built with bricks, stones or concrete hollow blocks instead of using concrete. Figure 1 presents a schematic overview of a fixed dome underground digester with its relevant components.

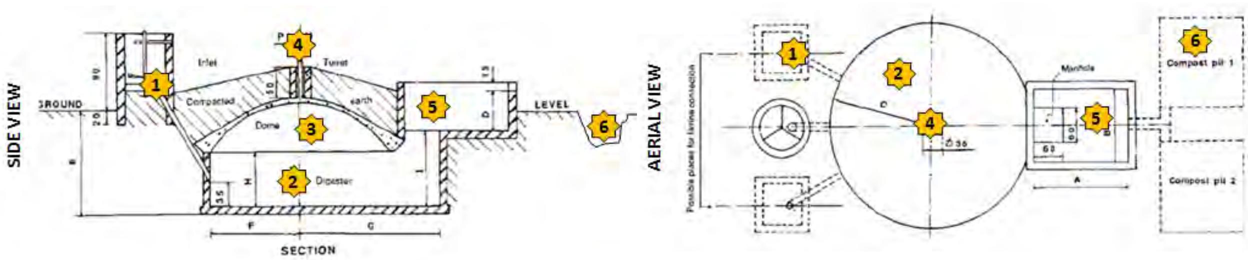


Figure 1: Side view and aerial view of typical fixed dome underground digester (GGC2047); 1: Inlet chamber with inlet pipe, 2: Digester, 3: Dome (gas storage), 4: Gas outlet, 5: Compensation chamber with overflow point, 6: Storage/compost pit

Major technical problems of the evaluated systems included insufficient slope (less than 5%) of the inlet pipe which led to frequent blockage (Chitwan 10 m^3, Chitwan 35 m^3) or which made operation impossible (Manila 24 m^3). Absence of downward gradient between compensation chamber and storage pits resulted in a backflow of rainwater into the digester, thereby diluting the active slurry content (Kaski 10 m^3). Lack of water condensation traps (all systems in the Philippines) also leads to blockage of gas pipes. The reasons of failure in the biogas reactor called Cradle (12m^3) was attributed to irregular feeding, and lack of operation and maintenance. Underlying causes for this is the lack of a proper transfer of technical knowledge and skills during the change of personnel responsible for operation. Furthermore, the reluctance of specific personnel to take charge in the operation was mentioned as additional reason for failure.

A rule of thumb for digester volume calculation is 100 L of digester volume required per person, (e.g. a prison with 200 detainees needs a 20 m^3 digester). This is based on the estimation that 3.3 L/pers. of diluted substrate (faeces, urine, flush water) is added and a Hydraulic Retention Time (HRT) of 30 days is envisaged. The design of fixed dome underground digesters normally considers gas storage volume to be 25-30% of the total digester volume and the volume of the compensation chambers between 55 and 60% of the dome volume. Digesters should not exceed a total volume of 100 m^3 else static reasons demand expensive structural reinforcements.

Figure 2: 100 m^3 digesters in series (Rwanda; Mottet, 2009)

Construction of multiple digesters in series as observed in Rwanda (Figure 2) is preferable to one single larger digester. On one hand, it facilitates maintenance work (e.g. internal re-coating with acrylic emulsion paint) as the digester under repair can be by-passed); on the other hand it is considered as an appropriate method to compensate for fluctuation in number of detainees (and the corresponding change in substrate quantity). The total volume of the digesters built in series needs to be appropriate for treatment of all the waste when the prison is occupied to its maximum. If the number in detainees declines, this does not affect the performance as the HRT increases, leading to better degradation of organic material and better hygenization of the feedstock.

Figure 3: Internal baffle wall (KfW, 2009)

For prisons with a single digester (capacity of 500 detainees and less), the inclusion of an internal baffle wall in the digester (Figure 3) or the 'non-straight' line layout of digester and compensation chamber is an option to increase the Solid Retention Time (SRT) without increasing the size of the digester (thus not increasing construction costs). Gas tightness of the dome is imperative and can be ensured by applying layers of acrylic emulsion paint. No concluding statements can be given regarding lifespan of the system as all evaluated biogas plants were relatively new: literature findings (KfW, 2009) indicate a digester lifespan of 20 years, piping lifetime of 7 years and the renewal of acrylic emulsion paint inside the dome every 4-6 years.

It is advantageous to use a standardized design (digester models, diameter of pipes) for all biogas systems in one country as it simplifies knowledge transfer, provision of training and uniformity of spare parts needed. Reinforcement rods constitute a considerable element of expenditure, thus should only be installed where necessary (slabs of compensation chambers, possibly in large domes, but not in walls, inlet and outlet chambers). The outlet gas pipe needs to be properly fixed in a turret. In colder climates, sufficient soil backfilling on top of the digester is important (e.g. recommended minimal depth underground on top of the reactor in Nepal is 40 cm) not only to ensure protection of the dome, but also to reach adequate counter-pressure and to minimize the temperature change between seasons and day/night, which is preferred for consistent microbial activity. In year-round warm climates (e.g. in the Philippines) a dome that is exposed to sunlight is considered beneficial as it helps increase the temperature of the digester, thus promoting gas production.

The gas pipes need to be installed as direct as possible, avoiding unnecessary elbows as this leads to reduction of gas pressure. It is absolutely essential to install condensation traps at the lowest points of the gas pipe. Vapour, a natural component of biogas, condenses in the pipe and eventually leads to blockage of the pipeline so that the gas does not reach the kitchen anymore. Regular emptying of these water traps is crucial (see 3.2.1).

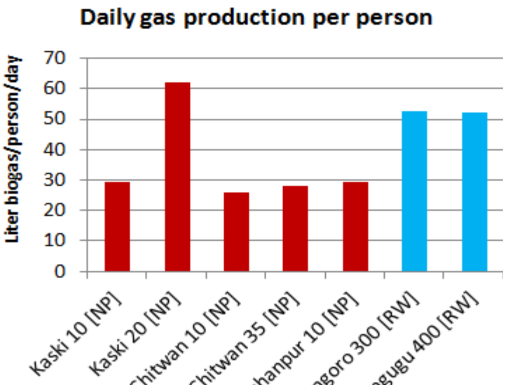
Regarding biogas stoves, the following points need to be taken into account: The approximate average biogas consumption rate per (household-sized) stove is 400 L/h. If LPG stoves are used, modifications are required to ensure proper burning. For this purpose, the nozzle hole needs to be enlarged to 3 mm diameter as methane has larger particles than LPG, explaining the need for a larger opening to attain the needed volume flow. The burner holes need to be enlarged to 4 mm diameter. The air intake ports needs to be provided with a regulating flap behind the nozzle to balance the needed volume for proper burning of the gas.

As hydrogen sulphide (H_2S), a natural component of biogas, is extremely reactive with most metals, kitchen equipment such as stoves and stovepipes are prone to corrosion. It is therefore advised to install a H_2S trap (Mottet, 2009): Two columns (one for desulphurization, one for regeneration) filled with iron oxide for absorption of H_2S; the H_2S reacts with the iron oxide to form iron sulphide and water. Addition of sufficient air converts the iron sulphide back to the oxide and leads to precipitation of elemental sulphur.

3.1.4 Outputs

The reduction of Chemical Oxygen Demand (COD) serves as an indication of the digester performance and can be calculated by comparing the COD of the input with that of the effluent. The larger the reduction, the more organic matter have been degraded and transformed into biogas. With the exemption of the Davao system, where most likely a mistake in sampling or analysis occurred, the COD reduction in all reactors in Nepal and the Philippines show very satisfactory ranges between 89.6 and 98.4%. The study in Rwanda compared the COD content of the effluent after digestion to the same effluent after post-treatment in the septic tanks.

The daily gas production per person was measured in the prisons of Nepal and partly in Rwanda. It ranges from 25.9 L/person/day (Chitwan 10 m^3) to 61.9 L/person/day (Kaski 20 m3) (see Figure 4). The large variations can be explained by the fact that in some reactors kitchen waste was also added, which considerably increases the gas yield. The measurements of the methane (CH_4) fraction in biogas revealed results between 57% (Kaski 20m^3) and 78% (Figure 5). The low CH_4 content in Kaski can also be explained by kitchen waste feedstock (rich in carbohydrates), which substantially increases the gas production while at the same time lowering the methane content, as kitchen waste releases high quantities of CO_2. The average CH_4 content in all evaluated operational systems is 70%.



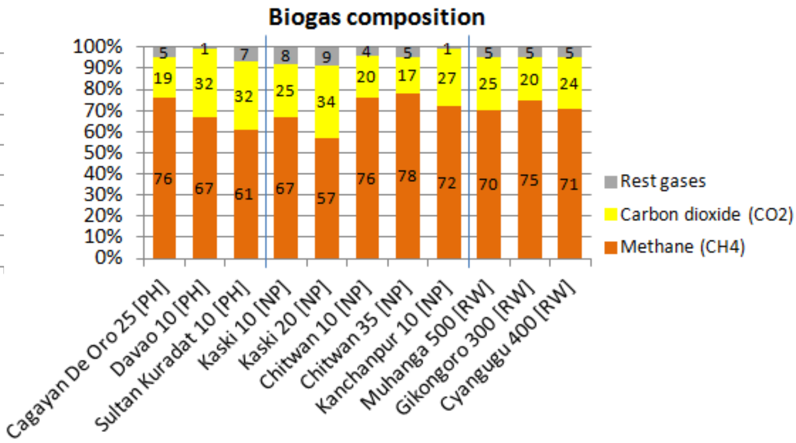


Figure 4: Comparison of daily biogas production per person

Figure 5: Comparison of biogas composition in AD systems of Philippines [PH], Nepal [NP] and Rwanda [RW]

The World Health Organization (WHO) lists two indicator organism for safe agricultural use of greywater, excreta and faecal sludge (WHO, 2006): E.Coli and helminth eggs. The quality of the effluent directly after the anaerobic digestion process was found not to be acceptable for restricted irrigation (crops that are not eaten raw) as particularly helminth eggs were not eliminated during the anaerobic digestion process. An adequate form of post-treatment is therefore required. Apart from using the old septic tanks for settlement of solids and therefore also partial elimination of pathogens, the reports advise an additional composting step (mix of effluent with fresh agricultural waste) or a soak-pit/drying bed (as practiced in Rwanda) as pathogens normally cannot survive in a dry environment. However, as helminth eggs are very resistant, this method first needs to be tested, properly analysed and proven. In any case, it has to be emphasized to only apply the effluent to products that are not eaten raw or are surrounded by peeling (e.g. banana).
On this aspect, the biogas systems in Rwanda are considered as example of best practice and, if space availability does not constitute a problem, can be seen as a model for replication. First of all, the digester installation in series leads to a higher HRT with a consequential higher reduction of pathogens (HRT 30-40 days; 0.5 log units). The digested effluent is further directed into the previously used septic tanks where sedimentation of remaining organic matter, helminth eggs and parasites takes place (SRT 15 years; maximum pathogen reduction). From there, the post-treated effluent flows in mud canals to a soak-away pit where liquid infiltrates into the soil (HRT some days, weak pathogen reduction) and the remaining organic matter accumulates, dries out and can finally be used as organic fertilizer. In Rwandese prisons, the organic manure is entrenched between banana trees or added as fertilizing mix to pepper seedlings (Figure 6).

Figure 6: Post-treatment in Rwanda: Septic tanks; canal for post-treated effluent; soak-away pits and dried residuals; entrenched manure in banana field; use of manure for pepper breeding (left to right; Mottet, 2009)

It is important to note that the digested effluent needs to be diluted with water before application on the plants to reduce the osmotic pressure (high salt content measured as electrical conductivity), and to dilute the high nitrogen content. This Rwandese method of post-treatment in septic tanks not only results in additional reduction of pathogens, but also to further COD reduction between 55 and 89% compared to the digested effluent.
Another option is to mix the digested effluent with raw material (e.g. agricultural waste) in covered compost pits. In the resulting exothermic aerobic digestion process, high temperatures (70°C) are generated that lead to elimination of remaining pathogens. However, this option requires more regular working efforts (turning of compost) as it has to be ensured that sufficient oxygen reaches the organic matter to be composted.

3.2 Operation & Maintenance

3.2.1 Stakeholders' responsibilities

Prior to the construction of a biogas system, a set of relevant points need to be discussed and agreed upon with the prison authority and the detainees. By means of user trainings/workshops, the detainees have to be informed about the biogas system, including:

- Water for anal cleansing & flushing toilets: Regulation of maximum quantity of water used per flush (3L).
- Use of detergents: No chlorinated substances but only easily biodegradable detergents should be used for toilet cleaning to avoid inhibition of the anaerobic digestion process. If chlorinated products must be used for the general disinfection of the toilet area (floors, walls, etc.), in case of epidemics for example, it should be avoided that the cleaning liquids enter the toilet opening and reach the AD to avoid inhibition of the anaerobic digestion process.
- Management of greywater: Greywater from washing hands, food, clothes and dishware as well as from showering is not a suitable feedstock for AD systems as it is highly diluted, i.e. low organic content leads only to minimal increase of biogas generation while requiring a large digester size to ensure sufficient HRT.
- Kitchen waste: Importance of adding kitchen waste to the digester (to increase gas production and to meet design requirements). Be aware of existing kitchen waste handling and 'competitors' (e.g. pig farmers in the vicinity who pick up kitchen waste and possibly pay for it)
- Particle size of kitchen waste: The size of particles needs to be reduced (as a general rule: pieces of max.5 cm, but this needs to be seen in correspondence to diameter of inlet pipe) before feeding kitchen waste into the digester in order to prevent blockage and to facilitate microbial biodegradation.
- Blockages: Counter-measures in case of blockages (mixing with water, stirring, de-blocking with long tube)
- Gas consumption: Necessity of total gas consumption produced every day to prevent overpressure with consequential methane slips through compensation chamber (GHG emission) or slurry overflow
- Expectations: It is important that the prison authorities and detainees have realistic ideas about what can be expected from the biogas system (it needs to be explained that biogas will only substitute a certain amount of previously used cooking fuel and the amount can be influenced by following the agreements such as kitchen waste feeding, minimized water flushing etc.). Additional changes/benefits will be a reduction in cooking time (e.g. 25-33% in Rwanda) compared to use of fire wood, less pot cleaning due to less soot, and absence of smoke.
- Biogas flame: Adjustment of nozzle and burner holes, regular cleaning of stoves is required
- User committee for O&M: A user committee needs to be appointed which is responsible for smooth operation (e.g. ensuring that all gas is consumed by using it between meal-preparing times for water cooking, bread baking or simply burning it) and maintenance (the reasons behind regular check-ups need to be explained, e.g. that gas leakages in the kitchen threatens the health of kitchen staff; instructions for basic repair work).
- Maintenance toolkit: A set of spare parts with tools has to be provided. It has to be pointed out that even relatively small problems (e.g. forgotten condensed water drainage, leakage of biogas in kitchen or blockage of inlet pipe) can lead to adverse consequences such as risk to human health (biogas leakage in kitchen), overflowing toilets with cumbersome repair work or even to a system standstill (blockage of inlet pipe).
- Incentives: The incentives (money, better conditions, kind) of the persons with assigned tasks (e.g. kitchen waste feeding, emptying of water traps, cleaning of stoves, leakage checks etc.) needs to be jointly negotiated and a controlling body has to be appointed which is responsible to check if tasks have been properly conducted.
- Continuity of AD knowledge and skill: It is crucial that the number of members in the O&M group remains constant. This will prevent loss of knowledge and skills when AD-competent detainees are released.
- Transfer of well-informed and powerful personnel: The frequent transfer of jail personnel also implies a risk that relevant knowledge is lost. Often even more critical is the departure of the 'head of detainees' (the person within the detention area with highest power). It was observed that the functionality of the AD system often correlated with the personal motivation and involvement of this person. In case of succession, significant attention needs to be dedicated to transfer the required knowledge and organizational understanding to ensure continued smooth AD operation.
- Effluent handling: The associated risks with effluent handling needs to be mentioned and methods shown to minimize health hazards. Protection clothes such as rubber gloves and boots should be worn and persons with open wounds should not be allowed to handle effluent. Directives need to be given that thorough hand washing with soap is required after every activity involving effluent touching.
- Application of effluent/digestate: Proper application of digestate needs training (e.g. post-composting, entrenchment of manure, dilution of effluent).

3.2.2 Health risks and mitigation measures

If a biogas system is properly designed, constructed, operated and maintained, the risks to human health can be kept within reasonable limits.

Although from a technical and economic point of view, reduced flushing water inflow is desirable (higher HRT, smaller dimensioning of digester i.e. lower costs), it needs to be in balance with the demand for sound hygiene. A compromise has to be found to avoid excessive water use and to still keep up the level of hygiene required to avoid transmission of diseases.
The compensation chambers need to be covered with reinforced slabs (detainees were reported to have fallen inside the chambers (EREP, 2004). Furthermore, gas leakage has to be avoided, especially in areas of human activity (e.g. kitchen). To minimize the risk of leaks, exposed gas pipes (prone to stumble over) need to be properly covered and vulnerable plastic pipes in the kitchen (connected to the stoves) should be protected from mechanical and thermal damages. As hydrogen sulphide (H_2S) is a highly toxic and flammable gas that is heavier than air, it tends to accumulate at the bottom of poorly ventilated spaces. However, due to its smell (similar to rotten eggs), it helps to detect leakages (methane and carbon dioxide are both odourless). Still, if the kitchen environment cannot be properly ventilated, the installation of a H_2S-trap as recommended by Mottet (2009) is advisable. Another safety device recommended is the installation of a simple gravel filter in the gas pipe to prevent back-flow of the flame (EREP, 2004). There is a theoretical risk of explosion if 6-12% of CH_4 is mixed with air (Deublein & Steinhauser, 2011). The knowledge of the detainees regarding AD and in particular the potential misuse of biogas as explosive device is considered a minor risk.
When manually desludging the digester, a prior ventilation of the digester is indispensable to avoid exposure to toxic gases and suffocation. In addition, as a result of the explosion issue mentioned above, open fire or smoking has to be prohibited when working in the digester. As mentioned above (3.2.1), special attention needs to be dedicated to any handling of effluent.

3.3 Economic aspects

In Rwanda and Nepal, the overhead of the implementing biogas company amounted to 50% of the total costs (i.e. material and labour account for 50% of the total costs, whereas the other 50% was charged by the company for their planning and supervision work). The average cost of a biogas system per cubic meter was found to be 230 US$ in the Philippines, 250 US$ in Nepal and 300 US$ in Rwanda. It has to be noted that the evaluations in Rwanda and Nepal used the total digester volumes for this calculation, while the Philippines-report based the cost/m^3 on the total system volume (digester + compensation chamber).

Based on the country reports, the savings from substitution of cooking fuel are: In Rwanda, the savings resulting from reduced consumption of fire wood amount to 26-53 US$/day. For Muhanga, a reduction of money spending was reported to be 40 %. The financial savings in Nepal amount to 17% (Chitwan), 22% (Kanchanpur) and 41% (Kaski due to kitchen waste addition) compared to the time before using the biogas system. In the evaluation of the Philippines, monthly savings of 5% is reported (Cagayan de Oro prison). Future operational costs need to be envisaged for replacement of damaged parts, repairing and desludging (every 5-10 years, EREP, 2004), but budget for it is context-dependent. Approximate payback periods were only calculated in Nepal. The results of the calculations, which did not consider price fluctuations and eventual costs of repairing and digester desludging, were 1.5 years (Kaski), 5.4 years (Chitwan) and 3.7 years (Kanchanpur).

3.4 Environmental aspects

As mentioned above, a substantial amount of firewood is saved by using biogas, leading to reduced deforestation in the vicinity of the prisons. Table 2 presents the results taken from the evaluation reports, emphasizing the total annual saving of firewood per prison.

Table 2: Overview of firewood savings per prison

	Location	*Digester size [m^3]*	*No. of detainees*	*Total firewood saving [tons/year]*
RW[1]	Muhanga	500 (5*100)	7604	**3.50**
	Gikongoro	300 (3*100)	3385	**1.75**
	Cyangugu	400 (4*100)	3499	**1.1-2.1**
NP[2]	Kaski	10	65	**3800L kerosene***
	Kaski	12	135	
	Chitwan	10	115	**10**
	Chitwan	35	155	
	Kanchanpur	10	106	**4**
PH[3]	Cagayan de Oro	25	1112	**18.25**
	Davao	10	1142	**13.14**
	Sultan Kuradat	10	270	**9.13**
	Manila	24	519	**n.a.**
	Cradle	12	220	**n.a.**

RW[1]: Rwanda; NP[2]: Nepal; PH[3]: Philippines * Equivalent to 8.5 t of fire wood
(Kerosene: 46 MJ/kg; 3800 L = 3040 kg kerosene [1 kg = 1.25 L]) = 139’840 MJ = 8.48 t of wood [16.5 MJ/kg])

Large differences between the countries were found which can to some extent be explained: Some of the detention facilities used improved cooking stoves but others use conventional method of cooking with open stoves, which explains the large consumption of wood. Furthermore, in the Philippines, hard wood such as pine, oak, beech hardly exists. For cooking purposes, almost exclusively lightwood is used with a lower heating value and often the wood is still moist. If (imported) hardwood is available, this expensive and exclusive wood type is predominately used for construction of buildings. Although the absolute number of firewood savings in Rwanda is small compared to the other prisons, the reduction of firewood consumption is reported to be between 25 and 40% in reference to wood volume.

3.5 Socio-cultural aspects

The biogas systems are nowadays, after an initial phase of slight hesitation, favourably perceived by the vast majority of detainees. The initial fears included risk of disease transmission and bad taste of food that was prepared with biogas (as it is generated from human waste). However, as no negative effects were observed, these concerns gradually faded away. The main advantages in comparison with the previous (septic tank) system were mentioned to be the improved hygiene in the toilets combined with the absence of overflowing toilets and especially the generated energy. The reports also state a change of perception of the detainees: from excreta that was seen as waste, towards considering it as a valuable resource of energy. It was observed that the biogas systems are perceived as energy systems rather than as sanitary treatment systems.
98% of the interviewed detainees in Nepal and 100% in Rwanda reported that the living conditions have improved since the installation of the biogas system (the report from the Philippines lacks this information). The following underlining arguments were given:

- Less smoke in the kitchen
- Improved sanitation and hygiene (also less insects)
- Cleaner environment (jail in general and kitchen)
- Time saving through cooking with biogas
- Money saving (substitution of expenses for previous cooking fuel)
- Assurance of being able to cook and eat (no more shortages of cooking fuel i.e. firewood)
- Less outbreaks of diseases

In some prisons where neighbours had previously complained about the odour and the overflowing faeces (which in some cases had even led to dislocation of people living around the prison area), jail staff nowadays face much fewer complaints from the neighbourhood.

4. Conclusions

As a technology is only as appropriate and good as its design, acceptance, operation and maintenance, these points deserve the main attention of any performance evaluation. The evaluation conducted in Rwanda, Nepal and the Philippines showed that satisfactory operation of a biogas system can be achieved if adequate attention is given to the site selection and dimensioning of the system. For this, it is crucial to understand the local climatic and geotechnical conditions, sanitary habits, waste flows and power relations in the prisons. Kitchen waste addition can boost (even double) the biogas production, but its use might be in conflict with potential competitors (e.g. local farmers who use it as animal feed). To deal with high fluctuation in detainee numbers, it is advised to install digesters in series instead of a single large one. This ensures sufficient hydraulic retention time for satisfactory reduction of organic matter, increased pathogen reduction and at the same time enhances biogas capture. This article listed relevant points that have to be discussed with detainees and prison authorities prior to the digester installation. It is absolutely essential to give proper training for the users in order for them to get an understanding of the requirements of a well-functioning system. In addition, a maintenance strategy needs to be in place that includes clear allocation of responsibilities, a task schedule and control mechanisms to check if duties have been conducted properly. Biogas systems are favourably perceived by the vast majority of the detainees as they have led to improved living conditions and reveal more benefits compared to the previously installed septic tanks. Rather than being regarded as sanitation system, the biogas technology is considered as an energy system. However, while a biogas system can be an appropriate treatment technology for blackwater (faeces, urine, flush water) and kitchen waste, it does not present a suitable solution for treatment of the highly diluted greywater (shower water, kitchen water).

Overall, experiences in Rwanda, Nepal and the Philippines revealed that the systems can run successfully and thereby improve the conditions of detention if the discussed set of relevant issues is considered right from the beginning. Key for this is the availability of AD knowledge, skills and experiences of the constructing company and the involvement of detainees at every stage. It has to be ensured that the AD knowledge is kept within the prison walls despite frequent turnover of people (detainees and prisons' staff) in charge of the system. The evaluations form an essential and integral part of assessing the appropriateness of the biogas systems, as they provide a reality-check, help to make weaknesses apparent and lead to adaptations of the system according to local needs and capacities.

References

- Deublein, D., & Steinhauser, A. (2011). *Biogas from Waste and Renewable Resources*. 2nd Edition, Wiley-VCH Verlag, Weinheim
- Devkota, G.P. (2011). Biogas Digester Assessment in Places of Detentions in the Philippines. Practical Action Consulting
- EREP (2004). Évaluation des systèmes d'assainissement adaptés au contexte des prisons rwandaises
- Guidotti, G. (2002). Biogas from Excreta – Treatment of faecal sludge in developing countries. A state-of-practice review. Sandec/Eawag
- Kreditanstalt für Wiederaufbau KfW (2009). Biogas Audit Nepal 2008; Volume 1,2,3, KfW Frankfurt, USTB Beijing
- Lohri, C. (2009). Evaluation of Biogas Sanitation Systems in Nepalese Prisons. Sandec/Eawag, Switzerland.
- Mottet, A. (2009). Évaluation des systèmes biogaz des prisons rwandaises, EREP, N°: 09-5001-AM
- Tilley, E., Lüthi, C., Morel, A., Zurbrügg, C., Schertenleib, R. (2008). *Compendium of Sanitation Systems and Technologies*, Swiss Federal Institute of Aquatic Science and Technology (Eawag), Duebendorf, Switzerland
- World Health Organization WHO (2006). *WHO guidelines for the safe use of wastewater, excreta and grey water*; Volume 4: Excreta and grey water use in agriculture