The Potential of Small-Scale Biogas Digesters to Improve Livelihoods and Long Term Sustainability of Ecosystem Services in Sub-Saharan Africa

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Contents

Executive summary ... 4
1. Introduction ... 9
   1.1. Background ... 9
   1.2. Project structure ... 9
2. Installation ... 11
   2.1. Identification of sites where flexible-balloon digesters should be piloted ... 11
   2.2. Selection of biogas unit size ... 22
   2.3. Sourcing of biogas digesters ... 22
   2.4. Installation of digesters ... 23
   2.5. Training of local people ... 25
   2.6. Documentation of engineering problems associated with technical implementation ... 30
   2.7. Key findings from installation ... 32
3. Impact on energy, water and labour ... 33
   3.1. Energy ... 33
   3.2. Water ... 35
   3.3. Feedstock ... 35
   3.4. Labour ... 36
   3.5. Key findings from analysis of energy, water and labour ... 37
4. Impact on carbon and nutrients ... 38
   4.1. Establishment of trials to identify optimum return of agricultural products from applied nutrients ... 38
   4.2. Measurement methods ... 41
   4.3. Results and discussion ... 45
   4.4. Key findings from analysis of carbon and nutrient flows ... 57
5. Impact on household air quality and pathogens ... 58
   5.1. Household air quality ... 58
   5.2. Pathogens ... 64
   5.3. Key findings from analysis of household air quality and pathogens ... 74
6. Socioeconomic analysis, exploring cost/benefits and willingness to pay ... 75
   6.1. Literature survey ... 75
   6.2. Baseline survey ... 75
   6.3. Follow-up survey ... 80
   6.4. Key findings from socioeconomic analysis ... 88
7. Systems modelling to optimise return of agricultural products and energy from biogas digester / farming system ... 89
   7.1. The value of replacing cooking fuel with biogas ... 89
   7.2. Value of bioslurry as an organic fertiliser ... 94
   7.3. Value of reduction in pathogens ... 100
   7.4. Value of improved indoor air quality ... 100

7.5. Example calculations for households in Tiribogo 101
7.6. Identification of regions where digesters are likely to be of value 104
7.7. Recommendations for conversion to biogas 106
8. Communication and User Engagement 110
8.1. Information booklets and posters for local communities 110
8.2. Summary report for government departments 110
8.3. Information sheets for rural financial institutions 111
8.4. Information sheet for manufacturers 111
8.5. Project website 111
8.6. Local businesses 111
8.7. Scientific Publications 112
8.8. Media coverage 113
9. Conclusions 114
9.1. What is the potential of flexible-balloon digesters to alleviate poverty? 114
9.2. What is the value of a flexible balloon biogas digester to a household? 115
9.3. What changes are needed to make flexible balloon digesters more successful? 120
Acknowledgements 124
References 124
Appendix A – Project work plan 135
Appendix B – List of 54 households surveyed for installation of biogas digesters 137
Appendix C – Questionnaire used in household survey for suitability for installation of flexible balloon biogas digesters 139
Appendix D – Responses on how to use bioslurry 142
Appendix E – Biogas information sheets 145
Appendix F – Information sheets translated into the local Bantu language, Luganda 155
Appendix G – Information sheets translated into Swahili 165
Appendix H – Media coverage 175

Executive summary

Key findings and recommendations

Advantages

- **Installation of a flexible balloon digester is simple**; installation takes only a few days and is easily learnt by householders
- **Payback time in Uganda is under 4 years**; this estimate only accounts for reductions in wood fuel and compost use, including health impacts would further reduce payback time.
- **Bioslurry is an effective fertiliser**; yields of crops treated with bioslurry are significantly higher than the control and not significantly different to crops treated with urea or compost.
- **Bioslurry reduces greenhouse gas emissions**; losses of nitrous oxide from crops treated with bioslurry are significantly lower that from crops treated with urea
- **Aerobic pathogens in bioslurry are significantly reduced by anaerobic digestion**; the mean reduction in total coliforms in the digestate was 4.58 log CFU / g sample
- **Household air quality is improved on conversion to biogas**; in the households trialled, carbon monoxide and particulate matter with a diameter of less than 2.5μm were reduced by an average of 25% on conversion from woody biomass fuel to biogas

Problems

- **Digesters are too expensive**; cost of flexible balloon digesters in Uganda is over 5 times the cost reported in Asia, which is more than farmers are willing to pay
- **Digesters are susceptible to damage**; protection is needed from sharp objects and sunlight
- **Labour is increased by conversion to biogas**; this is due to extra work needed for mixing and handling organic wastes
- **Anaerobic pathogens in bioslurry are not significantly reduced during anaerobic digestion**
- **Both anaerobic and aerobic pathogens are increased in the local environment**; this is due to spillage during handling of organic wastes to feed the digesters

Recommendations

- Conversion to biogas is only recommended for households with access to **20 – 30 dm^3 water each day per person** (either by re-use of household wastewater and additional water collection), and manure from over **0.5 cows, 2 pigs, 5 goats or 5 sheep** for each person in the household.
- Householders should consider the impact of the digester on household labour; labour will only be decreased by the installation if (**distance to wood) > (2 x distance to water) plus 1000m (10m^3), 1200m (8m^3), 1600m (6m^3) and 2400m (4m^3 digester)**
- Flexible balloon digesters can provide **payback within 4 years**, but installation should avoid sharp objects and construct a fence and shelter to protect the digester from damage
- Spillage and excessive handling of manures should be avoided when feeding the digester
- To bring household air quality within safe limits for CO (WHO = 6 ppm) and $PM_{2.5}$ (EPA = 250 $\mu g\ m^{-3}$), biogas use should be sufficient to **reduce firewood use to less than 10 kg day^{-1}**.

Key issues needing further research

- How can we reduce the cost of digesters to less than £65 / digester?
- How should we adapt the design / layout to minimise handling of organic wastes?
- What is the optimum rate of bioslurry application to different crops?
- How does composition of bioslurry change with different treatment conditions and feedstocks?
- Can combining anaerobic digestion and composting further reduce pathogens in organic wastes?

Key findings

In principle, biogas has great potential to play a major role in alleviating poverty in Sub-Saharan Africa (SSA), but uptake of biogas digesters has been less widespread than in other parts of the world. It was proposed that the lack of uptake might be due to the high upfront cost of the fixed dome design of digester, and that the cheaper flexible balloon design might provide a more affordable alternative. However, when flexible balloon digesters were installed in this project, the cost was over five times the cost reported in Asia; this may contribute to the low uptake of this design in Uganda compared to Asia. Installation of the digesters was a simple procedure; each installation took only a few days and the method used for installation was easily learnt by householders. Problems with this design include potential damage of the flexible tube by sharp objects and UV sunlight, poor hygiene during manual handling of manure, maintenance of gas pressure and the high cost. Most of these problems are easily solved by providing better advice and repair kits with the digesters, but further work is needed to reduce the price of flexible balloon digesters.

Household labour increased with installation of the biogas digester. The average reduction in time spent collecting firewood in households where digesters were installed was estimated to be 2.58 hours wk^{-1}, but the time needed to collect water increased by an average of 1.53 hours wk^{-1}. Together with the increased labour required to collect and mix manure and feed it into the digester (6.47 hours wk^{-1}), this increased total household labour by an average of 5.42 hours wk^{-1}. Mixing the manure is particularly time-consuming, representing nearly 50% of the extra labour; if time spent mixing manure and feeding the digester could be reduced, a biogas digester could potentially reduce household labour by an average of 10 min wk^{-1}. Changes in design and layout of the digester to reduce mixing and handling of manure are therefore of high priority for future work and would be likely to increase uptake of digesters.

The results of field trials suggest that yields of crops treated with bioslurry are significantly higher than the control. This is due to increased availability of nitrogen (N) and decreased losses to the wider environment. There is no significant difference between the yield and N content of bioslurry treated crops compared to those treated with urea or chicken manure, although this may be due to the small number of trials possible. Emissions of the greenhouse gas, nitrous oxide, were significantly lower from crops treated with bioslurry than from those treated with urea. Future work should include comprehensive crop trials to resolve the impact of the different treatment processes on crop yields and N losses. Further analysis is needed to determine the optimum application rate for the bioslurry and to establish the impact of the digestion process on the composition of the bioslurry.

The reduction in particulate matter with a diameter of less than 2.5μm ($PM_{2.5}$) and carbon monoxide CO due to conversion to biogas were modest (median = 25%); this was due to only partial conversion of each household to biogas. In order to achieve measureable improvements in human health due to improved air quality, more complete conversion to this technology will be needed.

Sanitation in the <u>wider environment</u> (water courses etc) was expected to be improved by installation of digesters. Aerobic pathogen indicators (*E.coli*) were reduced through the digestion process, although anaerobic indicators (*C. perfringens*) were not. The reduction in total coliform loads in the digestate means that an overall decline would be expected in the wider environment following widespread conversion to application of bioslurry rather than untreated waste. By contrast, the overall *E. coli* and total coliform loads significantly increased in the <u>local environment</u> (household area, yard etc) due to spillage of manure during feeding of the digester; improvement in digester layout and education could counter this observed increase in pathogen loads in the local environment.

The analysis of what householders are prepared to pay for tasks suggests an increase in the net labour costs equivalent to 226 US$ yr^{-1}, requiring extra labour of 96 min day^{-1}. This finding is in contrast to the assertion of previous studies that installation of digesters will reduce household labour, leaving more time for activities such as education (ISAT, 2007). The discrepancy is due to the balance of activities in individual households; for instance, households that are situated further from the forest will spend more time collecting wood and so save more time by converting to biogas, which could result in an overall labour saving rather than a cost. This illustrates the need to consider the individual circumstances of each household using a full systems analysis before recommending installation of a digester; a systems model that calculates the value of biogas to the household has been developed. Expenditure on fuel wood and compost was found to decrease by at least 79

US$ yr^{-1} and 53 US$ yr^{-1} respectively, giving a total saving in actual expenditure of 131 US$ yr^{-1} and a payback time of just under 4 years.

What is the potential of flexible-balloon digesters to alleviate poverty?

The socio-economic analysis presented in this report generated empirical evidence to quantify the role of biogas in poverty alleviation. This has been approached by carefully identifying household specific costs and benefits of flexible-balloon digesters and evaluating the net household welfare (gain/loss).

A key finding from this project has been that flexible balloon digesters are not as cheap to install in Uganda as has been reported to be the case in Asia. The flexible balloon digesters were purchased for the project at a cost of £335 each, which was £275 more than the reported cost of £60 each (Smith et al., 2011). The household survey revealed householders who were familiar with the benefits of biogas digesters were willing to pay only £65 / digester. Therefore, unless the cost of the flexible balloon digesters can be reduced, the potential for poverty alleviation provided by biogas digesters may be limited in Uganda. Costs might be reduced by better matching the size of the digester to the requirements of the household; in the current project $8m^3$ digesters were installed in all households for consistency in the experimental methods; these digesters were too big for some households and so costs could have been reduced by installing smaller digesters. Further technical and political measures could also be used to reduce the upfront cost of digesters.

Savings in household expenditure on wood fuel and compost amount to an average of 131 US$ yr^{-1} (202 £ yr^{-1}). At this rate of saving, the cost of the digesters purchased for the current project would be repaid within 4 years. If more benefits can be derived from the digester, a shorter payback period would be achieved. Factors such as the impact of the digester on human health have not been accounted for here, as these are still highly uncertain. They nevertheless represent a significant potential saving in expenditure, with an average of 24 US$ yr^{-1} (36 £ yr^{-1}) being spent on respiratory illnesses alone, and should be included in the calculation of payback time when more research has been done to quantify these benefits.

The activities required to operate a flexible balloon digester are collecting of water for mixing with feedstock, collecting cow dung or other feedstocks, mixing the feedstocks with water, feeding the feedstock into the digester and applying slurry to the fields. If the costs of labour were to be factored in, these tasks would cost the household a total of 373 US$ yr^{-1} (571 £ yr^{-1}) in terms of household labour, while the cost of labour for collecting fuel wood would be reduced by only 147 US$ yr^{-1} (225 £ yr^{-1}) resulting in a net additional labour requirement of 226 US$ yr^{-1} (346 £ yr^{-1}) (Table 6.4.1). This additional burden reflects a loss in household welfare, although it may be somewhat allayed by better distribution of tasks around the household. The saving in expenditure may also be more apparent to the household as it represents an actual reduction in expenditure, whereas the cost of labour is not apparent if alternative employment is not available.

What is the value of a flexible balloon biogas digester to a household?

Energy

The savings in firewood consumption observed in the nine households in Tiribogo where biogas digesters were installed averaged 6 kg day^{-1} = 2.190 t yr^{-1} (Table 3.1.1). An average of 204 £ yr^{-1} was spent on cooking fuel, providing 20% of the fuel for cooking (Table 7.5.1). Systems analysis suggested that all of this expenditure could be saved by cooking with biogas. The remaining fuel for cooking was collected from the forests. This amounts to a labour cost of 225 £ yr^{-1}. The average percentage of the household energy requirement that could potentially be replaced by biogas in the nine households studied was 83% and ranged from 57% to 100%.

Organic fertiliser

Analysis of the field trials conducted in this project suggests that when the same quantity of N is applied in bioslurry, chicken manure compost and urea, the yields of crops treated with bioslurry are significantly higher than the control, and there is no significant difference between the yield and N content of bioslurry treated crops compared to those treated with urea or chicken manure. This result demonstrates that bioslurry is an effective organic fertilizer. Emissions of the greenhouse gas, nitrous oxide, were significantly lower from crops treated with bioslurry than from those treated with urea. Future work should include comprehensive crop trials to determine the optimum application rate for the bioslurry. Further analysis of the impact of the digestion process on the composition of the bioslurry is also needed so that the impact of the feedstock and the digestion conditions on the availability of nutrients to the crop and to loss processes in the soil can be better understood.

Sanitation

In the current work, changes in indicator organisms, *E.coli* and *C. perfringens* were measured. The data shows that aerobic pathogen indicators (*E.coli*) were reduced through the digestion process but that anaerobic indicators (*C. perfringens*) were not. The reduction in total coliform loads in the digestate means that an overall decline would be expected in the wider environment following widespread conversion to application of bioslurry rather than untreated waste. By contrast, the environmental analysis suggested that sanitation was not improved around the households as a result of digester use. The overall *E. coli* and total coliform loads significantly increased between the baseline study and the period after installation. Loads in the local environment were observed to increase due to spillage of manure during feeding of the digester; improvement in digester layout and education could counter this observed increase in pathogen loads in the local environment. If deployment of digesters is to be scaled up, each installation should be accompanied by an education package to ensure good management of the digester and avoid local spread of pathogens. The design and layout of digesters should be modified to allow organic wastes to be swept into the digester without excessive handling; this is already possible with fixed dome digesters, but the cost of this design could be prohibitive. Sinking a flexible balloon digester further into the ground, so allowing a ground level inlet that funnels material into the digester, might help to reduce handling. Further work is needed to determine if this approach would work, and whether sharp objects and non-organic inputs would present a problem.

Future research should investigate the behavior of specific pathogens during treatment and post-processing application to land in order to recommend appropriate hygienic measures to protect people and the environment while maximizing the use of digestate as an organic fertilizer. Based on available data, the following recommendations would promote reduced risk to farmers and their families in SSA who are using anaerobic digesters and applying digestate to land:

- Post-digestion composting of bioslurry to promote further pathogen die-off
- Minimum direct skin contact and handling of organic wastes pre and post digestion and during composting.
- Good personal hygiene and handwashing with soap and clean water
- No application of bioslurry to foods grown close to the ground, unlikely to be peeled and to be consumed raw within 3 months of harvest
- Thorough cooking of bioslurry-fertilised food crops
- Training in operation of digester and handling of feedstocks and effluent for farmers and their families.

Household air quality

The concentrations of $PM_{2.5}$ measured prior to the installation of the biogas digesters in this group of homes were approximately sixteen times higher than the WHO guidance value for indoor $PM_{2.5}$. While the installation produced some limited reduction in measured levels, the size of the effect was modest, with significant improvements seen in only 6 of the 9 homes and the median reduction being approximately 25% resulting in average household concentrations being 367 micrograms m^{-3}. This value is still some fourteen times greater than the WHO guideline. Even after biogas installation all 9 homes recorded at least 40% of measurement time (over 9.5 hours from the 24 hour sampling period) exceeding the WHO guideline. A similar pattern was seen for CO.

The modest reductions in air pollution exposures seen within this pilot study are unlikely to produce measurable improvements in human health for this group of householders. The small effects can be explained by incomplete conversion of households to biogas. In order to achieve measureable improvements in human health due to improved air quality associated with conversion to biogas, more complete conversion to the technology will be needed. At the rates of emissions measured, to reduce the average concentration of $PM_{2.5}$ to within the EPA limit of 250 $\mu g\ m^{-3}$ would require firewood use to be less than 10 (range = 6-19) kg day^{-1}; and to reduce the average concentration of CO to within the WHO limit of 6 ppm would require firewood use to be less than 11 (range = 7-20) kg day^{-1}. This is equivalent to a 46-51% reduction in firewood use from the pre-biogas rates, which would be feasible as it is less than the calculated household energy potentially supplied by biogas (57-100%).

What changes are needed to make flexible balloon digesters more successful?

Cost

The socioeconomic analysis summarised in Table 6.3.6 suggests that even householders who are familiar with the benefits of digesters are only willing to pay ~US$100 (£65) for a biogas digester. A cost of ~£335 / digester is clearly too high for most rural householders. Technical and political means of bringing this cost down should be explored in future work. These could include improved tax incentives, local manufacturing of components, establishment of funding mechanisms to facilitate purchase of digesters, and use of cheaper materials and simpler manufacturing methods in producing digesters.

Damage of flexible tube

During the current project, damage of the flexible tube by sharp objects either during or after installation has been a common cause of system failure. These faults can easily be mended using a plastic patch and glue. Future installations should include a repair kit and instructions on repair so householders can get their system working again without having to wait for the installers to visit.

The plastic in the tube can be degraded by prolonged exposure to UV light. Instructions for construction of a shelter to protect the digester from sunlight should also be included with the digester.

Manual handling of feedstock

The results in section 5 show that, while total coliforms are decreased in the digestate compared to the feedstock, increases are observed in the environment due to manual handling and spillage of manure around the kitchen area. This effect is dependent on the design and layout of the system within the household; it is anticipated that significant reductions in pathogens in the environment could be achieved by redesigning the system to reduce handling. An education package for improving sanitation should be provided before installation (for instance hand washing after handling wastes). Information should be given to advise on the position of digesters (close to the animals, away from the kitchen). This may require development of hand pumps to maintain gas pressure. Issues of household sanitation are likely to differ between countries; in Ethiopia, many people live with animals inside the house, whereas in Cameroon, it is taboo in some areas to have animals near the house. Future work should focus on the layout and design of the system to minimize handling. This would also have the advantage of reducing the labour needed to run the digester.

Gas Pressure

Flexible tube digesters have a constant volume, which means that the biogas produced has a variable pressure, depending on the volume of gas in the digester. After prolonged periods of cooking, the gas pressure can drop. The gas pressure and activity of the micro-organisms decomposing the organic waste are also more affected by changes in ambient temperatures than in designs with better insulation, such as fixed dome digesters, that are constructed underground. This can be addressed by ***a***pplying weights to the balloon when the gas pressure drops.

Problems were observed during this project with the pipe that transports the gas from the digester to the kitchen bending, causing the gas line to block. An improved design should include a pipe that is resistant to bending at this point.

1. Introduction

1.1. Background

Thirty million Euros has been committed to the African Biogas Partnership Programme (ABPP) by the Netherlands Government to finance 70,000 digesters, knowledge management, fund management and technical assistance over a five year programme (2009 to 2013). With such initiatives already underway, the infrastructure and resources needed to effect energy production and waste management through small-scale biogas digesters are already being put in place. This provides a unique opportunity for research into implementation of digesters to immediately have an impact on the success of national programmes. Key questions remain as to the potential of alternative cheaper designs of digester to encourage wider uptake of the technology amongst the poorest members of a community and to provide a long-term energy supply and effective treatment of organic wastes, the need for adaptation of cooking equipment and farming systems to accommodate biogas technology, and economic returns from digesters.

1.2. Project structure

The work addressed 3 key questions

1. What is the potential of flexible-balloon digesters in SSA?
2. What changes are needed in farmer attitudes, equipment and design of farming systems?
3. What is the value of a biogas digester in terms of energy, organic fertiliser, reduction in deforestation, improved sanitation and improved household air quality?

The work focussed on the Ugandan programme because it is already well underway; UA have strong links with the programme as well as newly established companies, providers of digesters; and partners at MU provide strong expertise in biogas in Uganda. The questions were tackled by three MSc students (two registered at MU and one at UA), and one research assistant from UA. The students and research assistant worked together at sites situated in one village, the village of Tiribogo, Muduuma Sub-County, Mpigi district, near Kampala, Uganda (Fig. 1.1.1). By focusing efforts in just one location, it was anticipated that a solid foundation for the spread of the technology would be created. The work aimed to create a model approach for seeding the technology that can be used in other areas of Uganda and other countries in SSA.

Socioeconomic aspects of the potential of flexible-balloon digesters in SSA was considered by Moris Kabyanga (MSc1 - registered at MU), focusing on Tiribogo, but also taking in the surrounding area to give context to the work at Tiribogo. Site selection, installation and engineering issues, labour, energy and water and design of equipment and farming systems were considered by Vianney Tumwesige (MSc2 - registered at UA) and Lauren Harroff, a visiting graduate student from Clemson University, USA (VS). The impact of biogas digesters on resource flows (nutrients and carbon (C)) was investigated by Swaib Semiyaga (MSc3 - registered at MU), and the impact on household air quality and exposure to pathogens was measured by Andrew Apsley (the research assistant, RA1 from UA), MSc2 and VS. The sites where biogas digesters were installed and studied by MSc2, MSc3, RA1 and VS were all in Tiribogo. An economic value was assigned by MSc1 to the changes in resource flows and health induced by the biogas digester.

Figure 1.1.1 - Meeting at Tiribogo Muduuma Sub-County, Mpigi district, near Kampala, Uganda

2. Installation

2.1. Identification of sites where flexible-balloon digesters should be piloted

Selection of study area

The study area was selected according to selection guidelines that aim to identify a community and households that are likely to have high take-up of biogas digesters, and respond well to training opportunities, as well as allowing convenient access to the researchers doing surveys and making measurements.

Location **(**http://www.getamap.net/maps/uganda/mubende/_muduuma/)

Muduuma Sub-County, Mpigi District is located 36 km along Kampala Mityana highway. Tiribogo is 3 km off the highway. This is sufficiently close to Kampala to allow easy access for transporting samples to the lab, recharging battery packs for field analyses etc. The village includes ~280 households.

Community groups

Farmers in Tiribogo are part of Kananansi Farmer's Youth Group. This group aims to encourage best practice amongst the farmers. Any farmers not adhering to standards of good farming practice are excluded from the group. This presents a very reliable mechanism for transferring new technology to the population of Tiribogo.

Water supply

In order to be suitable for installation of biogas digesters, the supply of water should be sufficient throughout the year. Orskov et al (2013) estimate that ~100 dm^3 water day^{-1} $household^{-1}$ are needed to run a biogas digester for a four person household. The availability of water in the village was not quantified. However, villagers report that, in this area, irrigation is never required. No household complained about the distance between the home and water sources in relation to firewood. There are three stand-alone pipes (boreholes) in the village (Fig.2.1.1). Therefore, it is likely that sufficient water will be available in Tiribogo for biogas digestion throughout the year. Henry, the youth chairman, said "We have nine wells which are well-distributed in valleys throughout the village." Many of the households visited collected more than 40 dm^3 of water per day, which is currently used for household use and for animals.

Figure 2.1.1 – Stand-pipe in Tiribogo

Alternative fuel sources

A location where alternative fuel sources are scarce, expensive or declining is likely to have a high uptake of biogas as a fuel source. Tiribogo has no grid connection. Kerosene is used for lighting. Mainly firewood is used for cooking, although some householders use charcoal. No householders interviewed paid for firewood. The village is close to the 'forest reserve', where most of the trees have been cut for fuel, schools being the biggest consumers of the fuel wood (Fig.2.1.2). Villagers expressed concern for the declining density of trees in the forest.

Figure 2.1.2 - Deforestation in forest reserve near to Tiribogo

Farming

Tiribogo is mainly a crop growing community; livestock are kept to supplement income. Small banana/coffee gardens are usually planted around the house; vegetable gardens are not common. Most households also cultivate land away from the house, either on land where trees have been cleared or near the swamp. These fields are generally bigger than those near to the houses.

Feedstock

Sufficient quantities of feedstock, especially animal manures, are needed to produce biogas. Brown (2006) suggested that 1-2 cows or 5-8 pigs produce sufficient feedstock to provide biogas for a typical household. Cows and pigs are kept by most households (Fig.2.1.3). Households usually have at least 1 cow or pig. Some households keep 2 to 3 cows and 2 to 4 pigs. A few households kept goats and poultry in addition to cows and pigs. Cows are often grazed away from home. Pigs are mainly kept under coffee trees, but a few householders have small pig sties with concrete floors. The pigs are fed on cooked vegetable peelings. Crops can also provide suitable feedstocks. The major crops grown in Tiribogo include pineapples, maize and bananas. Other crops include vegetables and potatoes.

Figure 2.1.3 - Pigs and cows are kept in many households in Tiribogo

Current waste management

Most of the organic waste from animals (dung) is not composted. During the hot season, the dung dries on the ground; the dried dung is then collected and spread on the crops. The animal dung quantities are not large; this could be attributed to cows grazing away from home. Peelings (fruit waste, matooke and potato) are mainly used as feed for animals. Households without animals throw peelings and banana leaves directly onto crops. Compost heaps are not common.

Requirement for fertilizer

Villagers are already making good use of organic wastes, widely using compost as an organic fertilizer. However, it is unclear where this is sourced from, since compost heaps were not widely observed. Compost is applied at the start of the growing season and provides a slow release source of nutrients (Fig.2.1.4). Farmers expressed a shortage of compost, so the preferred use of bioslurry in Tiribogo might be in converting other forms of organic waste into a higher quality compost.

Figure 2.1.4 - Sowing of maize at Tiribogo, showing each plant set in a hole filled with well-rotted compost

Household air quality

Many households in Tiribogo have kitchens outside the main house with mainly three stone stoves. Some households have open roof kitchens to improve indoor air quality (Fig.2.1.5). Indoor air quality is an issue of concern for householders, and attempts to improve indoor air quality were observed, such as provision of ventilation next to the fire. Improvement in indoor air quality was one of the main advantages of biogas digesters recognized by villagers.

Figure 2.1.5 - The kitchen environment at Tiribogo

Selection of households

Introduction

A baseline questionnaire was taken to 54 households in Tiribogo, selected because they produce animal waste. The results of this survey were used to select nine households for installation of a flexible balloon biogas digester. The full list of householders interviewed is provided in the appendix B.

Method

A baseline questionnaire (see appendix B) was used to collect data on demand for biomass fuel, availability of feedstock and water, and ability to manage organic waste. The fifty-four households in the village that produce animal manure were visited and interviewed in a 30-minute structured questionnaire, consisting of a list of closed questions on how the household manages resources, such as farm, manure, water, fuel wood and kitchen residues. The questionnaires were completed during three visits. The proportion of households in Tiribogo with access to animal manure is relatively low because people are mainly involved in growing crops, which do not produce much organic waste as the crops are sold off, and so the crop residues are not retained in the village.

The householders interviewed were mainly women, but in some cases it was the husband, a labourer working within the family or one of the older children (Fig.2.1.6). A consent form was signed to ensure the householder agreed with the use that would be made of the collected data (Fig. 2.1.7). The data collected was used to generate fact sheets and to rank the households using a simple numerical weighting system while applying a multi criteria decision approach. Ranking of households for suitability for installation of a flexible balloon biogas digester considered four factors; availability of feedstock, access to water, requirement for biogas and ability to train others.

Figure 2.1.6 – Household interview

Figure 2.1.7 – Consent form signed

Availability of feedstock

The feedstock is the material that is fed to the digester for anaerobic digestion to take place. Different materials have different digestion properties, and result in biogas of different compositions and quality. In general, all types of organic waste can be used for anaerobic digestion as long as they contain protein, carbohydrates, fats, cellulose or hemicelluloses. Lignin, however, as found in wood products, is not easily broken down by anaerobic digestion (Riuji, 2009).

Selecting a consistent mix of substrates with high energy content that is readily available to the bacteria, such as simple sugars and fats, maximises biogas production. By contrast, feeding the digester highly variable substrates with nutrients locked away in compounds that bacteria cannot easily digest, such as lignin and cellulose, leads to poor biogas yields.

One of the most important factors to the successful implementation of biogas is the availability of the feedstock. The amount of biogas that could theoretically be produced depends on the type or breed of livestock and the livestock management system. For livestock kept in zero grazing conditions, the availability of that manure is 100%, whereas for cattle kept in stables only at night, manure available is ~50%.

In Tiribogo, cattle and pigs are kept in semi-zero-grazing environments, where they are grazed during the day, and penned at night for milking and security as shown in Fig. 2.1.8. Penning of cattle and pigs results in manure becoming dried and mixed with soil. Both effects are undesirable for use in the biogas digester. However, few householders kept their pigs in sties with concrete floors (Fig. 2.1.9).

Figure 2.1.8 – Penning animals at night results in drying of manure and mixing with soil

Figure 2.1.9 – Pig sty with concrete floor

The amount and nature of feedstock are key factors in determining the optimum size of biogas digester, the volume of water required and the amount of biogas to be generated. If the installation requires more feedstock than is available to the household, the digester will not perform effectively. Brown (2006) suggested 1-2 cows or 5-8 pigs would supply adequate feedstock for a single four-person household digester. The raw material for digestion must be conveniently available on a daily basis i.e. a minimum of 30 kg of cow manure or 15 kg of vegetable waste or equivalent per household per day (Smith et al., 2011). We used the average value, 20 kg water per day, as the cutoff as the organic waste was composed of a mixture of animal and other wastes.

The quantity of organic waste produced each day, W_{F} (kg fresh weight day^{-1}), was estimated as

$$W_{\mathrm{F}} = W_{\mathrm{L}} \times n \times p_{\mathrm{m}}. \qquad \text{Eqn. 2.1.1}$$

where W_{L} is the live weight of the animal (t), n is the number of animals contributing to the digester, and p_{m} is the production of manure for each kg of live weight (kg manure) (t live weight)$^{-1}$. The live weight of cows in Tiribogo was assumed to be 180 kg (W_{L} = 0.18 t cow^{-1}). If cows were put out to graze during the day and penned only at night, the number of cows in the household was multiplied by 50%, as only ~50% manure was fed to the digester (n = 0.5 x number of cows kept in the household). The amount of manure produced by cows (p_{m}) was assumed to be 90 kg (t live weight)$^{-1}$ (Chen, 1983). The live weight of pigs in Tiribogo was assumed to be 55 kg (W_{L} = 0.055 t pig^{-1}). Again, if penned only at night, the number of pigs in the household was multiplied by 50% (n = 0.5 x number of pigs kept in the household). The amount of manure produced (p_{m}) was assumed to be 75 kg (t live weight)$^{-1}$ (Chen, 1983). Organic wastes other than cow and pig manure provide additional feedstock that was accounted for similarly.

Fig. 2.1.10 shows the quantity of organic waste generated by households in Tiribogo. Households with capacity to generate more than 20 kg day^{-1} are considered to have potential to sustainably supply the required feedstock for a family biogas digester. The red line shows generation of 20 kg day^{-1} of waste; households with capacity to generate more than this required amount were scored as being able to sustain a biogas digester. Households below the red line were eliminated on the basis of not being in position to meet the minimum quantity of organic waste required to sustain a biogas digester. Seventeen households were able to generate over 20 kg organic waste day^{-1}. These were H1, H2, H5, H6, H10, H11, H13, H15, H16, H17, H20, H21, H24, H26, H27, H28, and H47. Household H11 produced over 97kg of cow manure every day, due to having a larger number of cows than other households.

Households were scored according to the amount of organic waste estimated to be available as follows:

30 kg day^{-1} organic manure plus 15 kg day^{-1} vegetable waste and above; max score = 10;
30 kg day^{-1} organic manure plus 15 kg day^{-1} vegetable waste and above; max score = 6,
30 kg day^{-1} organic manure plus 0 kg day^{-1} vegetable waste; max score = 4,
25-30 kg day^{-1} organic manure; score = 2;
below 25 kg day^{-1} organic manure; score = 0.

They were further scored according to the grazing regime used because this determines whether manure the household considers manure to be a valuable commodity or a disposal problem. The scores used have a range of 0-5 as opposed to the 0-10 range used for the amount of organic wastes. This approach ensures that the grazing regime has only 50% influence in selecting households compared to amount of organic waste. The ranges selected for the scores are subjective, but were arrived at by expert judgement. The scoring used was as follows:

zero grazing; score = 5;
night stabling; score = 3;
pastoral grazing; score = 0.

Households were also scored according to the manure management regime, again with a range of 0-5, as this could impact the value of the bioslurry to the household. The scores are show below:

mulching / composting; score = 5;
application of manure directly to crops; score = 3;
dumping of manure; score = 1.

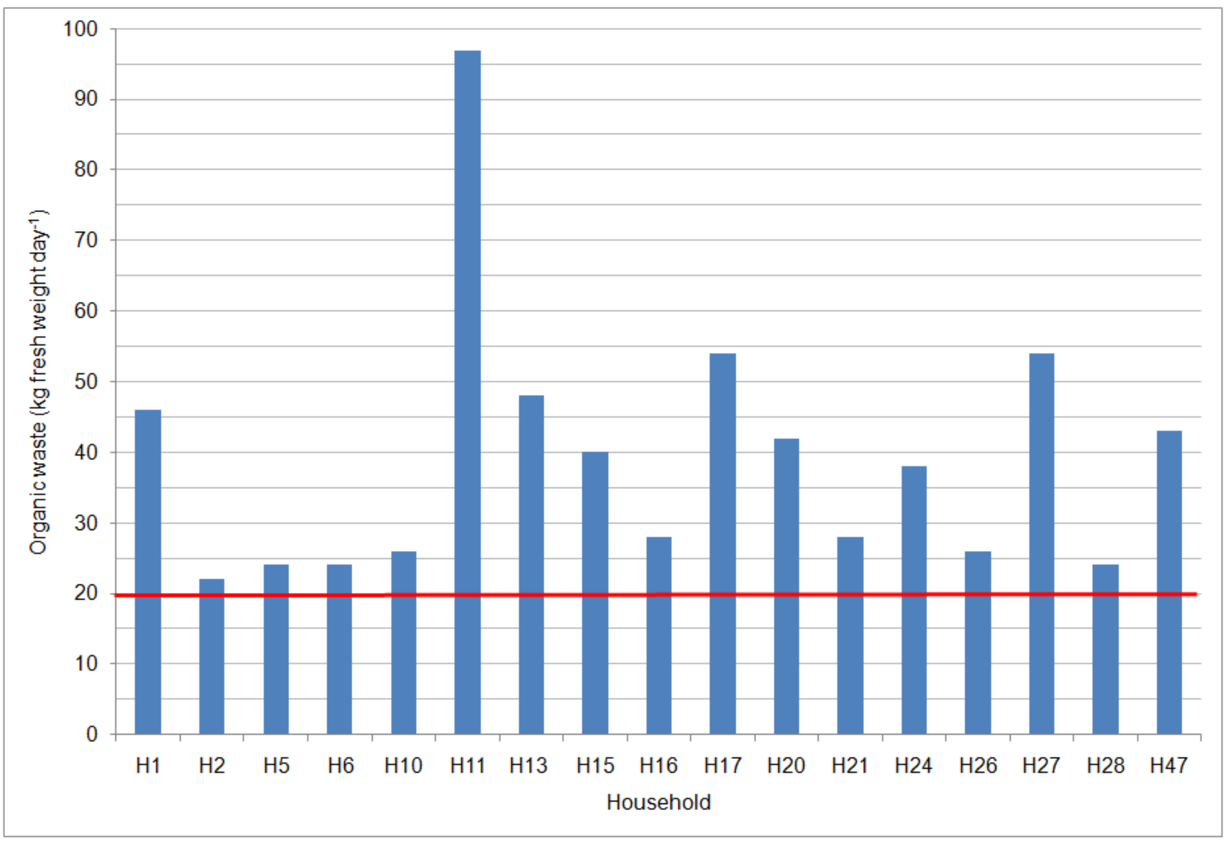

Figure 2.1.10 - Quantity of organic waste per households

Access to water

The amount of water required to run a biogas digester depends on the type and amount of feedstock. For optimal anaerobic fermentation the dry matter content must be between 2 and 5% (Preston, 2011). This means that for each 10 kg of dry matter there is a need for about 200 dm^3 of water. Pandey et al. (2007) expressed this as approximately equal volumes of water and dung being fed into the digester daily. From this, the daily requirement for water to run a biogas digester, V_W (dm^3 day^{-1}), was estimated as

$$V_W = W_F \times \frac{P_{DM}}{100} \times \frac{200}{10} = W_F \times \frac{P_{DM}}{100} \times 20 \quad \text{Eqn. 2.1.2}$$

where W_F is the amount of manure (kg fresh weight day^{-1}); and P_{DM} is the percentage dry matter in the manure. Assuming a dry matter content of 10%, this translates to

$$V_W = W_F \times 2 \quad \text{Eqn. 2.1.3}$$

Water is used in SSA households for drinking, cooking, hygiene (bathing, laundry, washing hands, food and dishes) and irrigation (Rosen and Vincent, 1999). The amount of water used by a household depends on the availability of the water source. WaterAid (2012) suggested that the average person in the developing world uses 10 dm^3 day^{-1} for drinking, washing and cooking. Much of this water could be recycled into the biogas digester, so requiring no additional labour for water collection. The volume of water collected per day, provided by the questionnaire, was used to calculate the volume of water needed as a percentage of the volume of water already collected by the household. This was then used to score the households according to water use as follows:

below 20%; score = 5;
21-40%; score = 4;
41-60%; score = 3;
61-80%; score = 2;
81-100%; score = 1;
above 100% = 0.

Fig. 2.1.11 shows the extra water that would be needed by each household to run a biogas digester assuming all household organic waste is used in the digester (households with negligible organic waste have been excluded from the figure). The majority of households would require an extra 40-100 dm^3 of water each day. H11 requires more water; due to the large volume of manure from the animals.

Householders in Tiribogo collected water either from a borehole or an open well. Fig. 2.1.12 shows the distance from the household to the water source. The majority of the householders interviewed spent under one hour collecting water for daily needs, but some householders spent over two hours. This information was used to calculate the time that would be required to collect the extra water needed to run a biogas digester using all the household waste (Fig.2.1.13). The result for house H11 is unusual in that they require a large amount of water and travel a large distance for water, and yet the time required to collect the extra water is small. This can be attributed to the use of a vehicle in water collection. For practical purposes, in view of the significant amounts of water needed, Batzias et al. (2005) suggested that water should be within a distance of 20 to 30 minutes from the installation. Therefore, 1 hour time to travel to and from the water source was set as the limit for an installation.

The distance to the water source was used to score households as follows:
100m and below; score = 5;
100-200m; score = 4;
210 - 300m; score = 3;
310 - 500m; score = 2;
above 600m; score = 1.

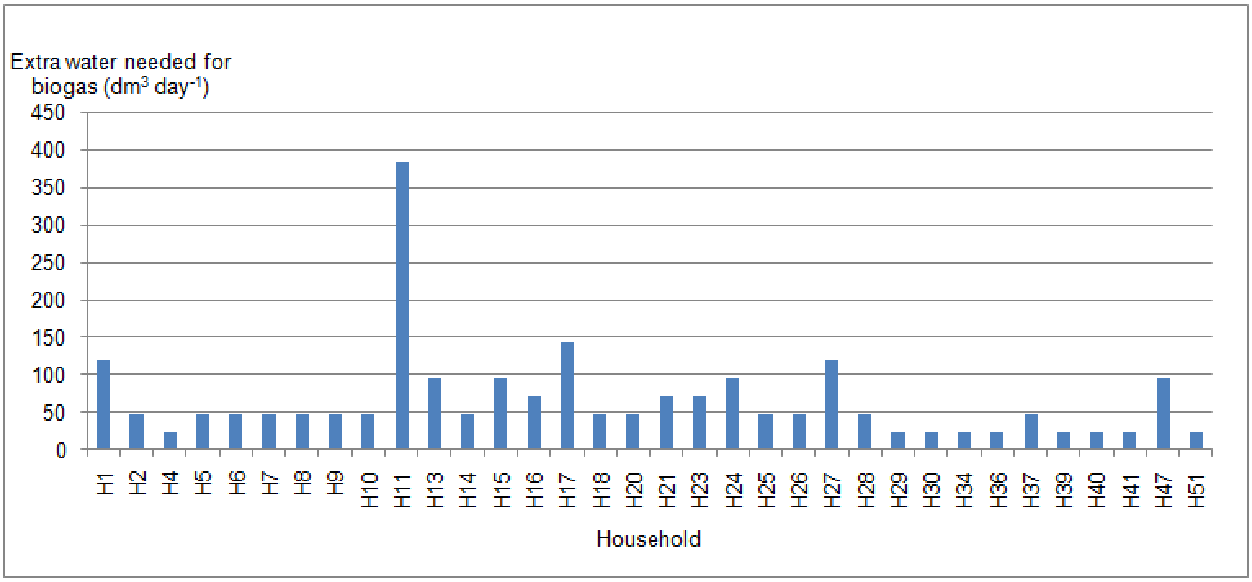

Figure 2.1.11 - Extra water needed by the household to operate a biogas digester

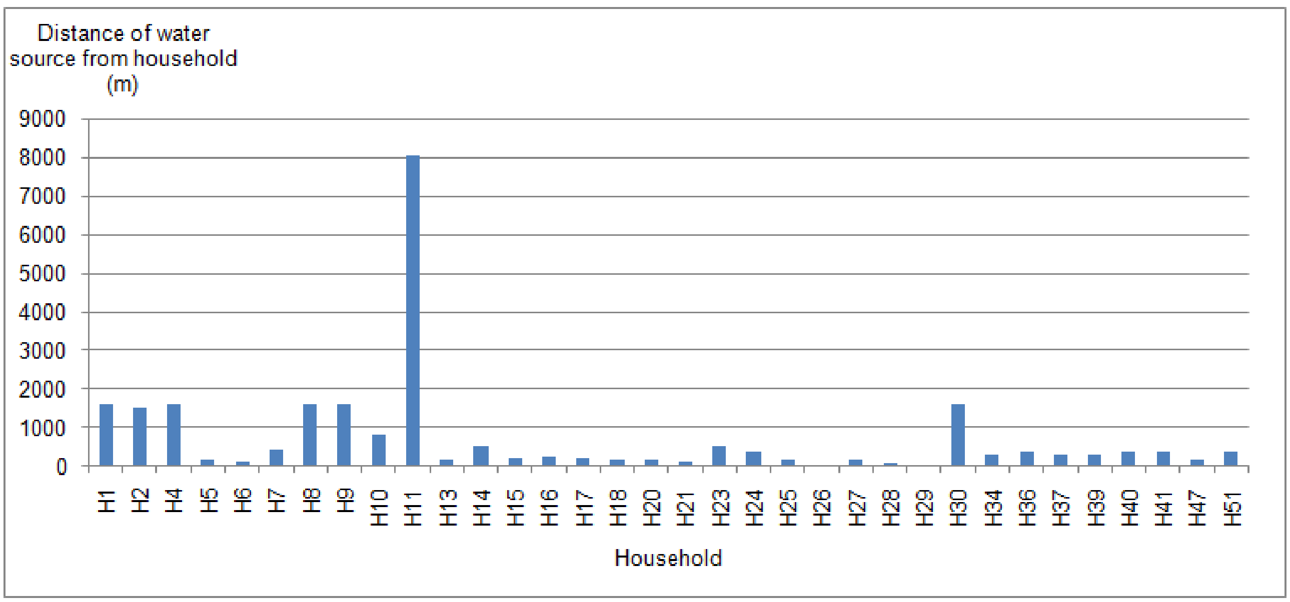

Figure 2.1.12 – Distance from household to water source

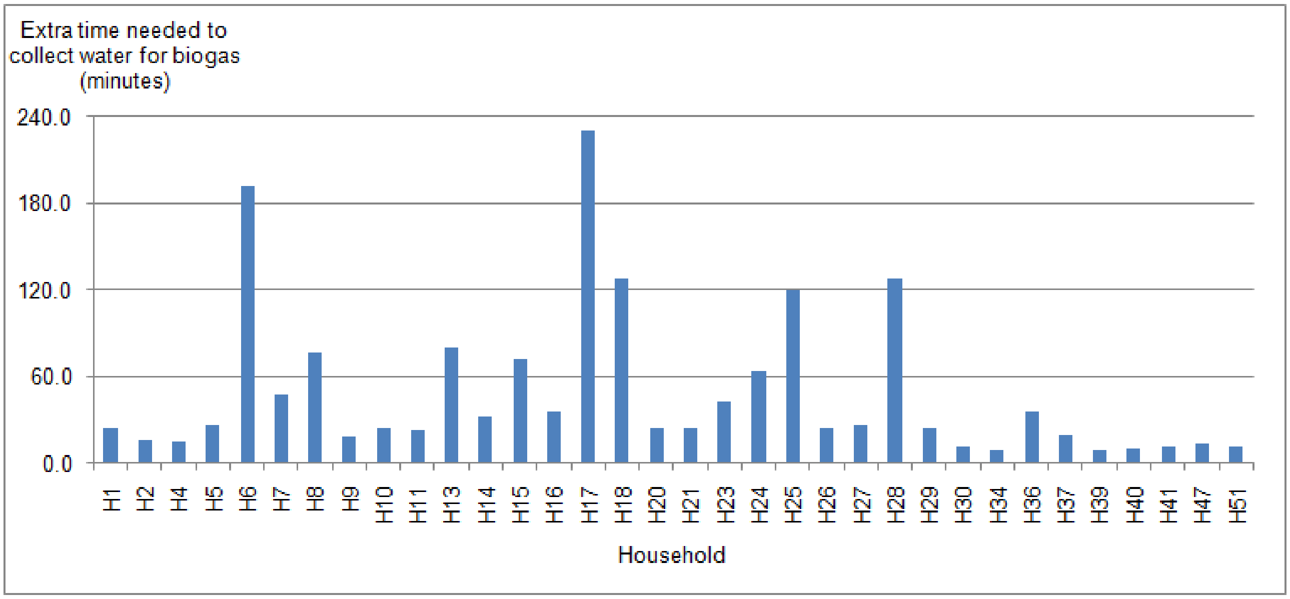

Figure 2.1.13 – Extra time needed to collect water for biogas (minutes)

Requirement for biogas

Together with availability of feedstock, the energy demand of the household determines the optimum size of the digester required. Installation of a biogas digester that produces more biogas than the household needs results in wasted time and labour in feeding the digester, and would require excess biogas to be vented, so releasing methane (CH_4), a potent greenhouse gas into the atmosphere.

Data from the questionnaire shows that the sources of energy for householders in Tiribogo are firewood and charcoal for cooking, kerosene and batteries for lighting. There are no biogas plants currently in use. An estimate of volume of firewood collected from the forest reserve was obtained in the questionnaire. Residents in Tiribogo collect and measure firewood in bundles, locally known as *kinywa* (Fig. 2.1.14). Householders assumed a bundle weighed from 10 – 40 kg.

Figure 2.1.14 – Bundle of firewood collected for fuel

Households were scored according to the use that would be made of biogas. Scores were 5 for use in cooking and 0 for no use for biogas. Households were also scored 5 for regularly boiling of water and 0 if water was not regularly boiled.

The potential biogas production from the organic waste available in the household was estimated using the approach outlined by Chen (1983). The volume of CH_4 produced, V_{CH4} (m^3 day^{-1}), is given by

$$V_{CH4} = P_c \times p_{CH4} \times W_{VS} \qquad \text{Eqn. 2.1.4}$$

where P_c is the efficiency with which volatile solids in the manure are decomposed (% volatile solids decomposed); p_{CH4} is the proportion of CH_4 produced when volatile solids decompose (m^3 CH_4 (kg decomposing volatile solids)$^{-1}$); and W_{VS} is the amount of volatile solids in the feedstock (kg volatile solids day^{-1}). The amount of volatile solids in the feedstock is given by $W_{VS} = W_F \times \frac{p_{VS}}{1000}$, where W_F is the amount of manure (kg fresh weight day^{-1}) and p_{VS} is the proportion of volatile solids in the manure (kg volatile solids (t fresh weight manure)$^{-1}$).

The volume of biogas produced, V_{biogas} (m^3 day^{-1}) is then given by

$$V_{\text{biogas}} = V_{\text{CH}4} \times \frac{100}{P_{\text{CH}4}} \quad \text{Eqn. 2.1.5}$$

where $P_{\text{CH}4}$ is the percentage of CH_4 in the biogas (~70%).

Using parameters provided by Chen (1983), biogas yields of ~40 dm^3 (kg cow dung)$^{-1}$, and ~60 dm^3 gas (kg pig dung)$^{-1}$ were obtained.

The estimate of potential biogas production was then used to score households according to potential for biogas production as follows:

above 2500 dm^3; score = 5;
2000 – 2400 dm^3; score = 4;
1990 – 2000 dm^3; score = 3;
1990 - 1500 dm^3; score = 2;
1400-1000 dm^3; score = 1;
below 1000 dm^3; score = 0.

The effect of including the production of biogas as a score is to give higher weight to the availability of feedstock as the potential biogas production is derived directly from this value.

Ability to train others

Because it is envisaged that the householders receiving biogas digesters will be trained in installation and maintenance of digesters, and will be given the opportunity to promote digesters and provide further training to others, the householders were scored according to their ability to train others. This was assessed according to previous experience and successes in training as a maximum score of 5 for householders with training ability, and 0 for householders without any ability.

Combined scores

All scores taked together give a maximum potential score for a household of 50 points. The summed scores are shown in Fig. 2.1.15. This shows the 9 highest scoring households, as listed in Table 2.1.1.

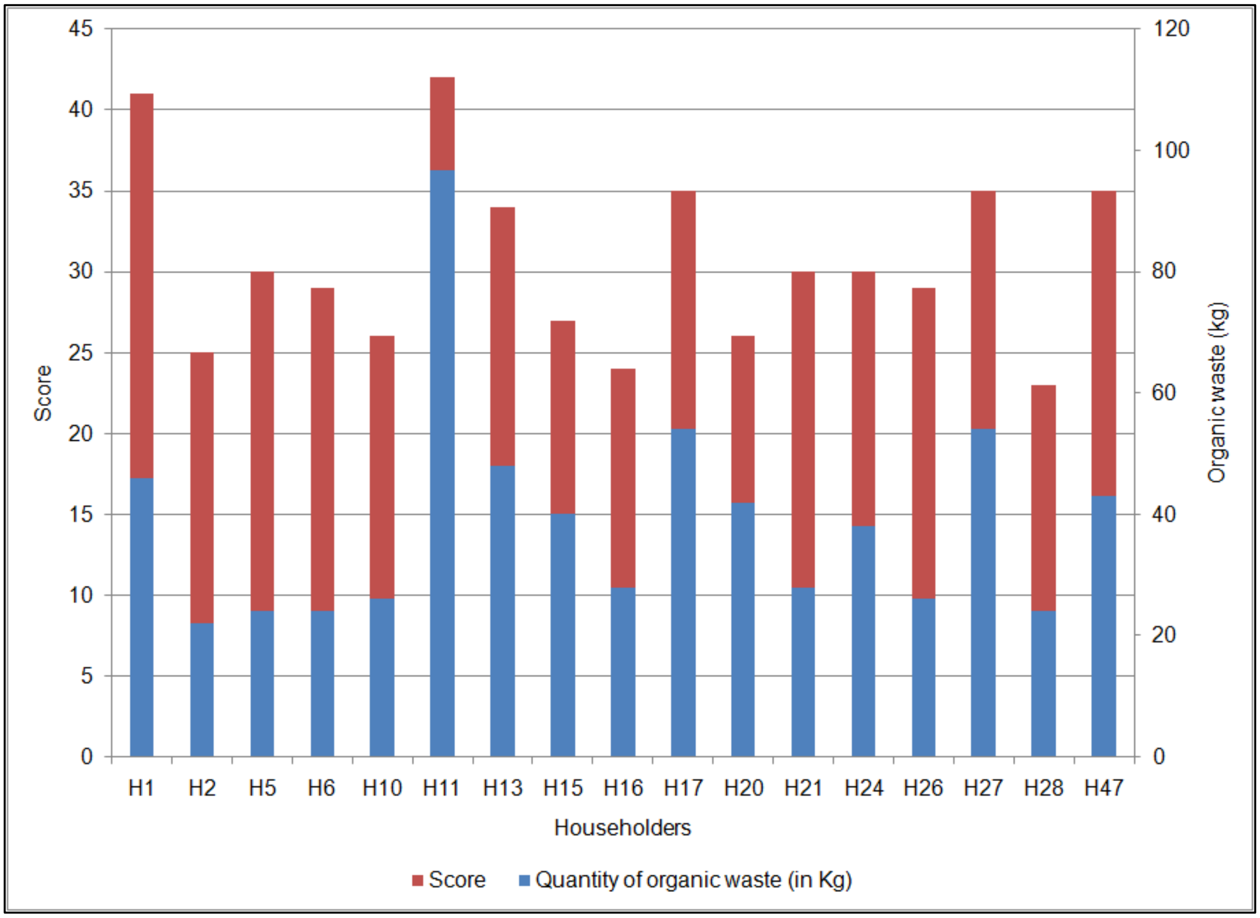

Figure 2.1.15. Scores for the 17 households producing over 20 kg day^{-1} organic wastes

Table 2.1.1 - Organic waste, water requirement and estimated biogas for households

	Householder code	Quantity of organic waste (kg day^{-1})	Water required (dm^3 day^{-1})	Estimated biogas (dm^3 day^{-1})	Score
Digesters installed	H11	97	290.4	4,312	42
	H1	46	92	1,960	41
	H17	54	162	2,280	35
	H27	54	162	2,440	35
	H47	43	129	2,510	35
	H13	48	144	2,240	34
	H5	24	72	960	30
	H21	28	84	1,200	30
	H24	38	114	1,640	30
Not installed	H6	24	72	1,120	29
	H26	26	78	1,080	29
	H15	40	120	1,760	27
	H10	26	78	1,240	26
	[1]H20	42	126	1,720	26
	H2	22	66	1,000	25
	H16	28	84	1,200	24
	H28	24	72	1,120	23

[1]Note – H20 was included in the study instead of H5 due to the high availability of biogas. H15 was not included because it was the same family as H13.

2.2. Selection of biogas unit size

The volume of digestate, V_{d} (m^3), is determined by the chosen retention time, T_{R} (days), and the daily volume of substrate (manure plus water) input, V_{s} (m^3 day^{-1})

$$V_{\mathrm{d}} = V_{\mathrm{s}} \times T_{\mathrm{R}} \qquad \text{Eqn. 2.2.1}$$

For a simple digester design such as this, to ensure complete digestion, the retention time should be at least 40 days (Price, 1981)

The ratio of the digester volume to the gasholder volume, V_{g} (m^3), is a major factor when designing a biogas digester. For a typical agricultural biogas plant, ratio $V_{\mathrm{d}} : V_{\mathrm{g}}$ is between 3:1 and 10:1, with the ratio most frequently being 5:1 - 6:1.

The volume of the gas is therefore less than

$$V_{\mathrm{g}} < \frac{V_{\mathrm{d}}}{3} \qquad \text{Eqn. 2.2.2}$$

Total volume of digester required, V_{t} (m^3), is given by

$$V_{\mathrm{t}} = V_{\mathrm{d}} + V_{\mathrm{g}} = \frac{4}{3} \times V_{\mathrm{d}} \qquad \text{Eqn. 2.2.3}$$

If the retention time is 40 days, then this can be expressed in terms of the volume of substrate as

$$V_{\mathrm{t}} = \frac{160}{3} \times V_{\mathrm{s}} \qquad \text{Eqn. 2.2.4}$$

The optimum digester volume was calculated for the selected households and resulted in 4 households requiring a 4m^3 digester; 3 requiring a 6 m^3 digester, 3 requiring a 8 m^3 digester and 1 requiring a 10 m^3 digester. To achieve more consistent experimental design, it was decided that a single size of digester would be preferred for all households. A digester size of 8 m^3 was selected as this was the volume of digester that most closely matched the requirement of most of the households.

2.3. Sourcing of biogas digesters

Because of the difficulties associated with obtaining flexible balloon biogas digesters in Uganda, the cost of the digesters is somewhat higher than was anticipated during the project planning. The digesters were obtained from Arjan Coenradie of the ChangeIT Foundation (info@changeitfoundation.com). The planned and expected costs of biogas digesters with volume 8m^3 and made from the more robust 850 g m^{-2} grade plastic are shown in Table 2.3.1.

This is consistent with other quotations received for Africa (8 m^3 digester C&F Kampala = £209/unit plus shipping costs – quality unknown; 6 m^3 digester from a Kenyan company, Biogas International, (http://www.biogas.co.ke/) = £437.12). There is a need to understand the reason for the relatively high costs of these digesters in SSA and to look for opportunities to reduce these costs.

Table 2.3.1 - Increased expenditure on biogas digesters

Item	Planned expenditure	Expected actual expenditure	Comment
1 x $8m^3$ anaerobic digesters made from 850 $g\ m^{-2}$ grade plastic	£60	£335	Reason for increased cost is the difficulty in sourcing the materials for biogas digesters in Uganda compared to other parts of the world
Number of digesters	10	10	
Total cost for digesters	£600	£3350	Difference in cost will be accommodated through savings in other parts of the project

The development of low cost biogas digesters using agricultural wastes will continue to be led by the private sector, but with government assistance. The scale of projects should be relatively small in order to make them affordable to the average family or community. However, the development of larger scale production and distribution of flexible balloon digesters are probably out of reach of the average local investor.

2.4. Installation of digesters

System description

The biogas digesters that have been installed are of the plug-flow type (Fig. 2.4.1). They consist of a bag with an elongated shape, with a length to width ratio of about 5:1. The wet organic waste is fed into one end of the digester and the effluent material comes out of the other end. The bag (digester) is mounted in a shallow ditch which supports the digester (bag) with the feedstock contained within it. The biogas produced bubbles out of the decomposing organic waste and is stored in the upper part of the bag. The gas is piped from the bag through a gas connection on top, and from there it is piped into the kitchen. In its least complex form, there are no systems for stirring or heating up the contents of the digester.

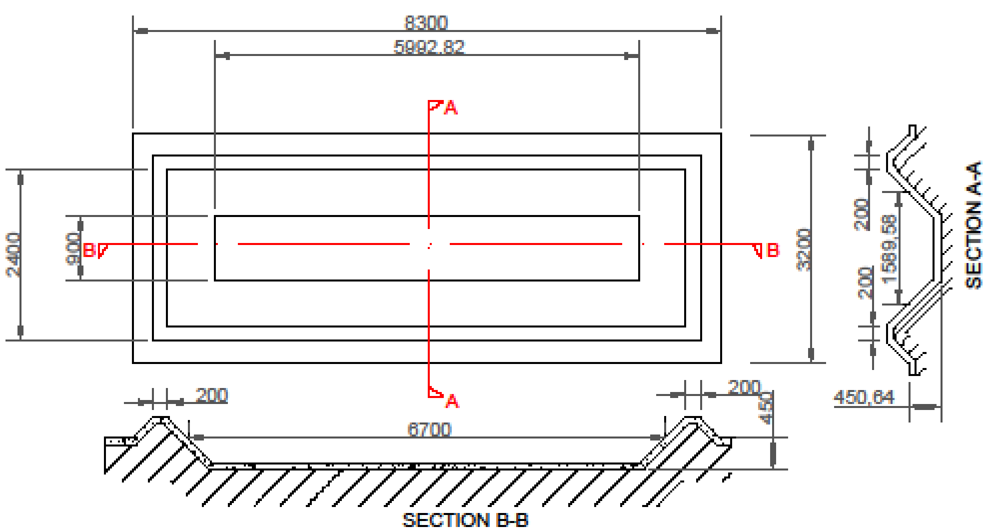

Figure 2.4.1 - Cross section of the plug-flow digester

The system is typically used for the digestion of animal manure and other organic matter. Any mixture should have dry matter content below 15% in order to flow through the digester (Arjan Coenradie, ChangeIT

Foundation, pers. comm.). For some types of feedstock, this means that water needs to be added to the mixture. The slurry occupies approximately 60-70 % of the digester volume; the remaining space is for gas storage (Arjan Coenradie, ChangeIT Foundation, pers. comm.). At average ambient temperatures of 25-30 °C, typical retention times are in the order of 40 days; this implies that the daily material input in litres should be 1/40th of the wet volume of the digester. Therefore, an 8 m^3 digester has a potential slurry content of 4.8 – 5.6 m^3 and should be fed with 120 – 140 litres of wet feedstock each day.

Installation description

A list of the items required for installation of the biogas digester is provided in Table 2.4.1 and depicted in Fig. 2.4.2.

Table 2.4.1 - List of items required to install the biogas digester

Item	Description
Digester Bag	Reinforced PVC, 0.85 kg/m2 (thickness) with standard flat dimensions: 6 x 2.6, Gas connection 1" thread
Inlet pipe	Diameter - 110mm PVC pipe with a 1.5m length
Outlet pipe	Diameter - 110mm PVC pipe with a 1.5m length
Fastening materials	30mm rubber strips from a car inner tube (8 m) and clamps
Hose pipe	1/2" hose pipe - 10m
Funnel	1 piece
Shovels	For ground work
Rope and pegs	Thin ropes (50m) and pegs for marking ground works
Measuring tape	For measuring excavation works etc
Sand paper	For rounding off inlet and outlet pipes

Figure 2.4.2 – Tools and materials used to install the biogas digester

The first step in the installation is the selection of the site. The site selected should be large enough for the digester bag, the inlet and outlet of the digester, and have additional space to enable the operator to walk around the installation. The ground should also be flat or slightly sloped. A position was selected on flat ground, close to the kitchen of the household hosting the digester. Installation of the digesters was combined with the training of local people in the installation. A full description of the installation method is given in the next section.

2.5. Training of local people

Training in installation

Householders were trained in installation of digesters; this was so successful that one householder installed his own digester without help from the team after having helped in the installation of a neighboring digester. Ditches with vertical walls were dug; the ditches were 10 m long, 1 m wide and 0.35 m deep from the bottom of the ditch (see Fig. 2.5.1). The corners and sides of the ditch were marked with pegs and rope. The ditch was excavated, putting the soil from the ditch around the edge of the ditch; this soil was used to make a wall around the digester. The depth and width of the ditch was measured regularly at several places in order to prevent digging too deep or too wide. The sides of the ditch were scraped off diagonally (see Fig. 2.5.2), arriving at the eventual dimensions of the ditch. The angle should be approx. 45 degrees in order to prevent caving in.

Figure 2.5.1 - Ditch with vertical walls

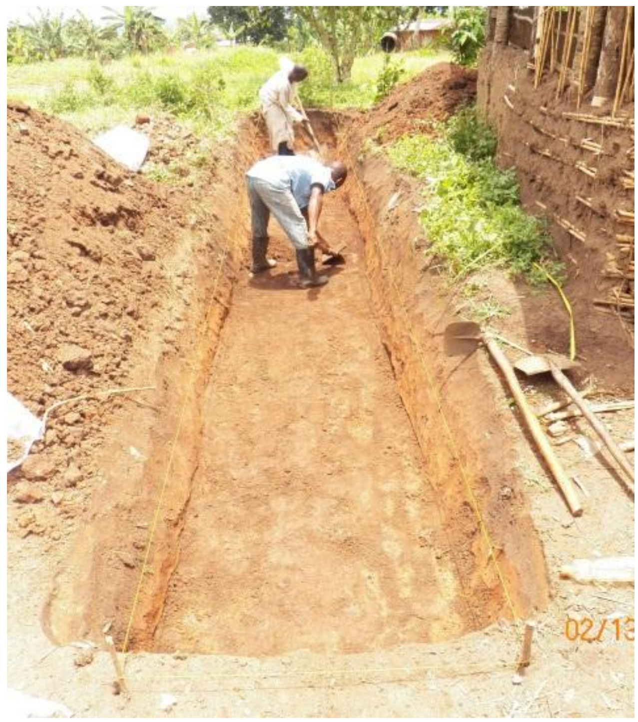

Figure 2.5.2 – Shaping of the sides of the ditch

Care was taken to ensure that the bottom and sides of the ditch did not have sharp rocks or roots sticking out. Rocks or roots that could potentially damage the digester bag were removed. The ditch was completed and the digester bag was gently placed inside with the gas connection facing the top. The inlet pipe was placed as shown in Fig. 2.5.3. The digester inlet pipe is made of a 4 inch PVC pipe, 1.5m long; it was connected to the two elbows as shown in Fig. 2.5.4. The digester inlet pipe was placed into the digester inlet sleeve and wrapped with a rubber band. The inlet pipe was later supported by an old car tire filled with soil.

Figure 2.5.3 - Digester in the ditch

Figure 2.5.4 - Inlet pipe

The digester outlet is made of the same 4 inch PVC pipe which is placed into the digester outlet sleeve and wrapped with a rubber band as for the inlet pipe. The gas hose tube was mounted on the gas connector on the digester bags (as shown in Fig. 2.5.5) and was taken inside the kitchen (see Fig. 2.5.6).

Figure 2.5.5 - Hose tube on a gas connector

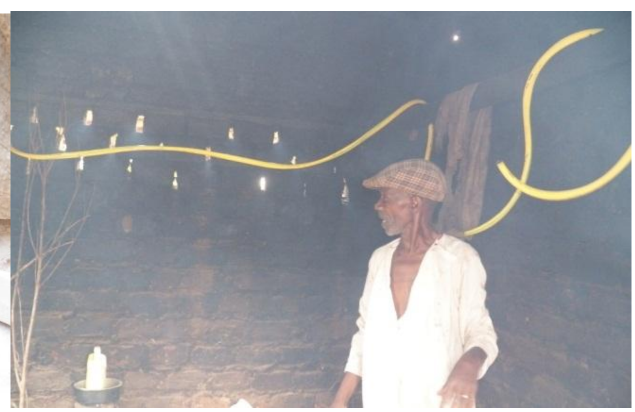

Figure 2.5.6 - Gas pipe into the kitchen

Training in startup and maintenance

Householders were shown how to prepare the feedstock before it is fed into the digester. We spent 40 minutes mixing cow manure with each householders, this enabled the consistency of the mixed manure to be adjusted before it was fed into the digester. After showing householders how to prepare the feedstock, they embarked on feeding the digester until it reached the required 2/3 of the digester capacity i.e. each household had to feed the digester with 20 barrels (volume ~250 litres) of mixed manure to kick start the digester. Each barrel is fed with 5 jerry cans of manure and 6-7 jerry cans of water (volume of jerry can = 20 litres) (Fig. 2.5.7 - 2.5.11).

Figure 2.5.7 - Heaped manure

Figure 2.5.8 - Team present during installation

Figure 2.5.9 - Manure in jerry cans

Figure 2.5.10 - Mixing barrel

Figure 2.5.11 - Mixing

Flexible balloon digesters need to be sheltered to keep the digester away from direct exposure to sunlight. Fig. 2.5.12 shows a digester shelter constructed from a plastic sheet with purchased materials costing 170,000 UGX. Fig. 2.5.13 and 2.5.14 show shelters made out of wooden stands and grass thatched. These are materials sourced from Tiribogo with no additional cost.

Figure 2.5.12 - Plastic sheet shelter

Figure 2.5.13 - Building the shelter

Figure 2.5.14 - Grass thatched shelter

After feeding the digesters the required amount of slurry, digesters were left for 21 days to allow gas to accumulate within the digester. The digester is strong enough to hold the body weight of a fully grown man after it is full of biogas (Fig.2.5.15 & 2.5.16).

Figure 2.5.15 - Two adults on top of the digester

Figure 2.5.16 - Cat on top of the digester

Testing biogas and awareness creation

A team of three comprising of Vianney Tumwesige (MSc2), Swaib Semiyaga (MSc3) and Lauren Hartoff (VS) travelled to Tiribogo for biogas awareness creation open day meetings with individual households. The open day meetings were done just before biogas use commenced. This was an orientation activity that enabled the biogas users to gain confidence about the whole system (Fig. 2.5.17 – 2.5.20). Biogas stoves were installed and biogas was tested. On this day, the information booklets (see Appendix E & F) were provided to the householders (Fig. 2.5.21). The contents of the booklet were discussed with the householders (Fig. 2.5.22).

Objectives of the awareness creation meeting:

- To inform households of biogas technology and its benefits. This know-how would be shared within the community;
- To demonstrate how biogas is made and works;
- To install the stove and test flammability of biogas (Fig. 2.5.17 & 2.5.18).

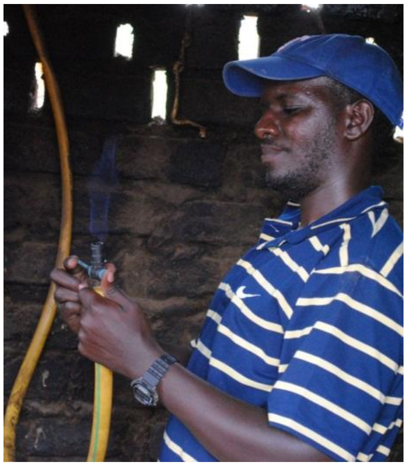

Figure 2.5.17 – Testing biogas

Figure 2.5.18 – Lighting the stove

Figure 2.5.19 – Biogas is hot

Figure 2.5.20 – Biogas in action

Figure 2.5.21 – Information booklet presented

Figure 2.5.22 – Awareness at household

Conclusion from training

Conducting a training session with the community requires lots of patience; many questions are asked leading to the same answer. It was decided not to use a step-by-step installation manual; this was in order to keep the householders and other volunteers engaged and empower them as part of the training team for other householders in the area. One householder managed to install the digester without help.

This was possible after he attended three installations where he was volunteering. This shows that the installation process is sufficiently clear to allow trainers to quickly learn the process so as to be able to train others.

2.6. Documentation of engineering problems associated with technical implementation

Sourcing Flexible Balloon Digesters in Uganda

Problem

Flexible balloon biogas digesters are not currently manufactured in Uganda. Importation of digesters greatly increases the cost (expected cost = £60 / digester; actual cost ~£335 / digester). This may make the cost of the digesters too high for many rural householders.

Possible solutions

Possible solutions include

Removal of barriers to uptake could be addressed by:

(a) **Improved tax incentives for renewables.** The Ugandan government needs to take action to remove existing policy barriers and make renewable energy developers eligible for tax and import duty exemptions and special tax deductions. *RECOMMENDATION: A summary report should be produced to provide information to appropriate government departments.*

(b) **Institutional strengthening of rural financial institutions.** There is a need to train the rural financial institutions in understanding and appraising renewable energy systems (biogas digesters) and develop a sound capacity to evaluate the viability of biogas projects for financing, monitor their performance, and debt collection. *RECOMMENDATION: An information sheet should be produced aimed at rural financial institutions. This should be sent to Ugandan institutions that might have an interest in funding biogas digesters and made available on the web.*

(c) **Promote technology for manufacturing biogas components.** There is a need to promote local manufacturing of high-quality components and related management expertise to improve overall efficiency of biogas production facilities. *RECOMMENDATION: An information sheet should be produced aimed at local manufacturing businesses. This should be sent to a number of Ugandan businesses, identified as having an interest in manufacturing parts for biogas digesters. It will also be made available on the web.*

(d) **Promote additional barrier removal**. Issues to be addressed include VAT, taxes, and additional tax incentives. *RECOMMENDATION: Recommendations for facilitating uptake biogas digesters should be included in a report sent to government departments.*

(e) **Establish a revolving fund** to provide financing specifically for digesters (access diverse funding sources);

(f) **Test application of methodology to produce digesters by folding plastics** – this is likely to produce digesters that are much less robust and with a shorter life-span than prefabricated digesters, but may provide an important option for cheaper digesters.

Damage of flexible tube by sharp objects during installation

Problem

The plastic in the tube can be pierced by sharp objects.

Solution

During excavation of the ditch to hold the digester, remove any sharp objects (roots or stones) from the walls of the ditch.

Damage of flexible tube by sharp objects after installation

Problem

The plastic tube is vulnerable to damage if not adequately protected from animals and other potential hazards.

Solution

Construct a fence around all or part of the digester to avoid animals damaging the digester. Damaged digesters can be mended using a patch and glue.

Figure 2.4.6 – Fixing faults: (a) Un-welded point on a digester (b) Glue applied to fix the digester (c) Taping the glued section

Manual handling of feedstock

Problem

Feedstock is carried and mixed in a bucket or container before it is fed into the digester using a funnel to transfer the feedstock into the digester. This increases labour and the handling is a potential source of increased infection.

Possible solutions

Position digester to minimize extra labour and handling of feedstock.

Gas Pressure

Problem

Flexible tube digesters have a constant volume, which means that the biogas produced has a variable pressure, depending on the volume of gas in the digester. After prolonged periods of cooking, the gas pressure can drop. The gas pressure and activity of the micro-organisms decomposing the organic waste are also more affected by changes ambient temperatures than in designs with better insulation, such as fixed dome digesters that are constructed underground.

Solution

Apply weight to the balloon when the gas pressure drops. Quantify the likely cooking time available from the digester each day so that a person cooking food is aware of the limitations in the amount of gas available before starting cooking. Consider further approaches to insulating the digester.

Gas Outlet

Problem

The pipe that transports the gas from the digester to the kitchen can bend, leading to possible blockage of the gas line.

Solution

Avoid bending the gas outlet pipe. An improved design might include a pipe that is resistant to bending at this point.

Damage of flexible tube by UV light exposure

Problem

The plastic in the tube can be degraded by prolonged exposure to UV light.

Solution

Construct a shelter over the digester to protect it from sunlight. Shelters in Tiribogo were constructed from thin plastics as well as from a thatched wooden frame.

2.7. Key findings from installation

A systematic scoring system was used to determine suitability of households to run a biogas digester based on availability of feedstock, access to water, requirement for biogas and ability to train others. The optimum size of the biogas unit was determined by the daily volume of substrate produced to achieve a hydraulic retention time of around 40 days. The cost of a flexible balloon digester was over five times the cost reported in Asia; this may contribute to the low uptake of this design in Uganda compared to Asia. Installation of the digesters was a simple procedure; each installation took only a few days and the method used for installation was easily learnt by householders. Problems with this design include potential damage of the flexible tube by sharp objects and UV sunlight, poor hygiene during manual handling of manure, maintenance of gas pressure and the cost. Problems with this design include potential damage of the flexible tube by sharp objects and UV sunlight, poor hygiene during manual handling of manure, maintenance of gas pressure and cost. Most of these problems are easily solved by providing better advice and repair kits with the digesters, but further work is needed to reduce the price of flexible balloon digesters.

3. Impact on energy, water and labour

3.1. Energy

Households in Tiribogo use firewood to meet their daily cooking fuel needs. This firewood is collected from Lwamunda Forest Reserve. A detailed household survey was administered using a questionnaire which captured information about the firewood source and distance from the households to the forest reserve. The moisture content of the firewood was measured using a Protimeter Mini (Fig. 3.1.1). This hand-held digital moisture meter was designed for general purpose moisture detection applications. It has two-pins located at the top of the main body with range from 6% to 90% wood moisture content. A weighing scale with a range of 0 - 100 kg was used to measure the weight of firewood used each day by the selected households (Fig. 3.1.2). This measurement was taken over the course of a week; the average firewood used is shown in Table 3.1.1.

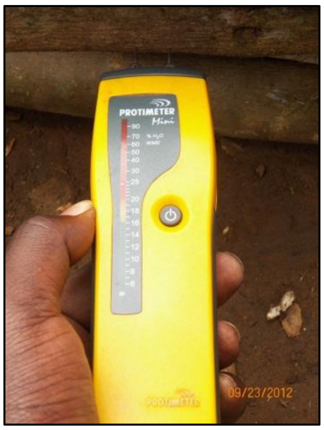

Figure 3.1.1 - The Protimeter Mini

Figure 3.1.2 – The weighing scale

Figure 3.1.3 – Weighing daily firewood use

According to Bailes et al. (2007), well-dried fuel contains 10-20% water, while fresh cut wood may contain more than 50% water by mass (wet basis). Firewood in Tiribogo had a moisture content ranging from 17 – 48 %. The high moisture content reduces efficiency and makes it harder to sustain a good secondary combustion. The moisture slows down combustion and cools the gases produced by pyrolysis. The high moisture content in wood may have contributed to the high firewood consumption shown in Table 3.1.1

Note that a number of assumptions have been used to estimate the time spent collecting wood (Table 3.1.1). Future work should measure the time spent collecting wood more directly.

The time spent collecting firewood was estimated from a simple analysis of the speed of walking completed with the householders in Tiribogo (Table 3.1.2). Using an average speed of walking of 88 m min^{-1} and assuming all wood used each day is collected in one trip, the average time spent collecting wood each day was calculated from the distance to the wood source. Note that this neglects the time spent finding or cutting the wood, and so may greatly underestimate the total time spent collecting wood.

The time spent collecting firewood after biogas was then calculated from the ratio of wood collected before and after biogas installation. This assumes that if less wood is needed, householders will carry the same amount of wood in each trip, and will collect wood less frequently.

Table 3.1.1. shows the daily firewood consumed; before biogas digesters were installed, households consumed 19 – 30 kg day^{-1}; after installation of the digester, this was reduced to 6 – 24 kg day^{-1}. The average reduction in time spent collecting firewood was a 2.58 hours week^{-1}. The demand for fuel wood

depends on the size of the family, but other factors such as moisture content and tree species have an impact on the quality of wood. H1, H11, H21 and H27 walked a round-trip of 2 to 4 km to collect firewood. As the forest reserve is rapidly depleting, the distance to collect firewood is expected to increase each year.

Firewood will remain as one of the main sources of fuel for cooking in Tiribogo, but households with digesters have the capacity to supplement their cooking fuel with biogas. H20 was able to reduce firewood consumption from 24 kg day^{-1} to 5.6 kg day^{-1}, H24 consumed 3kg of firewood less. However, H17 consumed 2.6 kg more firewood; this could be attributed to returning school children during the holiday at the time of measuring firewood consumption.

Table 3.1.1 - Firewood consumption

House-hold	Distance to firewood source (km)	Average firewood use before biogas (kg day^{-1})	[2]Time spent collecting firewood before biogas (min day^{-1})	Average firewood use after biogas (kg day^{-1})	[4]Time spent collecting firewood after biogas (min day^{-1})	Change in time (min day^{-1})
H1	1.8	30	158	[3]24	127	-32
H11	1.8	[1]23	158	[3]17	117	-41
H13	0.9	[1]23	79	[3]17	59	-21
H17	0.5	19	44	21.6	50	6
H20	0.25	24	22	5.6	5	-17
H21	1	20	88	[3]14	62	-26
H24	0.3	19	26	16	22	-4
H27	2	24	176	[3]18	132	-44
H47	0.9	24	79	[3]18	59	-20

[1]Average firewood use before biogas estimated from the average across households where measurements were available (23 kg day^{-1})
[2]Time spent collecting firewood estimated from the distance to wood and the average speed of walking (88 m min^{-1} – Table 3.1.2)
[3]Average firewood use after biogas estimate from the average observed change in firewood use where measurements were made (-6 kg day^{-1})
[4]Estimated from the time spent collecting firewood before biogas and the ratio of wood collected before and after biogas

Table 3.1.2 – Speed of walking

	Distance walked (m)	Time taken to walk distance (secs)	Speed of walking (m min^{-1})
H17	370	264	84
H17	300	125	144
H20	30	30	60
H24	480	354	81
H47	270	227.5	71
Average			88

3.2. Water

Distance to the water source was estimated by pacing between the household and the water source. Time to walk to the water sources was recorded using a stop watch.

Water is needed in the household for both domestic and non-domestic activities. Households in Tiribogo use water for a broad range of purposes, from the small quantities needed for drinking and cooking to larger volumes used for bathing, cleaning, washing, gardening and beer brewing.

Water is manually carried using a jerry can from a well/pond or a borehole for domestic use. At the same time, these jerry cans are used for water storage. There are no irrigation systems in Tiribogo. However, water is used when spraying crops with pesticides. Distances and time spent collecting water varies between households with the majority of homes in Tiribogo walking under 1 km to fetch water (Table 3.2.1).

Table 3.2.1 - Extra volume of water needed by households with biogas digesters to mix with the feedstock

Home	Distance to water source (km)	Average water use before biogas (dm^3 day^{-1})	Time spent collecting water before biogas (sec day^{-1})	Extra water needed for biogas (dm^3 day^{-1})	Time spent collecting water after biogas (sec $day^{-1)}$	Change in time (min $day^{-1)}$
H1	1.8	300	3600	60	4800	20
H11	1.8	120	7200	120	7200	0
H13	0.61	60	1200	60	1800	10
H17	0.35	80	1500	80	2400	15
H20	0.03	80	600	80	900	5
H21	0.1	120	1500	60	3000	25
H24	0.48	80	1500	80	2560	18
H27	0.26	120	1800	80	2600	13
H47	0.27	180	1800	90	2500	12

In general, water is one of the major factors reported by householders as limiting biogas production. However, in Tiribogo, 6 out of the 9 selected households were less than 500 m from the water source. H1 and H11, walked 1.8 km to the water source. Time taken to collect water varied. Households collecting water from a borehole needed to queue due to private ownership of some boreholes. Time spent queuing up for water reduces time available for other activities in the home. Nevertheless, the additional time required to collect water for the biogas digester was less than 25 minutes per day in all households.

Some households were only allowed to collect water at specified times (ie after dark), and this may have limited uptake more than the total time required to collect the water. Many community water sources are drying up, and anxiety over the reliability of the water source may be another factor. H1, H11, H13, H21 and H47 reported that time spent to collect water was the biggest challenge in using their digesters. Water was reported to be a major challenge for five households out nine with biogas digesters.

3.3. Feedstock

Manure collection

Livestock facilities use manure management systems to collect and store manure. These systems depend on the livestock size and grazing methods. In Tiribogo, manure collection was related to grazing method used. The animals spent the day grazing away from home and they only returned in the evening.

The farm size did not affect the manure management system.

After installation of the digesters, the manure was collected in solid form from the livestock holding area, taken to the mixing drum and later fed into the digester. Households in Tiribogo spend 5-10 minutes transporting manure from the livestock area to the mixing drum.

Manure mixing

The feedstock is deposited in an old oil drum containing water. The feedstock is mixed using either a spade or 1.5m long stick with a diameter of more than 4 cm until a consistent mix is attained. The mixing time ranges from 15 to 40 minutes, time of mixing is dependent on how dry or wet the manure is. Some households preferred to soak the feedstock for a couple of hours before they started to mix it. As the feedstock is soaking, the household spends this time tending to other household chores.

Feeding the digester

Finally, households feed the mixture into the digester through the inlet pipe. Some households have basins around the inlet pipe to prevent feedstock from spilling onto the ground. Many households in Tiribogo spends 10 to 20 minutes feeding the digester.

Slurry collection and application

With the exception of H24, many households had not started using the slurry by the time the project ended. H24 was applying the slurry on a section of a banana plantation to see if there would be any visible growth differences with the other parts of the banana plantation where slurry was not applied.

3.4. Labour

Contrary to the expectation, more labour is required from the household in order to run a biogas digester. The estimated extra labour needed to run the digester is shown in Table 3.4.1. This ranges from 20 minutes to 70 minutes every day.

Table 3.4.1 - Extra labour required to run a biogas digester

Home	Changes in labour due to installation of a biogas digester (min day^{-1})						Functioning digester?
	Firewood collection	Water collection	Manure collection	Manure mixing	Feeding the digester	Total	
H1	-32	20	7	35	15	45	N
H11	-41	0	10	35	15	19	N
H13	-21	10	10	30	15	44	Y
H17	6	15	5	30	15	71	Y
H20	-17	5	8	30	15	41	Y
H21	-26	25	8	40	15	62	N
H24	-4	18	6	30	15	65	Y
H27	-44	13	5	30	15	19	N
H47	-20	12	10	35	15	52	Y

The last column of Table 3.4.1. indicates whether the digester is currently functioning or not. It was suggested that the amount of labour needed to run the digester might be the main reason why householders were unable to keep the digester working. However, the results suggest there is no such relationship. H1, H11, and H21 all cite water collection as the primary reason for not feeding their digesters. The calculations in Table 3.4.1 suggest that H1 and H21 have the highest increase in time spent for water collection (20 minutes and 25 minutes, respectively). The hardship of water collection for H11 is not accurately represented by Table 3.4.1 because the household brings water in with trucks. Therefore, there is no time spent walking to collect the water, but water is still a valuable and limited resource, as they must pay to use the trucks. H27 has one of the lowest labour increases out of the nine households (19 minutes). The digester at this household was not functioning due to a large tear in the PVC material of the bag. The tear was repaired just before the conclusion of this study, and all observations and conversations with the householder indicate that the digester will be maintained and used routinely. The owner of H27 is very enthusiastic about using the digester and does not see the increased labour as a deterrent. From the calculations in Table 3.4.1, H17 and H24 experience the two greatest increases in required labour; yet, these two households have used their digesters more consistently and for a longer period of time than any of the other houses in the study. This observation shows that the success of the digester is not entirely dependent on change in labour. H17 and H24 both have very positive attitudes towards biogas and value the other benefits related to the system such as the provision of fertilizer and a cleaner burning cooking fuel. H20 was skeptical of digester use when the systems were installed, but realized the potential advantages after other households began cooking with biogas. This household pumps water from a borehole directly to their yard so the change in labour is lower than in many other households. H47 also has a higher increase in labour than many households (52 minutes), but they are very enthusiastic about using the biogas for cooking and do not seem to mind the extra labour. It seems that total labour is not the factor limiting uptake of biogas. It may be that water collection is a deciding factor because it is collected as a daily chore whereas firewood can be collected in advance and stockpiled until it is needed; it requires resources to be shared with others, and so extra demand has associated potential to cause disputes; and it is a limited and variable resource, so householders may be anxious about their ability to collect sufficient water at all times of year.

3.5. Key findings from analysis of energy, water and labour

The average reduction in time spent collecting firewood in households where digesters were installed was estimated to be 2.58 hours wk^{-1}, but the time needed to collect water increased by an average of 1.53 hours wk^{-1}. Together with the increased labour required to collect and mix manure and feed it into the digester (6.47 hours wk^{-1}), this increased total household labour by an average of 5.42 hours wk^{-1}. Mixing the manure is particularly time-consuming, representing nearly 50% of the extra labour; if time spent mixing manure and feeding the digester could be reduced, a biogas digester could potentially reduce household labour by an average of 10 min wk^{-1}. Changes in design and layout of the digester to reduce mixing and handling of manure are therefore of high priority for future work and would be likely to increase uptake of digesters.

4. Impact on carbon and nutrients

4.1. Establishment of trials to identify optimum return of agricultural products from applied nutrients

Training at University of Aberdeen

Laboratory training for C and nutrient analysis was carried out at UA for MSc3 during March and April, 2012. The MSc student was initially trained in basic health, safety and risk assessment of routine laboratory procedures and protocols, which are required for a safe working environment. All the nutrient and C analyses were performed on soil samples and digestate from an anaerobic digester. The student was trained in measurements of soil pH using a pH meter and the required calibration procedure, determination of gravimetric soil water content and determination of the organic matter content of samples using a furnace for combustion. Inorganic N (nitrate (NO_3^-) and ammonium (NH_4^+)) analysis was performed by a potassium chloride extraction followed by colorimetric analysis on a Flow Injection Analyzer. The student was shown how to operate the instrument and prepare calibration standards. The total N and C content of samples was performed by flash combustion on an Elemental Analyzer. The student was also trained in phosphorous (P) analysis, which was extracted from samples by two methods; an acetic acid extraction to estimate the bio-available P (labile form) and a sulphuric acid digestion to measure the total P concentration. P analysis was performed colorimetrically on a Flow Injection Analyzer. In addition, the MSc student was trained in the analysis of greenhouse gases (carbon dioxide (CO_2), CH_4 and N_2O) using a gas chromatograph and how soil gas fluxes are determined using static headspace chamber methods. Training for determining NH_3 emissions from digestate was performed in a sealed chamber by trapping the NH_3 volatilized in a boric acid indicator solution and the concentration determined by back titration using 0.01 N hydrochloric acid. Throughout all the analysis the student was shown how to operate the instruments by trained technical staff from UA, how to process the data collected and the necessary calculations required for expressing results in appropriate units.

Trials in Kabanyolo and Tiribogo

Description of site

In Kabanyolo and three other farms in Tiribogo, a randomized complete block design was established, including 3 replicates of the 4 treatments, A = No fertilizer, B = treatment with bioslurry, C = treatment with chicken manure which is the common practice in Tiribogo and D = treatment with a chemical fertilizer (Urea). The block size for each replicate measures 13.5 m x 3 m, which is 40.5 m^2. The individual treatment was allocated to each 3 m x 3 m plot by a simple randomized procedure. The blocks were positioned along the gently sloping gradient to minimize site variation due to fertility gradient, pest and disease drift, soil erosion between blocks and also within plots (Fig. 4.1.1). Land was prepared by deep ploughing followed by leveling for equal field distribution and eradication of weeds using a hoe. Experiments were run in the crop growing season of October 2012 to January 2013. Baseline measurements were taken before application of fertilizer to get the measurements of nutrient concentrations within the soils. Analysis was done in Makerere University laboratories at College of Engineering, Design, Art and Technology (CEDAT) and at College of Agricultural and Environmental Sciences (CAES).

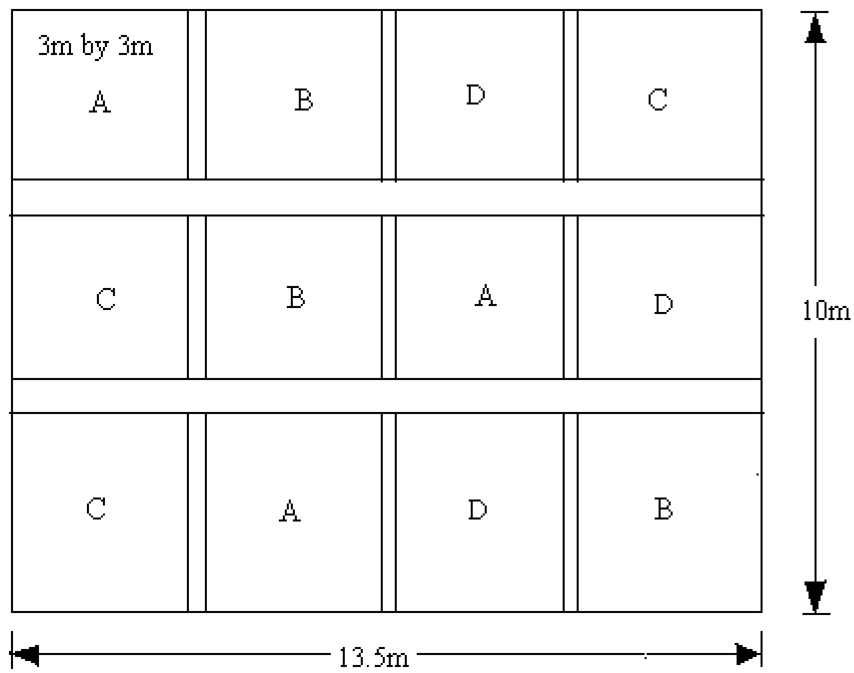

Figure 4.1.1 - Example of a randomised block design for different treatments at experimental plots

Type of crop

The initial survey identified Maize (*Zea mays L*) to be a common seasonal crop for all the selected households. In addition many crops such as bananas, pineapples, cabbages, sweet potatoes, passion fruits, tomatoes, ground nuts, coffee, yams, and pumpkins, etc are grown. Even though different farmers opt to apply slurry to different crops, it was decided to run all trials on maize to reduce the complexity of the trials and ensure comparability. Each 3m x 3m plot contained 55 holes for sowing at a spacing of 70 cm by 30 cm (Fig.4.1.2); three seeds were sown per hole, which were later thinned to one plant per stand. Maize (*Zea mayz L.*) of variety *Longe 4* was planted (Fig. 4.1.3 & 4.1.4)

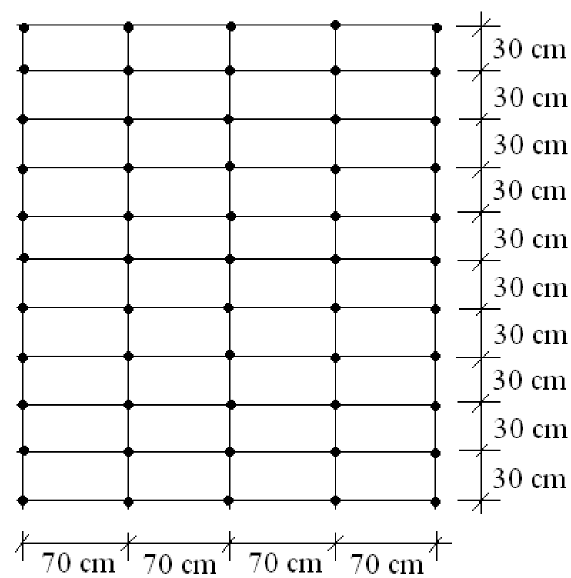

Figure 4.1.2 – Layout of maize plants in each plot

Figure 4.1.3 – Demarcation of plots (3m x 3m)

Figure 4.1.4 – Sowing of maize

Treatments

Four treatments were considered on each farm (urea, chicken manure compost, bioslurry and control) with three replicates making 12 plots per farm. Different treatments were assigned to each plot randomly (each treatment was written on a piece of paper, folded and randomly placed in each plot). Fertilizers were applied in each hole at a total rate over the season of 60 kg N ha^{-1}.

Control

A control was included on which no fertiliser was applied.

Bioslurry

The initial N content of the bioslurry was analysed to be ~1 g N dm^{-3}. Therefore, application of bioslurry at a rate of 60 kg N ha^{-1} requires (60 kg N ha^{-1} x 1 g N dm^{-3} x 1000 g kg^{-1} x (3m x 3m) plot / 10^{4} m^{2} ha^{-1}) = 54 dm^{3} bioslurry plot^{-1}. As there are 55 plants per plot, this is approximately equivalent to 1 dm^{3} per plant. Using split application of ¼, ½, and ¼ at 0, 20 and 55 days after sowing respectively (after the work of Dosch & Gutser, 1996), 250 ml were applied per hole at the time of sowing (Fig. 4.1.5 and 4.1.6). Two samples of bioslurry used were taken for further analysis to confirm the true rate of N present at the time of sowing so that the total amount could be corrected on the next applications.

Figure 4.1.5 – Collection of slurry from the digester

Figure 4.1.6 – Application of slurry at sowing

After sowing, it was realized that the bioslurry used contained an average of 3.75g N dm^{-3}. This implied that each plant needed 260 ml to make a total rate of 60 kg N ha^{-1} if that bioslurry composition was used. This was based on to correct the remaining amount of slurry since 250 ml was used during planting.

Urea

Urea contains 46% N, so for an application rate of 60 kg N ha^{-1}, 1.2 kg of urea was applied to each plot, which is equivalent to 22g per plant for plots 55 plants $plot^{-1}$. For split applications of 1/3 and 2/3 at the time of sowing and after 4 weeks respectively, 7.5g was applied to each plant at sowing time and 14.5g after 4 weeks.

Chicken manure compost

The chicken manure compost treatment followed common practice in Tiribogo, which is to fertilise maize during sowing using a composted mixture of chicken droppings and coffee husks. The N content of this compost is ~ 2% N $100g^{-1}$. Therefore, to apply N at a rate of 60 kg N ha^{-1}, 2.7 kg of chicken manure compost is needed per $9m^2$ plot. This requires 50g of chicken manure compost per hole in a plot with 55 plants. Following normal practice, this was applied in a single application at time of sowing. Samples were collected and taken to the lab to confirm the N content in the applied compost.

4.2. Measurement methods

Greenhouse gas emissions (CO_2, CH_4, and N_2O) were measured from each plot on a fortnightly basis for 3 months. Nutrients (NO_3^--N, NH_4^+-N, phosphate-P) were also measured in each plot on a fortnightly basis for 3 months. Other measurements taken on each plot on a fortnightly basis included soil moisture content, total N, total C, total P, total K, and pH.

Methane, carbon dioxide and nitrous oxide

Fluxes of CO_2, CH_4 and N_2O were trapped using a static chamber technique following the approach of Huchinson & Mosier (1981). Chambers for gas sampling were constructed using plastic buckets (Li et al., 2000) of 5.0 dm^3 with a height (H) of 21 cm and a diameter (d) of 10 cm at the top and (D) of 17.5 cm at the bottom. A pressure release device was installed in the bucket. The bucket was fitted with an air lock through which the gas was sampled. The chamber was fitted into the ground at a depth (h) of ~5 cm. Air samples were taken at time zero and after covering the soil surface for 60 minutes. A sample was taken using a 20 ml gas tight syringe which was initially flushed to ensure adequate mixing of air within the chamber (Bourdin et al., 2009). To check for linearity in gas production, samples were taken at 0, 20, 40 and 60 minutes. The sample taken was injected into a pre-evacuated 7 ml gas tight vial, overfilled to be under positive pressure and then transported and stored in the laboratory for subsequent analysis by gas chromatography. This procedure was used for measurement of CO_2, CH_4 and N_2O fluxes (Miles et al., 2006). The chambers installed in the plots are shown in Fig. 4.2.1. A diagram of the chamber system is given in Fig. 4.2.2. Air and soil temperatures were also measured using a digital thermometer during gas sampling.

Figure 4.2.1 – Gas sampling chambers installed in field trials at Kabanyolo

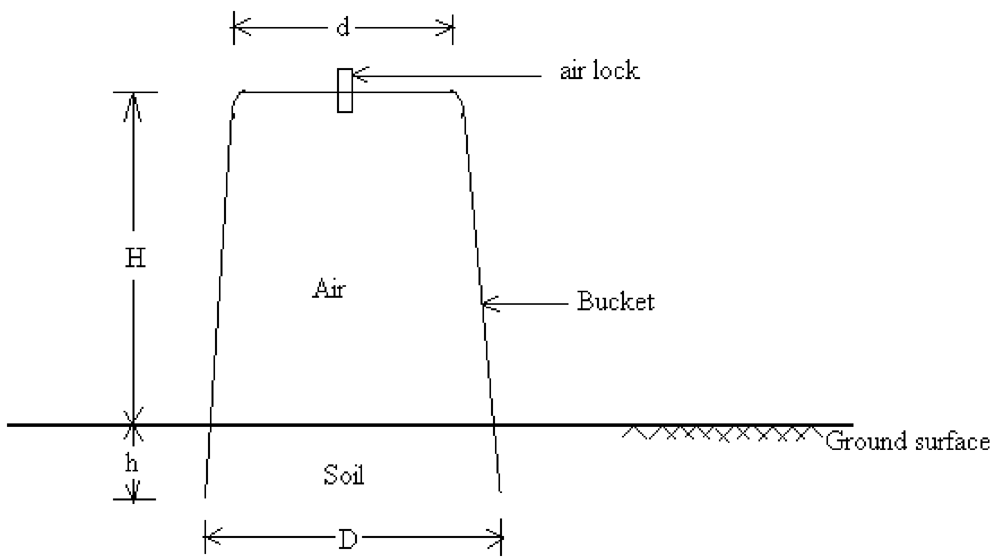

Figure 4.2.2 - Chamber used for gas sampling

The gas chromatograph is equipped with two channels; one coupled to an electron capture detector to determine the concentrations of N_2O and the other to a flame ionization detector to determine the concentration of CH_4 and CO_2 detected following methanization. All the three gases were analyzed from injection of one sample. The results provide an estimate of the CO_2, CH_4 and N_2O flux per unit area of the chamber per hour. These were used to estimate the emissions of these greenhouse gases per hectare over each sampling time. The detailed procedure is illustrated below.

1. Vials are evacuated using a vacuum pump. Fig. 4.2.3 shows the vacuum pump available at School of Engineering in Public Health Engineering Laboratory. Rubber tubing and a Y-Junction are used to enable evacuation of two glass vials at a time.

Figure 4.2.3 - Two glass vials being evacuated with a vacuum pump

2. One sampling bucket was placed in each plot. Three air samples were taken immediately after placing the chambers into the soil as shown in Fig. 4.2.4.

3. A gas sample was taken after 60 minutes from each bucket.

4. Each bucket was positioned at a time difference of ~2 minutes from one another to allow time during for collection of samples.

5. Two randomly placed buckets were used to collect samples for testing linearity in gas production. Samples were taken at 0, 20, 40 and 60 minutes (8 samples).

Figure 4.2.4 – Taking gas samples from the sampling buckets in field trial at kabanyolo

Ammonia flux

A modification of the flux chamber method is used to measure ammonia flux. Due to lack of power in the study area, it was not possible to measure ammonia using more sophisticated methods, such as using a wind tunnel, which needs power to operate. Back titration using 1N HCl was used to recover the trapped ammonia in boric acid (H_3BO_3) indicator. This indicator was made by dissolving 20 mg methyl red and 100 mg bromocresol green in 100 ml of 95% ethanol to make 100 ml of mixed indicator solution. 20 g of granular H_3BO_3 was added to 800 ml of distilled water, 20ml of prepared mixed indicator solution and 0.84 ml of 0.1N NaOH. The whole solution was made up to 1 dm^3 with distilled water. This H_3BO_3 indicator was used to trap emitted ammonia (NH_3). 25cm^3 of this acid trap (H_3BO_3) was added to a petri dish (9 cm in diameter, 1.5 cm high) placed on the soil surface inside the chamber. The chamber was pushed into the soil to a depth of ~5 cm. After 24 hours the acid trap solution was transferred to a plastic container and titrated against 0.1N HCl until the colour changed from green to orange. Ammonia was determined as milligrams of N that would be lost during the sample exposure to regulated air flow in the system. The N loss is calculated from the following formula (Miles et al., 2008) using the volume of HCl (ml) consumed in titration of H_3BO_3:

$$NH_3\text{-N (mg)} = \text{amount of HCl (ml)} \times \text{[HCl] (mol dm}^{-3}\text{)} \times MW_N \text{ (g mol}^{-1}\text{)}$$

where the molarity of HCl can be determined by standardization with NaOH and MW_N is the molecular weight of N, 14.01 g mol^{-1}.

Weather conditions

Air temperature was measured at 1m above the ground following the approach of Mapanda et al. (2011) while soil temperature was measured at 2–5 cm depth, measured in-situ at three randomly selected positions in each plot using a digital thermometer with 0.1 m long stainless steel probe (Salomon and Rhode, 2011). Precipitation was measured daily with a rain gauge at the experimental sites. Rainfall and temperature affect the rate of gas emissions and the nutrient flows in soils. Temperature was needed to convert gas concentration from ppm to mg m^{-2} hour $^{-1}$ using the ideal gas equation. All measurements were taken from 1 September 2012 to 1 February 2013.

Characterisation of soil

The mean moisture content, organic matter content, total solids, pH, total P, total N, total C, total potassium, NH_4^+-N and NO_3^--N were quantified using procedures described by Okalebo et al. (2002) for soil, feedstock, bioslurry and chicken manure. The soil was further tested for clay, silt and sand content. From each plot, ten soil samples were taken from randomly selected plants on top of the hole (covered after sowing maize). These were mixed together and one sample was packed in a ziploc bag and taken to the lab for analysis, three replicates were used. After germination, soil samples were taken from areas very close to the maize plant. Soil sampling was done on a fortnightly basis for a period of three months ((Fig. 4.2.5 & 4.2.6).

Figure 4.2.5 - Soil sampling in Tiribogo

Figure 4.2.6 – Collecting soil samples

The soil was analyzed for mineral-N, moisture content, pH, total N, organic matter, available-P, potassium and texture (%clay, %silt and %sand). The analysis was carried out following procedures described by Okalebo et al. (2002).

Moisture content and mineral-N (NH_4-N and NO_3-N) were analysed immediately on fresh samples, whereas pH, total P, total N, total organic C and available P were analysed on samples that were air dried and sieved through a 2 mm sieve.

Moisture content was determined by taking the weight difference between the wet sample and the sample after drying the sample for 24 hours at 105 °C.

The soil pH was measured using soil: distilled water ratio of 1:2.5 with a pH meter, after one hour of mechanical shaking.

Total N was determined using the Kjeldahl method in accordance to Okalebo et al. (2002) where a mixed catalyst was added to 0.5g of ground air dried soil sample followed by 5 ml of conc. H_2SO_4 and then digested for 2 hours at 350 °C. The mixture was then cooled and steam distilled to capture N. Mineral-N was extracted by shaking 10g of a soil sample with 50 ml of 2 M KCl for one hour and then filtered to obtain the extract. Nitrate-N was determined by adding Devarda's alloy to the extract followed by steam distillation into a boric acid indicator and then titrating with 0.005 M H_2SO_4 in a burette.

Characterisation of chicken manure compost

Samples of chicken manure were obtained from 3 randomly selected homes in Tiribogo.

Characterisation of bioslurry

Two samples were taken from each digester that was producing slurry; only two digesters were already in use at the time of the analysis. Total- N was determined in the lab using procedures described by Okalebo et al. (2002). Total N in the samples for the first digester was 0.84 & 0.89 g N dm^{-3} and for the second digester was 1.05 and 1.08 g N dm^{-3}.

Calculation of the required quantities of fertilisers

For a 3 x 3 m plot, at a plant spacing of 70 x 30 cm, there is a total of 55 plants.

Bioslurry

Assuming approx. 1 g N dm^{-3} of slurry, a total of 54 dm^3 of bioslurry should be applied per 9 m^2 plot. This means a total of ~1 dm^3 bioslurry per plant for a total of 55 plants in the plot. Hence for split applications, there is a need of about 250 ml at time of sowing, 500ml after 20 days and the remaining 250 ml after 55 days.

If the N content of slurry is variable over time, it may be difficult to maintain the consistent rate between treatments of 60 kg N ha^{-1}. In order to ensure consistency, the total N content of the slurry will be measurd before each application and the quantities will be corrected to apply the desired amount.

Chicken Manure

Assuming the N content of the sample is ~2 g N $(100g)^{-1}$ manure, approximately 2.7 kg of chicken manure should be applied per 9 m^2 plot to achieve an application rate of 60 kg N ha^{-1}. This comes to ~49 g of chicken manure per plant.

Urea

Urea has a fixed N content of 46%. Therefore 1.2 kg should be applied per 9 m^2 plot. This comes to ~22 g of urea per plant.

Data analysis

All data was statistically analysed in SPSS (v.20). Data was checked for normality and homogeneity of variance, and if appropriate log_{10} transformed. Multiple comparisons of means were performed by one-way analysis of variance (ANOVA) and if appropriate followed by Tukeys pairwise multiple comparisons procedure, unless otherwise stated. Comparisons of two means was performed by Student's *t*-test

4.3. Results and discussion

Soil characterisation

The soil texture was classified as sandy loam for H17 and H24, sandy clay loam for H27 and clay for Kabanyolo as shown in Table 4.3.1.

Table 4.3.1 - Characteristics of soil from experimental plots (mean ± standard deviation)

Soil characteristic	Household			
	H17	H24	H27	Kabanyolo
Organic Matter (%)	3.96±0.14	2.07±0.29	2.91±0.27	3.41±0.14
Ammonium nitrogen (mg kg^{-1})	13.27±2.62	10.07±2.60	23.33±0.51	25.80±1.51
Nitrate-nitrogen (mg kg^{-1})	11.03±0.61	16.93±2.47	0.13±0.01	0.19±0.01
Total nitrogen (%)	0.18±0.04	0.16±0.02	0.13±0.01	0.19±0.01

Soil characteristic	Household			
	H17	H24	H27	Kabanyolo
Moisture content (%)	26.97±1.75	22.27±0.65	23.33±0.51	25.08±1.51
Available phosphorus (mg kg^{-1})	5.57±0.66	42.31±6.40	4.20±1.27	7.51±0.76
Potassium (mg $100g^{-1}$)	0.34±0.07	0.93±0.11	0.32±0.03	0.39±0.11
Sand content (%)	67	62	56	44
Clay content (%)	13	17	21	41
Silt content (%)	20	21	13	15
Classification	Sandy loam soil	Sandy loam soil	Sandy clay loam soil	Clay soil

Nutrient flows

Air and soil Temperature

The variation in air and soil temperature was measured in the entire growing season with the average air temperatures ranging between 28.0°C and 32.0°C, whereas the average soil temperatures ranging between 22.2°C and 26.2°C. As shown in Fig. 4.3.1, the soil temperature pattern followed a similar pattern as air temperature.

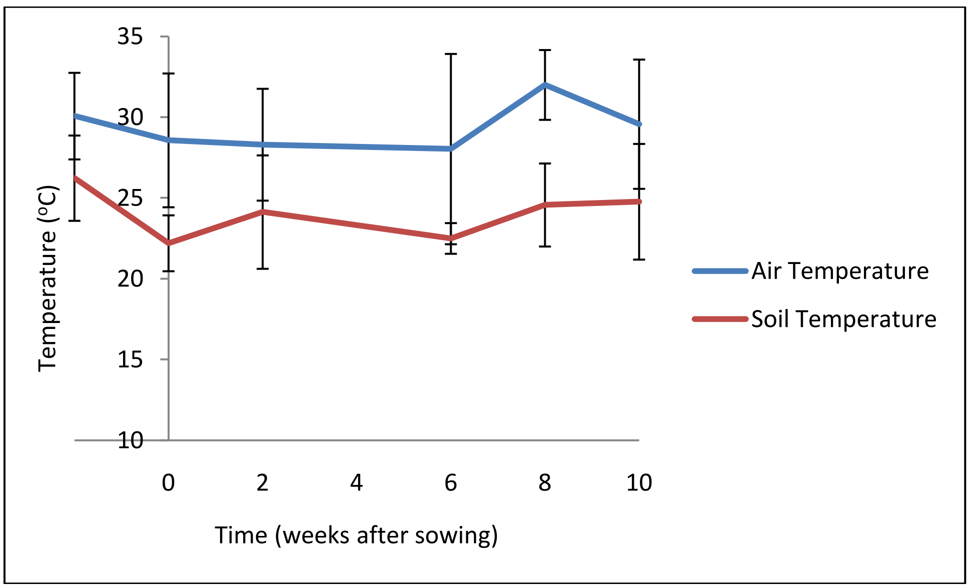

Fig 4.3.1 – Measured air and soil temperature

Moisture content

For all treatments, mean (standard deviation) water content varied between maximum of 26.67% (2.83) in chicken manure treatment at the time of sowing and the minimum of 12.21% (2.19) at two weeks after sowing (Fig. 4.3.2). This low moisture content could be attributed to the high soil temperature in the same week as shown in Fig. 4.3.1, potentially leading to evaporation of soil water. The soil pH also ranged from 4.9 to 8.4 through the season with an average pH of 6.39 (0.56) (Fig.4.3.3).

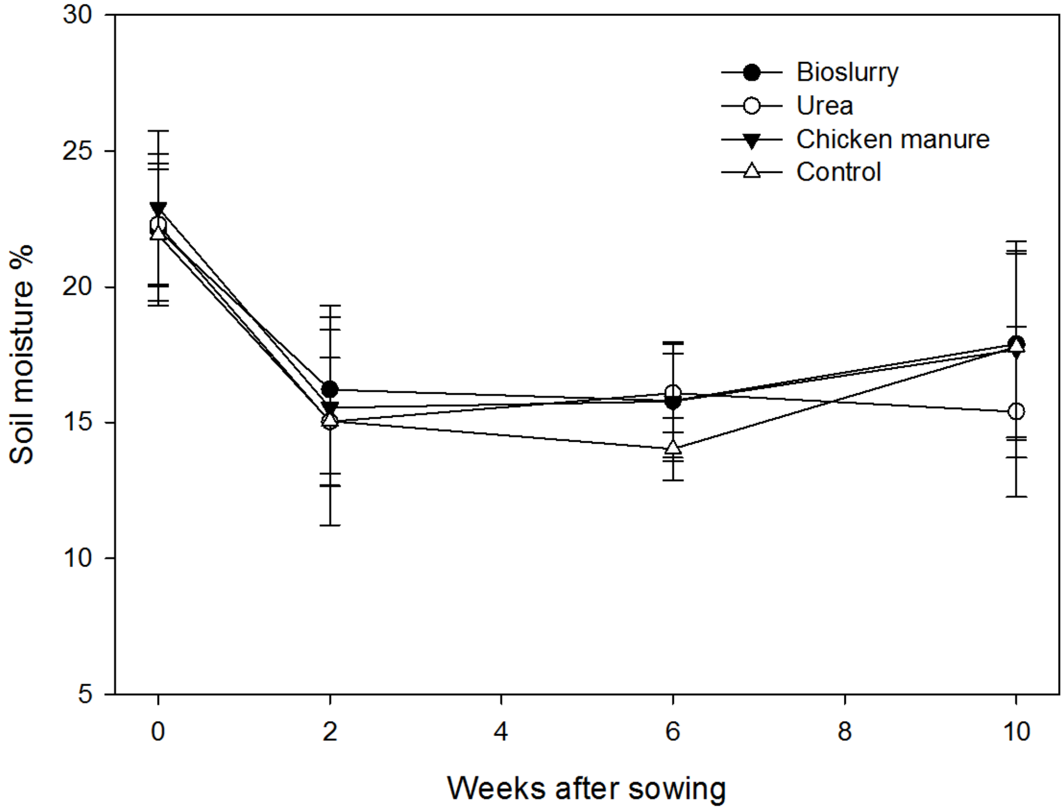

Figure 4.3.2 – Moisture content variation in different treatments

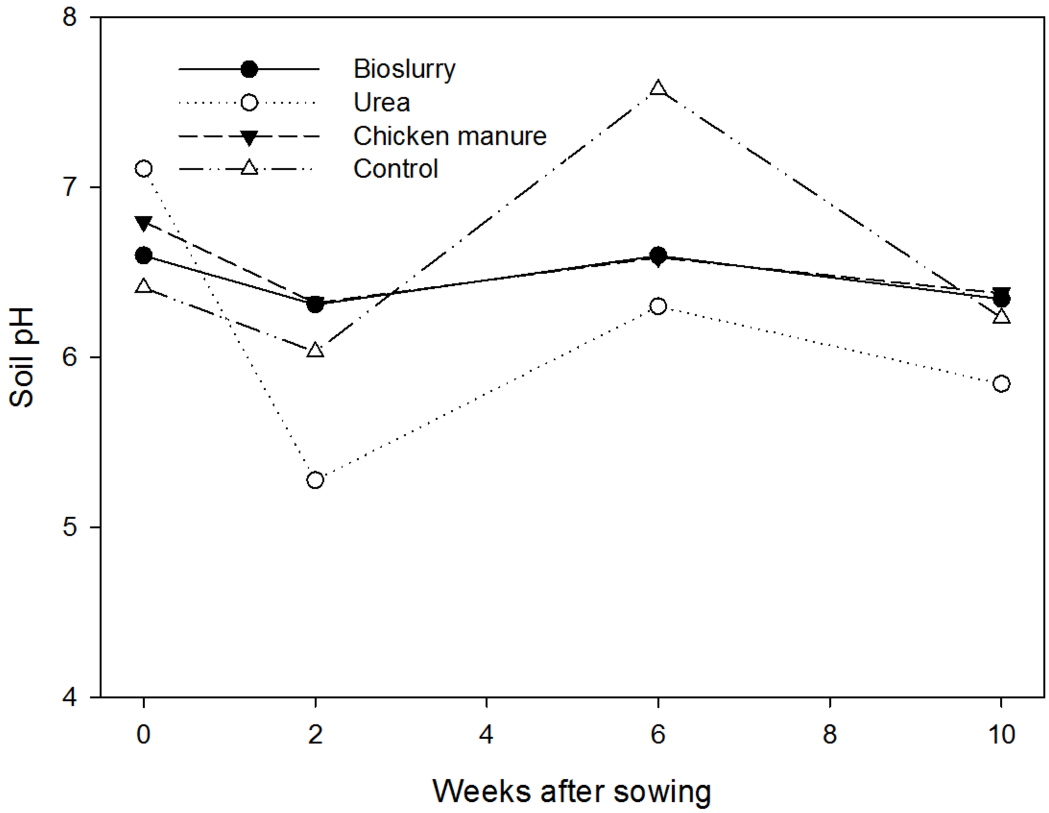

Figure 4.3.3 - Variation of soil pH

Nitrogen variation in feedstock and bioslurry

Fig. 4.3.4 shows the difference between the N in the feedstock (input) and bioslurry (output) on different measurement occasions. The average moisture content of the feedstock and bioslurry was found to be 93.0% and 93.4% respectively. The mean N content in the feedstock was 4.1 g N dm^{-3}, which was significantly greater (P<0.05) than the mean N content in the bioslurry (3.6 g N dm^{-3}). The results imply that a small quantity of N can be lost during the digestion process, but this most likely depends on the performance of the digester; for example. the difference between the feedstock and bioslurry N content in the fifth measurement is negligible.

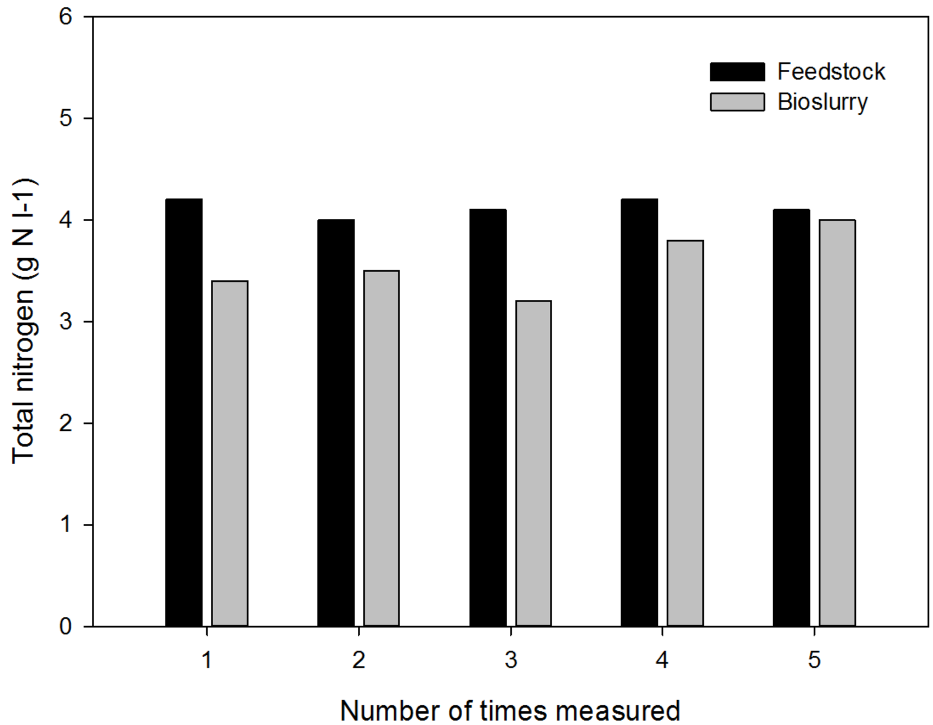

Figure 4.3.4 – Nitrogen variation in feedstock and bioslurry

Soil carbon and nutrients

Mineral nitrogen

Fig. 4.3.5 shows the variation in soil ammonium and nitrate over the period of the experiment. The levels of nitrate and ammonium are very much increased by the application of urea. Applied urea is hydrolysed to ammonium by urealytic microorganisms, making N available for plant uptake. The released ammonium is subsequently nitrified to nitrate as shown by the large accumulation of nitrate in soils (Fig.4.3.5) compared to the all the other treatments. Soil nitrate was significantly higher (P<0.05) in the urea treatments 6 weeks after sowing, most likely as a result of the second application of urea after 4 weeks. Soil nitrate pools did not increase significantly with the application of bioslurry, chicken manure compared to the control (no application), and remained below 100 kg NO_3^--N ha^{-1}. This was a surprising result, as the application of bioslurry to soils was expected increase ammonium concentrations, due to the generally high concentrations in bioslurry that makes it a suitable fertiliser providing an immediate plant available N source. There were no significant differences in amount of soil ammonium observed in the different treatments; this was most likely a result of the high variability in ammonium levels observed in the urea treatment.

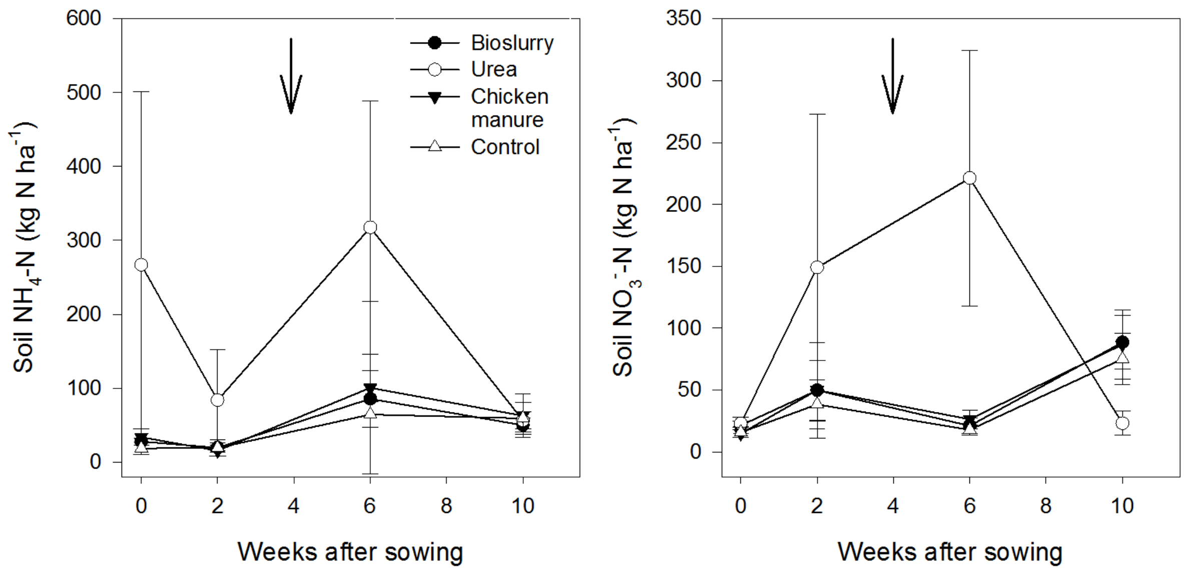

Figure 4.3.5 - Variation of mineral-N over 10 week period. The arrow represents the second application of urea in the split application in this treatment.

Total carbon and nitrogen

Fig 4.3.6 shows the changes in total soil C and N in the different treatments. The levels of total N measured are not very different in the 4 treatments. Total soil N concentrations were not significantly different between different treatments or over time in the same treatments. Although the overall trend was a decrease in total soil N with a mean of 3440 kg N ha^{-1} (at week 0) to 2246 kg N ha^{-1} (week 10) for all the treatments. Total soil C concentrations did not differ significantly between treatments or and did not change significantly over time in any of the treatments.

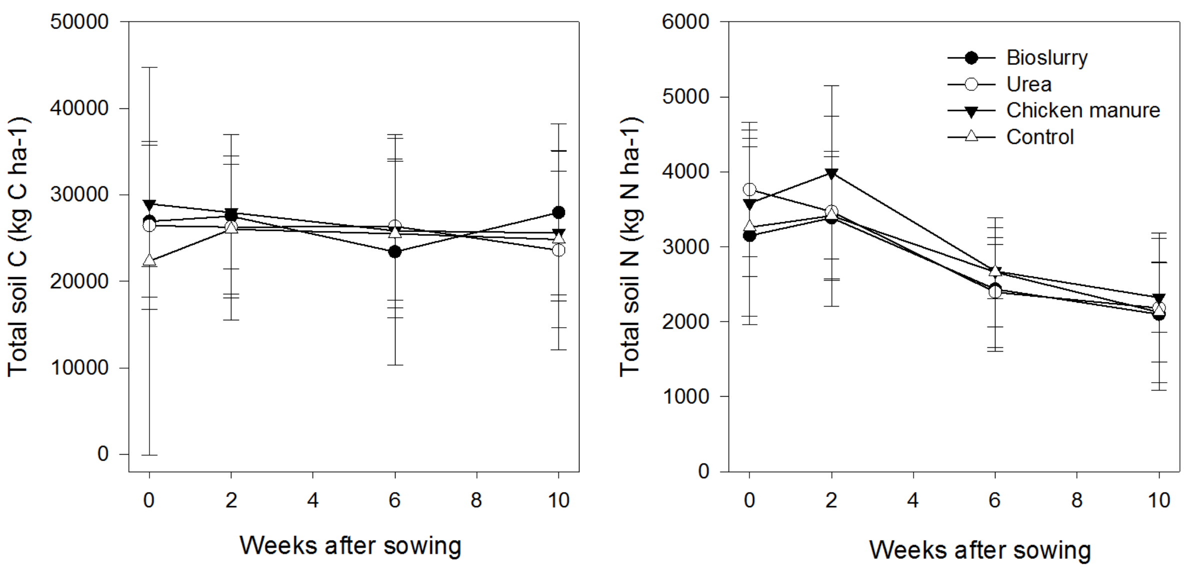

Figure 4,3,6 - Total soil carbon and nitrogen

Gas emissions

Nitrous oxide, methane and carbon dioxide

Figure 4.3.7 shows the total quantity of N_2O emitted from the experimental plots over the 10 week measurement period, calculated from the integration of the weekly measured soil fluxes. The data suggests that soils fertilized with urea resulted in the highest N_2O emissions with total N loss as N_2O-N of 5.5 kg N ha^{-1} over 10 weeks followed by chicken manure (1.6 kg N ha^{-1} over 10 weeks), control (0.43 kg N ha^{-1} over 10 weeks) and the bioslurry treated soil (-0.14 kg N ha^{-1} over 10 weeks). The application of bioslurry induced the lowest N_2O emission from experimental plots and the data suggest that bioslurry might result in soils acting as a weak N_2O sink. One-way ANOVA on ranks between mean N_2O emissions showed significant differences between treatments. However multiple comparison between means revealed that only N_2O emissions with the application of urea was significantly higher ($P<0.05$) than N_2O emissions from bioslurry applied soils. This has implications for the greenhouse gas balance of soils fertilised with bioslurry, which could result in a low N_2O loss from the applied nitrogen in the form of bioslurry compared to more conventional fertilisers such as urea.

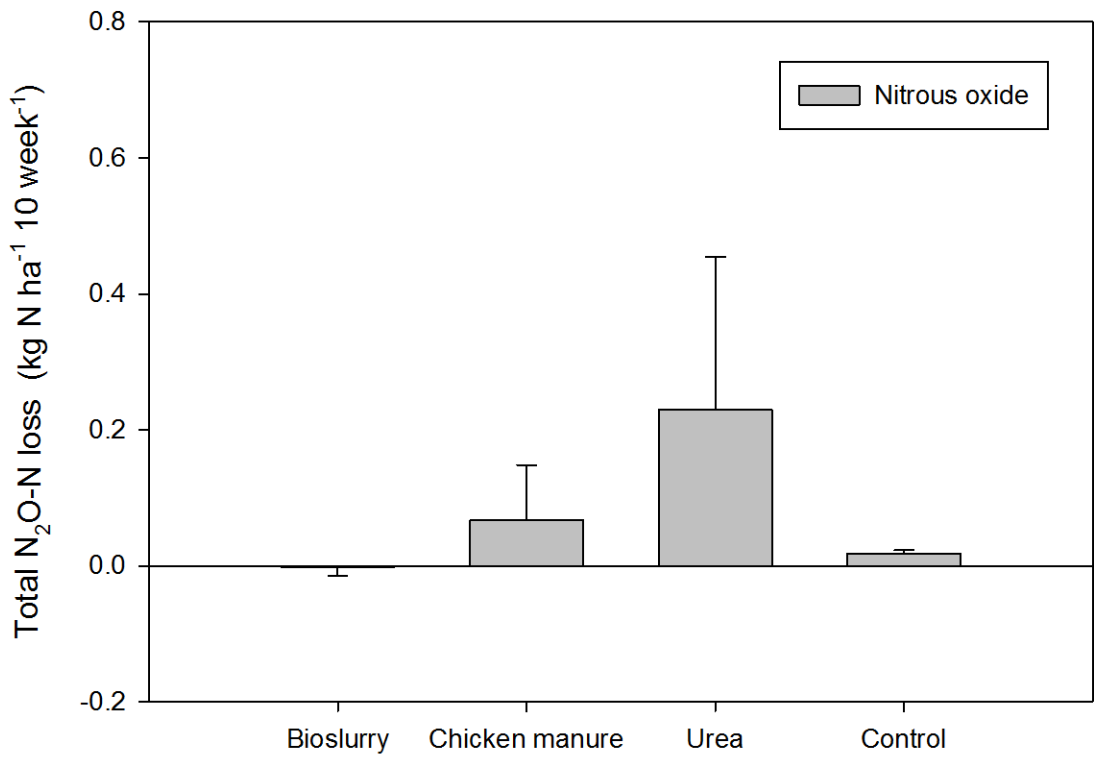

Figure 4.3.7 Total N_2O emitted over the 10 week measurement period. BS: Bioslurry CM: Chicken manure U: Urea C: Control treatment.

Figure 4.3.8 shows the total CO_2-C loss over the 10 week measurement period from the different experimental treatment plots. There was no significantly difference in CO_2-C emissions form soil between the different treatments. Soil emissions varied from 130 kg CO_2-C ha^{-1} over 10 weeks in the bioslurry treated plots to 229 kg CO_2-C ha^{-1} over 10 weeks in the chicken manure treated plots. Although CO_2 losses were not significantly different between treatments, an organic fertilizer, such as chicken manure, should result in greater soil CO_2 losses due to the input of an organic carbon source; the mean data suggests this occurs, but due to the high variability of the result it is not significant.

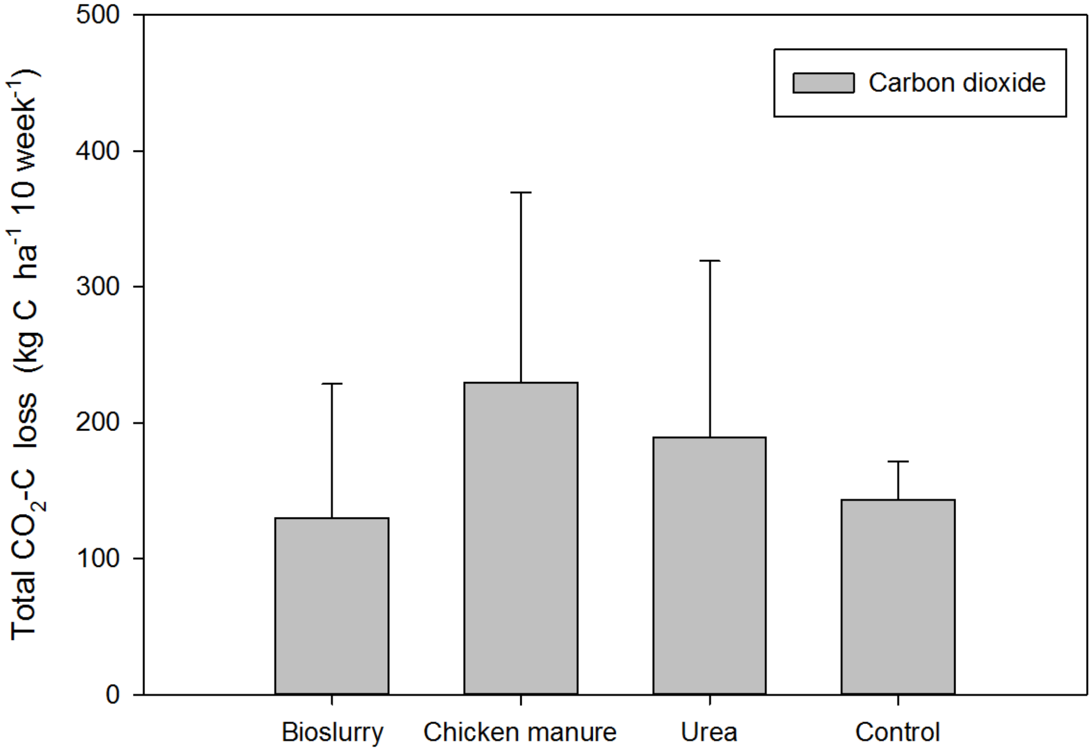

Figure 4.3.8 Total CO_2 emitted over the 10 week measurement period. BS: Bioslurry CM: Chicken manure U: Urea C: Control treatment.

Figure 4.3.9 shows that the total CH_4 fluxes from soils treated with biolsurry, chicken manure, urea were not significantly different from one another and were very close to zero with a large variability within treatments. Only the unfertilised control treatment exhibited a significant (P<0.05) net negative CH_4 flux (-0.018 kg CH_4-C ha over 10 weeks) when statistically compared to zero. Therefore, unfertilised soils acted as a CH_4 sink. This was likely to be a result of the low soil moisture content allowing the aerobic process of CH_4 oxidation to take place. The evidence for CH_4 oxidation in the fertilized treatments is unclear, but could be due to CH_4 oxidation being inhibited in soil by N application, which has been reported to occur with inorganic fertilisers.

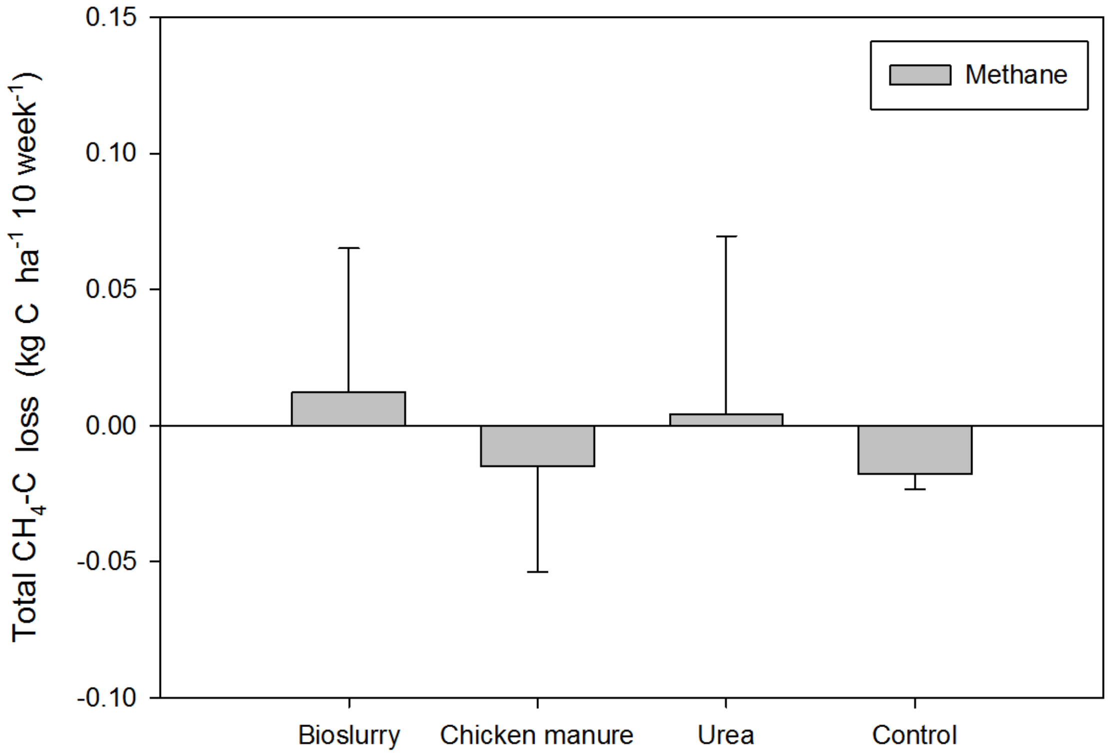

Figure 4.3.9 Total CH_4 emitted over the 10 week measurement period. BS: Bioslurry CM: Chicken manure U: Urea C: Control treatment.

Ammonia emissions

Ammonium emissions are presented in Fig. 4.3.10. Measurements of ammonia emissions were taken after sowing on the 20/12/12 and one month later, on the 22/01/13. On the first measurement occasion, highest mean levels of ammonia emissions were observed in urea treatment (nearly 5 times the emissions from the control), followed by chicken manure treatment (just over 1.5 times the control), followed by the bioslurry which had emissions less than 0.4 times greater than the control. On the second measurement occasion, ammonia emissions from the chicken manure treatment had increased while that of urea and bioslurry had decreased. These patterns reflect the amount of NH_4^+ observed in the soil in the different treatments (Fig. 4.3.5). The increase in emissions may be due to mineralization of N in chicken manure while the decrease of ammonia emissions in urea and bioslurry may be due to uptake by the crop or loss of NH_4^+ to the wider environment. One problem encountered was the high temperatures leading to evaporation of the boric acid indicator, leaving behind crystals that could not be titrated with HCl. Unfortunately, this meant the results were not replicated. No NH_3 emissions were observed in control plots on the second measurement occasion. Contrary to observations in other work that suggests the N in bioslurry is converted to provide a high concentration of NH_4^+, the N content of the bioslurry seems to be less susceptible to loss by volatilization than the N in chicken manure or urea. Since NH_4^+ volatilization can be a significant source of N loss in hot conditions, this suggests more N will remain in the soil to be taken up by the crop.

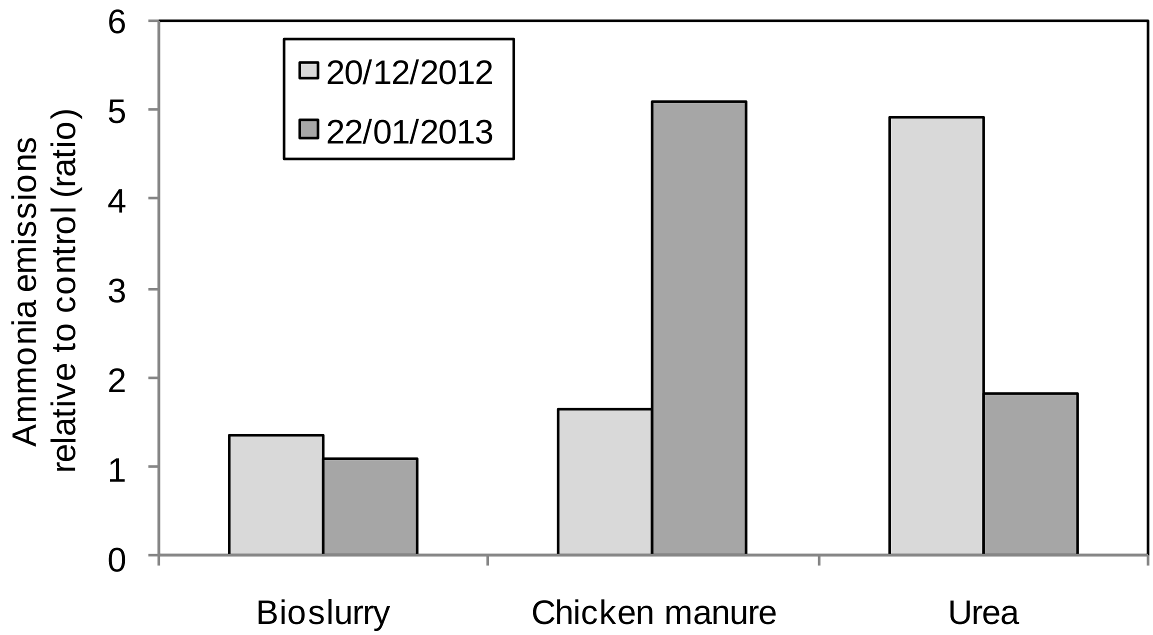

Figure 4.3.10 - Ammonia emissions relative to emissions from the control

Crop yield

At eight weeks after sowing, the maize crop was notably larger in the plots fertilized with chicken manure and bioslurry than in the plots fertilized with urea or the control (Fig. 4.3.11).

Plot fertilized with Urea

Plot with no fertilizer (Control)

Plot fertilized with Chicken Manure

Plot fertilized with Bioslurry

Figure 4.3.11 – Qualitative evaluation of different fertilizers at eight weeks after sowing

The yields for the different treatments are as shown in figure 4.3.12. There was a significant difference in the grain yields between the different treatments ($P<0.05$) and pairwise multiple comparisons revealed that the bioslurry treatment yielded significantly more ($P<0.05$) than the control treatment. There was no significant difference between the yield of maize seeds or stalks between the different treatments.

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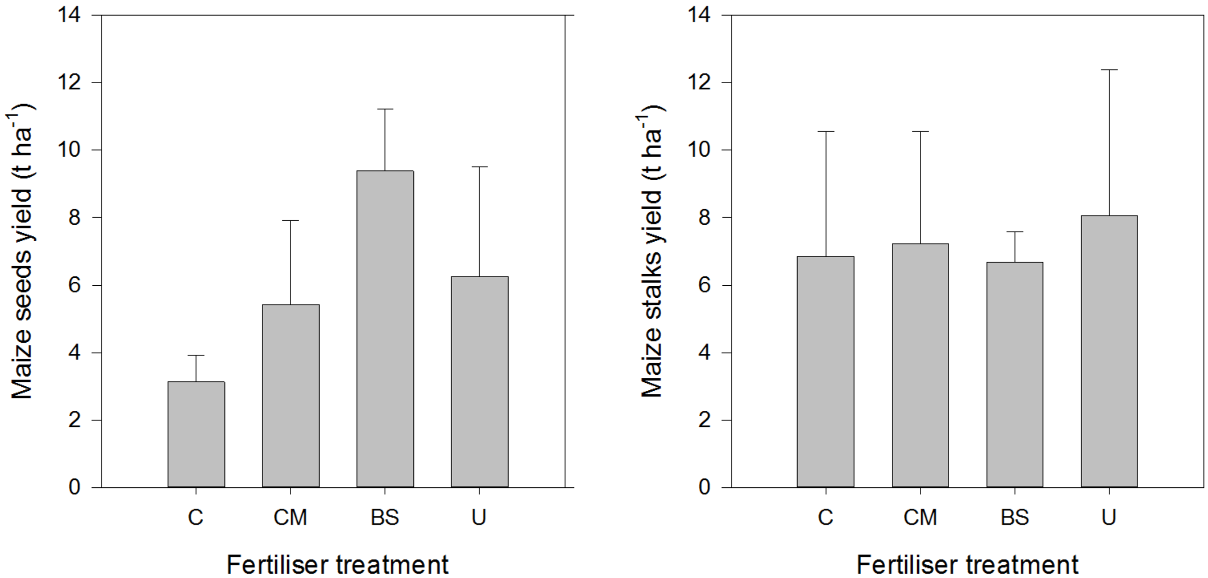

Figure 4.3.12 – Crop yields from different treatments. C: Control treatment. CM: Chicken manure BS: Bioslurry U: Urea.

The N content of the maize stalks and grain in the different treatments are shown in Fig. 4.3.13. The N content of the grain in the bioslurry treated plots appeared higher than in the other treatments, but this was not statistically significant.

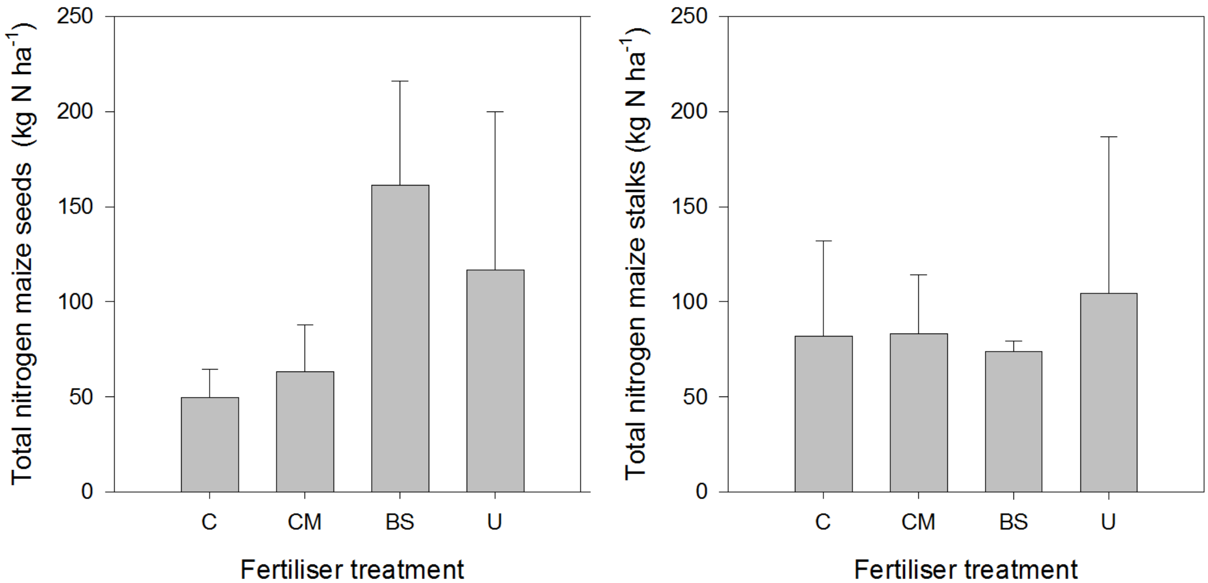

Figure 4.3.13 – Nitrogen content (kg N ha^{-1}) of crops from different treatments. C: Control treatment. CM: Chicken manure BS: Bioslurry U: Urea.

4.4. Key findings from analysis of carbon and nutrient flows

Analysis of the results suggests that when the same quantity of N is applied to soils as bioslurry, chicken manure compost or urea, N_2O emissions are significantly suppressed in the bioslurry treatments compared to the urea treatment. However, there are no significant differences between the treatments in emissions of CH_4 and CO_2. The data imply that application of bioslurry results in negligible N loss as N_2O from the soil; this result has important implications for global change. Ammonia emissions are also much reduced in the bioslurry treatments compared to chicken manure and urea. The yields of crops treated with bioslurry appear to be higher than the yields of crops treated with urea or chicken manure, but yields with bioslurry were only significantly different from the control plots. This is due to the high variability of results; more extensive trials would help to better determine significance. The result shows that bioslurry can be an effective fertiliser compared to conventional fertilisers or composted chicken manure. One advantage of using bioslurry as a fertiliser is the likely reduction in environmental damage due to greenhouse gas emissions. Losses of N during anaerobic digestion are very low; this could be used as an indicator for good reactor performance as the use of bioslurry as an effective fertiliser relies on retention of N during the anaerobic digestion process. Future work should include comprehensive crop trials to determine the optimum application rate for the bioslurry. Further analysis of the impact of the digestion process on the composition of the bioslurry (e.g. form of nitrogen) are required, so that the impact of the feedstock and the digestion conditions on the availability of nutrients to the crop and to processes in the soil that result in greenhouse gas emissions and loss of soil nutrients can be better understood.

5. Impact on household air quality and pathogens

5.1. Household air quality

Measurement methods

Household air quality was monitored in the nine homes that had been selected to receive the installation of a biogas digester in the village of Tiribogo. Household air quality was assessed by measuring the airborne concentration of two primary pollutants: $PM_{2.5}$; and CO. These metrics were chosen as they are commonly used to determine both outdoor and indoor air quality by national and international health protection agencies (e.g. WHO and US EPA). The TSI SidePak AM510 (Fig. 5.1.1) measures mass concentration by the use of optical scattering techniques and was used to monitor and log mass concentration of fine particulate. The CO data logger covered the 0 to 1000 ppm measurement range (Fig.5.1.2). Its operating temperatures range from -1 to 40^{o}C. This instrument was taped on the upper side of the cooling boxes which contained the TSI SidePak. Both devices were set to measure and log concentrations every minute over a 24 hour period.

Figure 5.1.1 - TSI Side Pak

Figure 5.1.2 – Lascar CO Logger

Monitoring took place within the room space in the household where the majority of cooking was reported to take place and, where possible, was carried out over a 24 hour period. Concentrations of both pollutants were logged every minute. The collected data was downloaded, time-weighted averages were calculated and peak (1 minute) concentrations found. The $PM_{2.5}$ concentrations collected by the SidePak were corrected by a factor 0.295 to account for the difference in density of the aerosol used to calibrate the SidePak and that created by the combustion process of organic matter.

Results

Tables 5.1.1 and 5.1.2 show the results of indoor air quality monitoring before and after installation of the digesters. Table 5.1.1 displays results for $PM_{2.5}$, while Table 5.1.2 displays results for CO. The means from Table 5.1.1 show that average concentration, peak concentration, percent of time greater than the US EPA 'hazardous' limit of 250 μgm^{-3}, and percent of time greater than the instrument measurement threshold all decreased from before to after installation of the biogas digester for $PM_{2.5}$. The percent time when levels were greater than the WHO limit of 25 $\mu g\ m^{-3}$ actually increased with installation of a biogas digester, but only slightly. The percent of time greater than the instrument threshold is important because all times greater than the threshold were recorded as 5900 μgm^{-3}, although the actual value was probably higher. This means that the average concentration reported for pre-installation is likely more conservative than that reported for post-installation. Table 5.1.2 shows that the average concentration, peak concentration, and percent of time greater than the WHO limit of 6 ppm decreased between pre- and post-installation for CO.

The column on the right for both tables shows the percent change of the average concentration for each home, where a negative percent change indicates a decrease in concentration. All homes except for H13, H17, and H27 showed a decrease in average $PM_{2.5}$ and CO concentration. The percent increase of $PM_{2.5}$ was exceptionally high (3171%) for H13. This trend can be easily explained because the family was cooking with charcoal in a larger room prior to installation of the digester. During the installation process, the family switched to using firewood instead of charcoal and began cooking in a smaller kitchen. When the post-installation measurements were taken the family had only just begun to use biogas for cooking and had not yet tried cooking many foods so they were mostly using biogas for making tea and firewood for all other foods. Outlier analysis revealed that H13 was an extreme outlier (> 3^{rd} quartile plus 3 times the interquartile range) and that H27 was a moderate outlier (>3^{rd} quartile plus 1.5 times the interquartile range) for $PM_{2.5}$. For CO, H27 was found to be an extreme outlier, and H13 was a moderate outlier. No explanation is currently known for the increases observed in H27. Tables 5.1.3 and 5.1.4 show the means and medians of percent change with and without the outliers. With both outliers excluded, the average percent decrease for $PM_{2.5}$ and CO was 32%.

Even with an average 32% decrease in $PM_{2.5}$ and CO, households with digesters were still exposed to unhealthy levels of both pollutants. The EPA Air Quality Index classifies 150 μgm^{-3} $PM_{2.5}$ as very unhealthy and 250 μgm^{-3} $PM_{2.5}$ as hazardous, and WHO recommends a 24 hour mean to be 25 μgm^{-3} or less for $PM_{2.5}$. In Tiribogo, the average $PM_{2.5}$ level for post-installation was 367 μgm^{-3}, exceeding all of the above guidelines. The average CO level post-installation was 6.2 ppm, only 0.2 PPM above the WHO recommendations.

Limitations of this study

Due to delays in digester installation and time limitations, this study could not include replicate measurements at each digester household. Each of the nine homes in the study with digesters was sampled only one time before and one time after digester installation. Without replicated sampling occasions for each home, the results are more susceptible to influence by unique circumstances such as visiting relatives in the household, children home from school (or away at school), and large celebrations that would influence the amount of cooking performed and therefore the levels of indoor air pollution. Variations in the types of trees used for firewood and moisture content in the wood would also affect cooking time and level of air pollutants. Also due to time limitations, the post-installation data was collected within a week or two weeks of a family first being able to light their stove with biogas. In this short period of time many families had not yet experimented with cooking different types of food and were not using their biogas to its full capacity. After a few months of experience with the biogas, many families are now using biogas more often and have replaced more traditional cooking with biogas than they had when the data for this study was collected.

Conclusion from indoor air quality measurements

Levels of two primary markers of air pollution, CO and $PM_{2.5,}$ in household kitchens generally decreased by about a quarter following the installation of a supply of biogas for cooking. Six of the nine households experienced improved air quality. Overall the improvements were modest and concentrations of air pollutants tended to remain above international health-based guidelines. Future studies should follow up with families who have been using biogas for longer periods of time to determine if CO and $PM_{2.5}$ levels decrease further once biogas use becomes more established within household cooking practices.

Table 5.1.1. Indoor air pollution by particulate matter in cooking area before and after installation of biogas digesters

Home ID	Pre-Installation						Post Installation						% Change Avg. Conc.
	Sample Time	Avg. (SD) PM2.5 Conc (μgm^{-3})	Peak PM2.5 Conc (μgm^{-3})	% Time > WHO Limit (25 μgm^{-3})	% Time > EPA Limit (250 μgm^{-3})	% Time > Instrument Measurement Threshold (5900 μgm^{-3})	Sample Time	Avg. PM2.5 Conc (μgm^{-3})	Peak PM2.5 Conc (μgm^{-3})	% Time > WHO Limit (25 μgm^{-3})	% Time > EPA limit (250 μgm^{-3})	% Time > Instrument Measurement Threshold (5900 μgm^{-3})	
1	24 h	83 (222)	2324	29	8.7	0.0	22 h, 48 min	57 (150)	2537	49	4.2	0.0	-31
11	22 h, 23 min	211 (531)	5040	38	17	0.0	24 h	110 (235)	2642	43	13	0.0	-48
13	23 h, 14 min	21 (57)	1560	34	0.40	0.0	24 h	687 (1404)	5900*	62	29	2.0	3171
17	24 h	187 (600)	5900*	59	14	0.4	7 h, 36 min	234 (420)	3826	71	26	0.0	25
20	21 h, 45 min	350 (504)	4600	69	38	0.0	20 h, 43 min	261 (835)	5900*	41	17	1.1	-25
21	24 h	828 (1520)	5900*	60	37	3.1	24 h	366 (887)	5900*	55	25	0.56	-56
24	22 h, 20 min	722 (1500)	5900*	83	31	3.7	24 h	562 (1224)	5900*	54	27	0.30	-22
27	24 h	189 (428)	4460	32	17	0.0	24 h	602 (1291)	5900*	51	30	2.6	219
47	24 h	1160 (1920)	5900*	64	41	7.3	18 h, 14 min	423 (1067)	5900*	61	23	0.64	-64
Mean	**23 h, 18 min**	**416 (393)**	**3597**	**52**	**23**	**2**	**21 h, 2 min**	**367 (221)**	**3002**	**54**	**21**	**0.8**	**-12**
												Median % Change	-25

*indicates that the maximum concentration of the SidePak was attained and likely exceeded

Table 5.1.2. Carbon monoxide in cooking area before and after installation of biogas digesters

Home ID	Pre-Installation				Post-Installation				% Change Avg. Conc.
	Sample Time	Avg. (SD) CO Conc. (PPM)	Peak CO Conc. (PPM)	% Time > WHO Limit (6 PPM)	Sample Time	Avg. (SD) CO Conc (PPM)	Peak CO Conc. (PPM)	% Time > WHO Limit (6 PPM)	
1	24 h	1.5 (4.6)	52	8.1	24 h	0.93 (4.8)	89	4.6	-38
11	22 h, 4 min	7.4 (16)	226	26	24 h	2.3 (8.6)	157	24	-69
13	23, 18 min	3.4 (13)	340	14	24 h	5.6 (13.2)	75	20	65
17	24 h	4.8 (13)	224	49	24 h	4.9 (9.8)	79	25	2.1
20	21 h, 45 min	5.6 (5.3)	26	44	24 h	5.1 (14)	109	22	-8.9
21	24 h	10 (17)	214	45	24 h	5.4 (9.8)	71	24	-46
24	22 h, 51 min	10 (13)	106	42	24 h	7.3 (11)	108	38	-27
27	24 h	3.5 (7.3)	84	21	24 h	18 (42)	308	40	414
47	24 h	31(4.6)	272	57	24 h	6 (12)	109	26	-81
Mean	**23 h, 20 min**	**8.6 (9)**	**172**	**34**	**24 h**	**6.2 (5)**	**123**	**25**	**-28**
								Median % Change	**-27**

*indicates that the maximum concentration of the SidePak was attained and likely exceeded

Table 5.1.3. Average percent change in $PM_{2.5}$ in cooking area with installation of biogas digesters

	Including all homes	Excluding H13	Excluding H13, H27
Mean Percent Change Average Conc.	352%	0%	-32%
Median Percent Change Average Conc.	-25%	-28%	-31%

Table 5.1.4. Average percent change in CO in cooking area with installation of biogas digesters

	Including all homes	Excluding H27	Excluding H13, H27
Mean Percent Change Average Conc.	24%	-25%	-32%
Median Percent Change Average Conc.	-27%	-33%	-38%

5.2. Pathogens

Methodology

Sample Collection

Environmental samples for microbial analysis were taken from each of the nine homes with digesters installed at three time periods: prior to digester installation, after digester installation but prior to using the biogas, and after cooking on the biogas has begun (Fig.5.2.1 - 5.2.4). Nine non-digester homes were also included in the study as controls. Five or six samples were taken from each home. Table 5.2.1 shows each house with the dates that samples were collected.

Table 5.2.1. Dates of environmental sample collection (swabs and boot swabs)

Home ID	Digester (Yes/No)	Date Samples Collected (mm/dd/yy)		
		Pre-Installation	During Installation	Post-Installation
H1	Y	9/4/12	10/2/12	1/15/13
H11	Y	9/4/12	10/25/12	1/15/13
H13	Y	8/28/12	9/25/12	11/16/12
H17	Y	8/21/12	9/18/12	12/5/12
H20	Y	8/28/12	9/15/12	1/15/13
H21	Y	8/28/12	10/24/12	11/16/12
H24	Y	8/21/12	9/18/12	11/16/12
H27	Y	9/11/12	10/24/12	12/5/12
H47	Y	8/21/12	9/25/12	1/15/13
HA	N	ND	10/24/12	ND
H25	N	ND	9/25/12	12/12/12
H37	N	ND	9/18/12	12/12/12
H101	N	ND	10/2/12	2/5/13
H102	N	ND	ND	1/22/13
H103	N	ND	ND	1/28/13
H104	N	ND	ND	1/28/13
H105	N	ND	ND	1/28/13
H106	N	ND	ND	2/5/13
H107	N	ND	ND	2/5/13

*ND=not done

Sterile cotton-tipped swabs were used to collect samples from residents' hands, door handles and dishes. Fabric shoe over covers were used to collect samples from the floors of homes, the ground around the outside of homes, and from the area where animals are kept if it was near the home. For these samples, the sole of one shoe was rinsed with water, scrubbed with a brush to remove dirt, rinsed with disinfectant, rinsed with water again to remove the disinfectant, and then dried with a clean paper towel. The fabric shoe over cover was then placed over the shoe, and the sample collector walked around the sample area. After walking around the sample area twice, the shoe cover was removed and placed in a clean plastic bag in a chill box.

Figure 5.2.1. Swab sample of hands

Figure 5.2.2. Swab sample of door handle.

Figure 5.2.3. Swab sample of dishes

Figure 5.2.4. Boot swab around animals

Samples were also taken from the influent and effluent of the digester (Fig. 5.2.5). Influent samples of mixed manure and water were collected in a sterile plastic tube. Effluent was allowed to drain from the digester for several seconds before a sample was collected in a sterile plastic tube. All samples were stored in a cool box until they could be moved to a refrigerator in the laboratory.

Figure 5.2.5. Mixing manure for influent sample

Sample Analysis

Samples were analysed in the laboratory for the presence of indicator organisms including *Escherichia coli*, total aerobic coliforms, *Clostridium perfringens*, and *Enterococcus faecalis*. *E. coli* and total coliforms were measured using the viable count method. Serial dilutions were made with buffered peptone water and plated on Chromocult agar (Fig. 5.2.6). Environmental samples were incubated for 24 hours at 44°C, and samples from the digester influent and effluent were incubated for 24 hours at 37°C. The samples from shoe covers and digester influent and effluent were also plated on Chromoselect agar and incubated anaerobically at 44°C for 24 hours to analyse the presence of *C. perfringens* and *E. faecalis*.

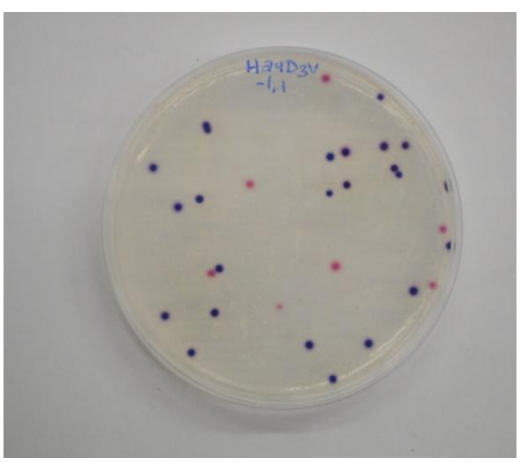

Figure 5.2.6. Example plate for analysis

Results

Feed and digestate results

Analysis of feed and digestate samples showed a reduction in pathogens through anaerobic digestion. Nineteen samples were collected over a three-month period from eight of the digesters installed in Tiribogo. The ninth digester was not active during the time of study due to a tear in the PVC material. The mean difference between log of colony forming units (CFUs) in the feed and digestate was calculated for each type of bacteria, and a paired *t*-test was used to determine if the difference between the means of the feed and the means of the digestate were significant. Fig. 5.2.7 shows the change in bacterial loading between feed and digestate, and Table 5.2.2 displays the results of statistical analysis.

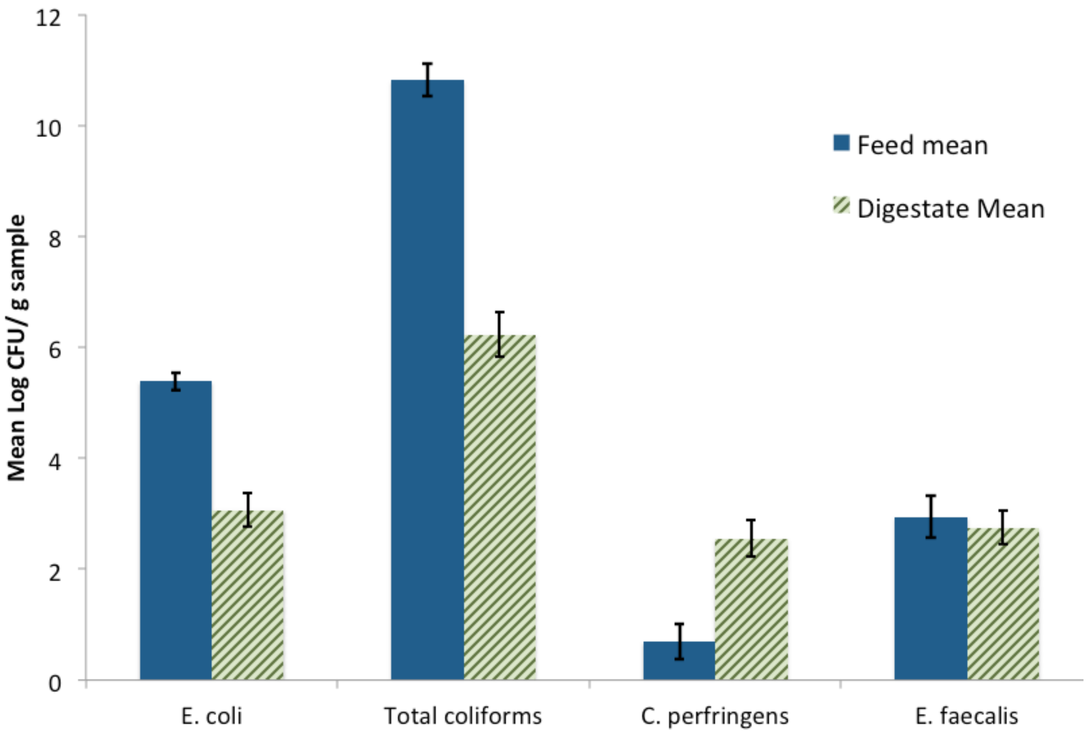

Figure 5.2.7. Bacteria reduction in digester

Table 5.2.2. Summary statistics of difference in bacteria between feed and digestate

Bacteria	Mean difference (Feed- Digestate) (log CFU/ g sample)	Standard deviation of difference	95% Confidence Interval	t-statistic	Two-tail p value
E. coli	2.32	1.62	(1.54, 3.10)	6.25	6.83E-06
Total Coliforms	4.58	2.15	(3.54, 5.62)	9.28	2.78E-08
C. perfringens	-1.86	1.67	(-3.53, -0.192)	-4.86	1.25E-04
E. faecalis	0.192	1.70	(-0.626, 1.01)	0.49	0.63

From Table 5.2.2, the mean reduction for *E. coli* (M =2.32) and total coliforms (M =4.58) were significantly greater than zero with p =6.83E-06 and p =2.78E-08, respectively. The mean reduction for *C. perfringens* (M =-1.86) was significantly less than zero with p =1.25E-04, indicating a statistically significant increase of *C. perfringens* through the digestion process. The change in *E. faecalis* was not statistically significant with p = 0.63. The data shows that aerobic pathogen indicators were reduced through the digestion process but that anaerobic indicators were not.

Table 5.2.3 shows the log decrease of *E. coli* and total coliforms and the average of the two values for each household. The table also shows the number of paired samples (feed and digestate) collected from each digester. The number of samples varied based on the activity of the digester. The samples were only collected from digesters that were being fed and were actively producing gas. From literature, retention time is known to influence reduction of bacteria (Kearney et al., 1993; Kumar et al., 1999). The retention time for this study was a minimum of 40 days but variable for each household depending on individual feeding rates. The highest average decrease was observed in home 11. This particular household did not feed the digester consistently due to difficulties accessing water. Other households who inconsistently fed the digester included homes 1 and 21. Home 47 was only sampled once before a tear in the digester impeded use for the duration of the study period. Homes 17, 20, and 24 were fed consistently during the sampling period. The average log decrease for these homes was lower than that for all of the homes combined, but was still comparable or higher than the values reported in literature [Kumar et al., 1999].

Table 5.2.3. Individual home analysis for feed and digestate results

Home	**Log Decrease: Feed to Digestate**			
	No. of samples	***E. coli***	**Total coliforms**	**Average**
1	1	3.70	4.38	4.04
11	2	5.97	6.99	6.48
13	3	1.87	2.66	2.27
17	3	2.35	6.36	4.36
20	3	1.03	2.89	1.96
21	2	1.70	4.33	3.02
24	4	1.75	4.11	2.93
47	1	2.36	7.85	5.11

Environmental microbiology

Table 5.2.4 displays results for changes in *E. coli* and *C. perfringens* counts for each digester household. All samples from hands, dishes, door handles, in the home, and outside the home were averaged to find the overall log decrease for each organism. Samples taken in the intermediate time period were excluded from this analysis to allow focus on the overall change observed.

Table 5.2.4. Summary of digester homes with *E. coli* and *C. perfringens* data averaged from swab and boot swab samples

Home ID	**Number of Household Members***	**Cows**	**Pigs**	**Animals Grazed Away From House (Yes/No)**	**Manure Management**	***E. coli* Pre-Installation* (Log CFU/ sample)**	***E. coli* Post-Installation* (Log CFU/ sample)**	**Log Reduction *E. coli* (Log CFU/ sample)**	***C. perfringens* Pre-Installation* (Log CFU/ sample)**	***C. perfringens* Post-Installation* (Log CFU/ sample)**	**Log Reduction *C. perfringens* (Log CFU/ sample)**
H1	20	5	2	Y	Compost	1.45	1.79	-0.34	1.7	< 3.40	(-1.70, 1.70)**
H11	4	16-18	11	Y	Applied directly to field	0.680	1.18	-0.5	2.22	< 3.40	(-1.18, 2.22)**
H13	7-10	4	8	Y	Applied directly to field	< 3.40	0.48	(-0.48, 2.92)**	< 3.40	< 3.40	(0, 3.40)**
H17	8	6	3	N	Manure dried before application to field	< 4.40	2.27	(-2.27, 2.14)**	< 3.40	3.70	(-3.70, -0,30)**
H20	6	5	1	N	Manure dried before application to field	< 3.40	1.94	(-1.94, 1.46)**	< 3.40	2.20	(-2.20, 1.20)**
H21	10	3	2	Y	Unknown	< 3.40	0.71	(-0.71, 2.69)**	< 3.40	3.85	(-3.85, -0.450)**
H24	4	5	3	N	Applied to trench in the field	3.2	1.45	1.75	< 3.40	< 3.40	(0, 3.40)**
H27	9	5	7	N	Unknown	1.89	2.34	-0.45	3.88	4.31	-0.43
H47	10	5	4	N	Manure dried before application to field	3.2	2.18	1.02	< 3.40	< 3.40	(0, 3.40)**

***** Bacteria loads calculated as mean of all sample types for each household. Boot swabs taken around the animals were excluded for comparison purposes because they were only available for select households.

** Log reduction expressed as a range based on the pre-installation log CFU value equaling between zero and the limit of detection.

Fig. 5.2.8 shows the results from shoe over covers inside homes before, during, and after digester installation as well as non-digester homes at the time periods during and after digester installation. The results show an increase in *E. coli* after digester installation for digester homes, which could be related to increased handling of manure. However, the *E. coli* load in the digester homes after installation was not greater than that of the non-digester homes during the same time period. The homes with no digester contained more *E. coli* during installation than the homes with digesters. There was no change in the non-digester homes between the "during" and "after" periods, which lends some confidence that the observed increase in digester homes over the same time period was due to the installation of the digester. No change in *C. perfringens* was observed across digester or non-digester homes. Note, the statistical significance of these results has not been established due to lack of statistical power.

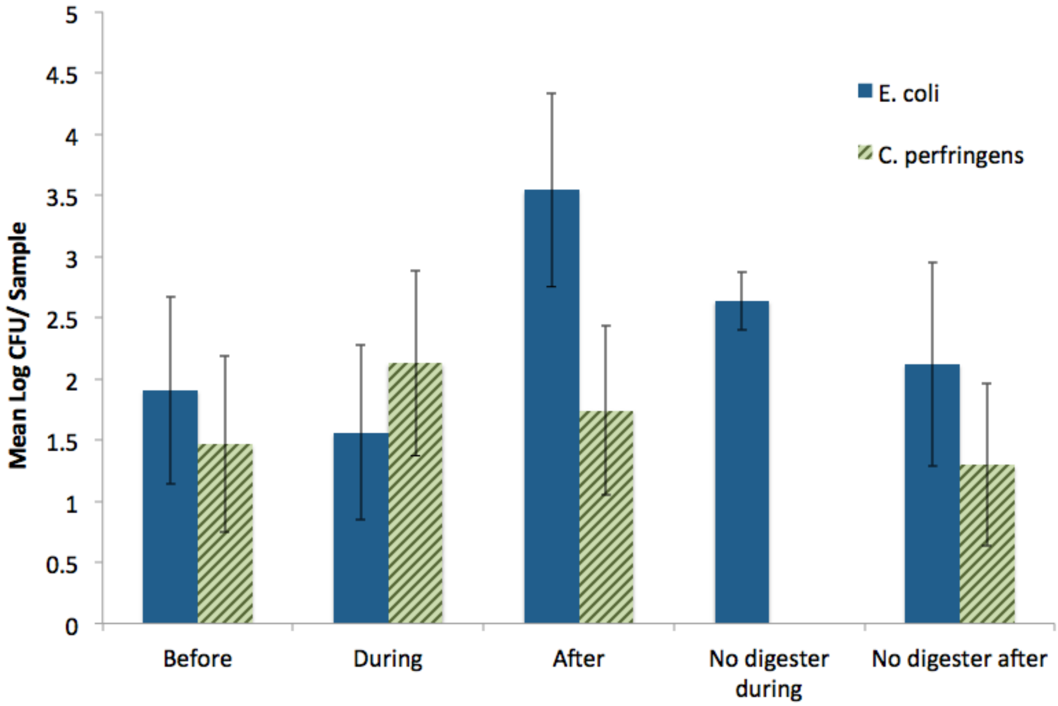

Figure 5.2.8. In-home shoe over covers

Fig. 5.2.9 shows the results for shoe over covers outside the home during the same time periods as in Fig. 5.2.8. *E. coli* showed a similar trend for boots swabs outside the home as it did for boot swabs in the home (Fig. 5.2.8). *C. perfringens* also increased for digester homes during and after installation, which suggests that stockpiling of manure in the "during" time period caused increased contamination. No-digester homes showed no significant change in *E. coli* or *C. perfringens.*

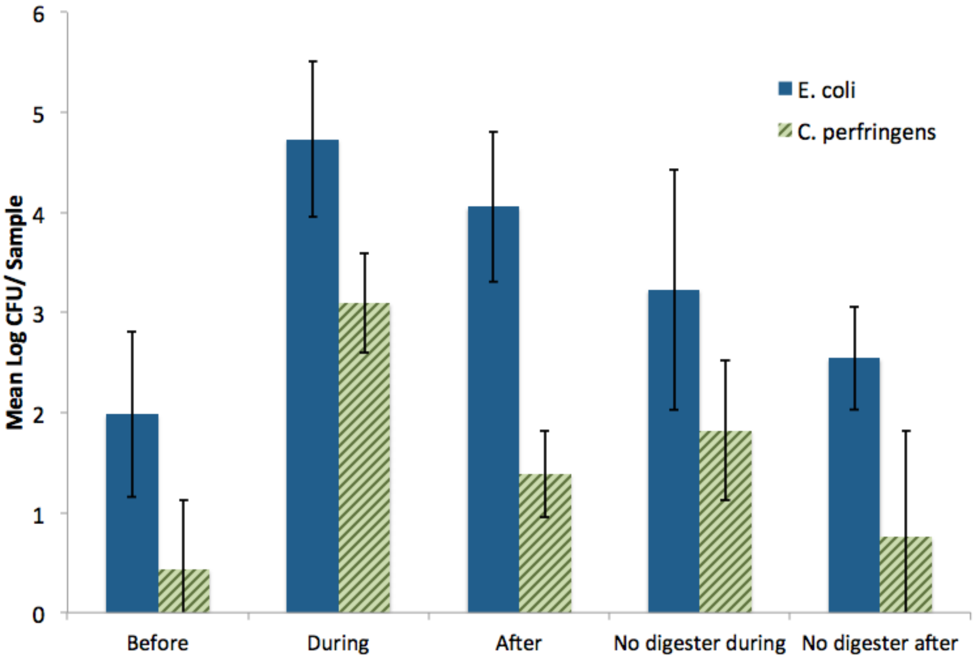

Figure 5.2.9. Shoe over covers outside home

Fig. 5.2.10 below shows the results for boot swabs taken around the animals from households where animals were kept within 30 meters of the house. The results show an increase in *E. coli* from digester homes, although the is not statistically significant (as visualized by the overlapping error bars). *C. perfringens* does display a significant increase after installation. The observed increase is surprising because manure removal for use as digester feedstock was expected to decrease bacterial loads. Since many households already removed their manure for fertilizer prior to digester installation, the use of anaerobic digestion may not have been as effective for bacterial reduction as expected. More data should be collected in order to increase the statistical power of this study.

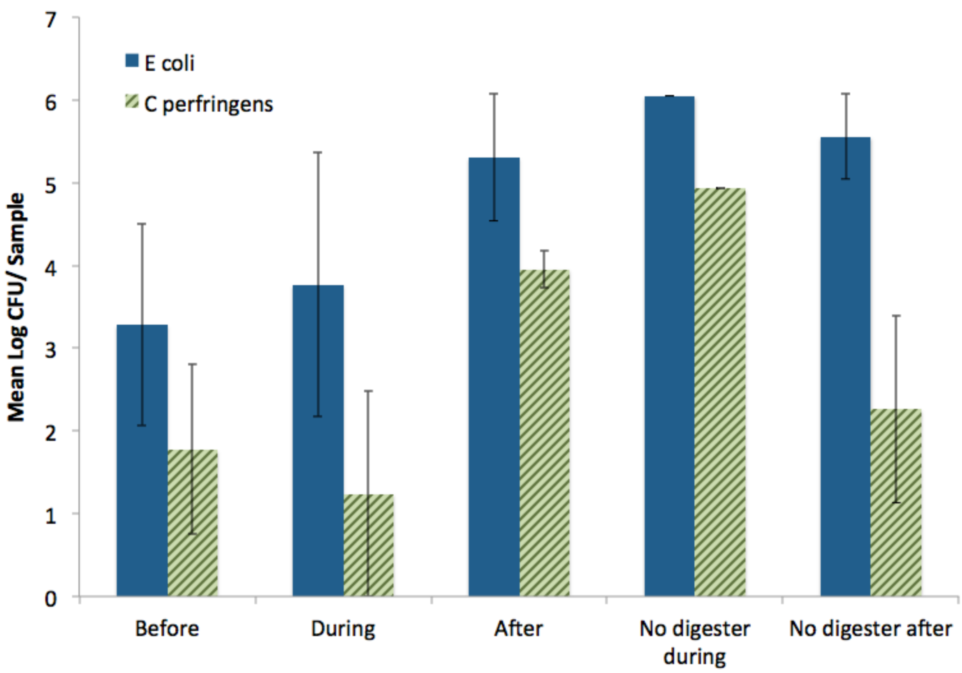

Figure 5.2.10. Boot swabs around animals

Fig. 5.2.11 shows the results from swabs taken from the dishes around the houses. *C. perfringens* was not enumerated for swab samples so the figure only displays results for *E. coli.* The high variability of the data makes it difficult to draw conclusions from the figure. There was a tenuous decrease in *E. coli* from before to after digester installation, possibly related to increased awareness of sanitation issues. However, the high degree of variation in the non-digester homes suggest the result are more likely to result from chance.

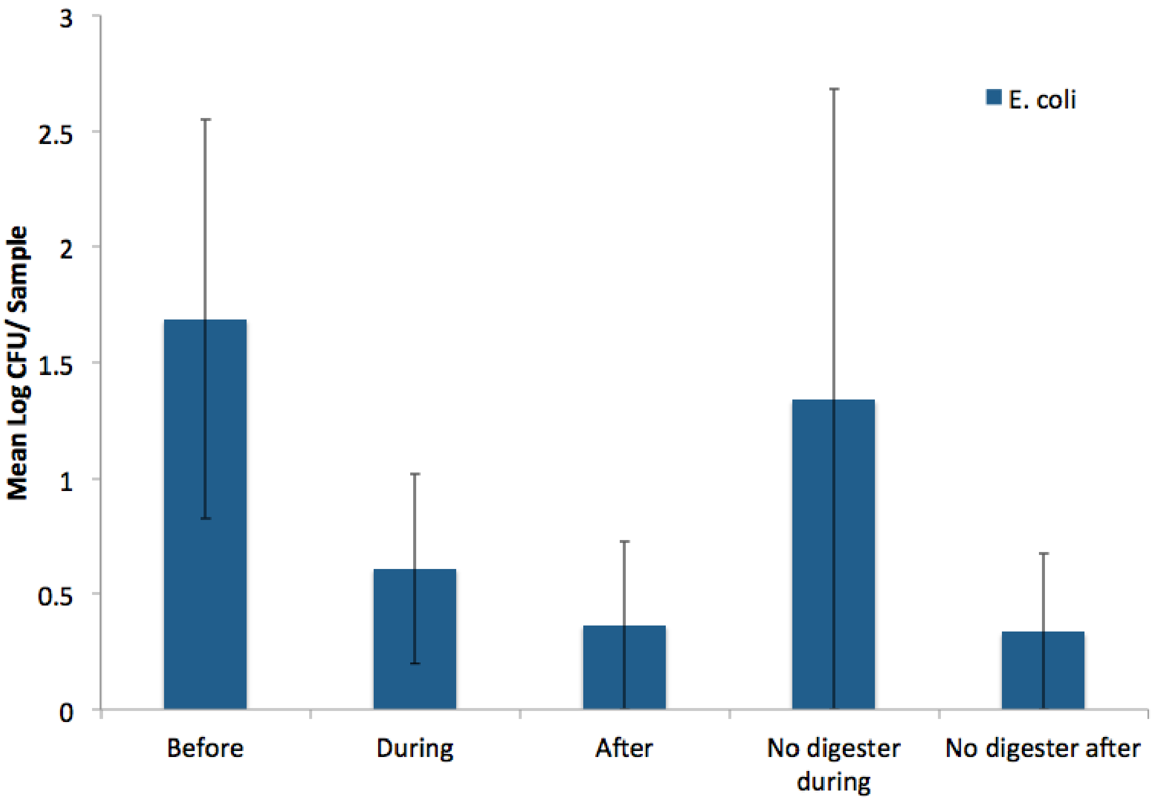

Figure 5.2.11. Swabs from dishes

Fig. 5.2.12 and Table 5.2.5 display results for the means of all sample types before, during and after digester installation for digester homes. Fig. 5.2.12 below shows a consistent increase in total coliforms and *E. coli* across the time periods. The mean reduction for *E. coli* (M =-0.84) was negative, indicating an average increase of 0.84 log units, and the p-value of 0.025 indicates statistical significance. The mean reduction of total coliforms (M = -1.96) was also found to be significantly less than zero with p = 0.0033. The mean decrease of *C. perfringens* (M = -0.090) was not significant (p = 0.10).

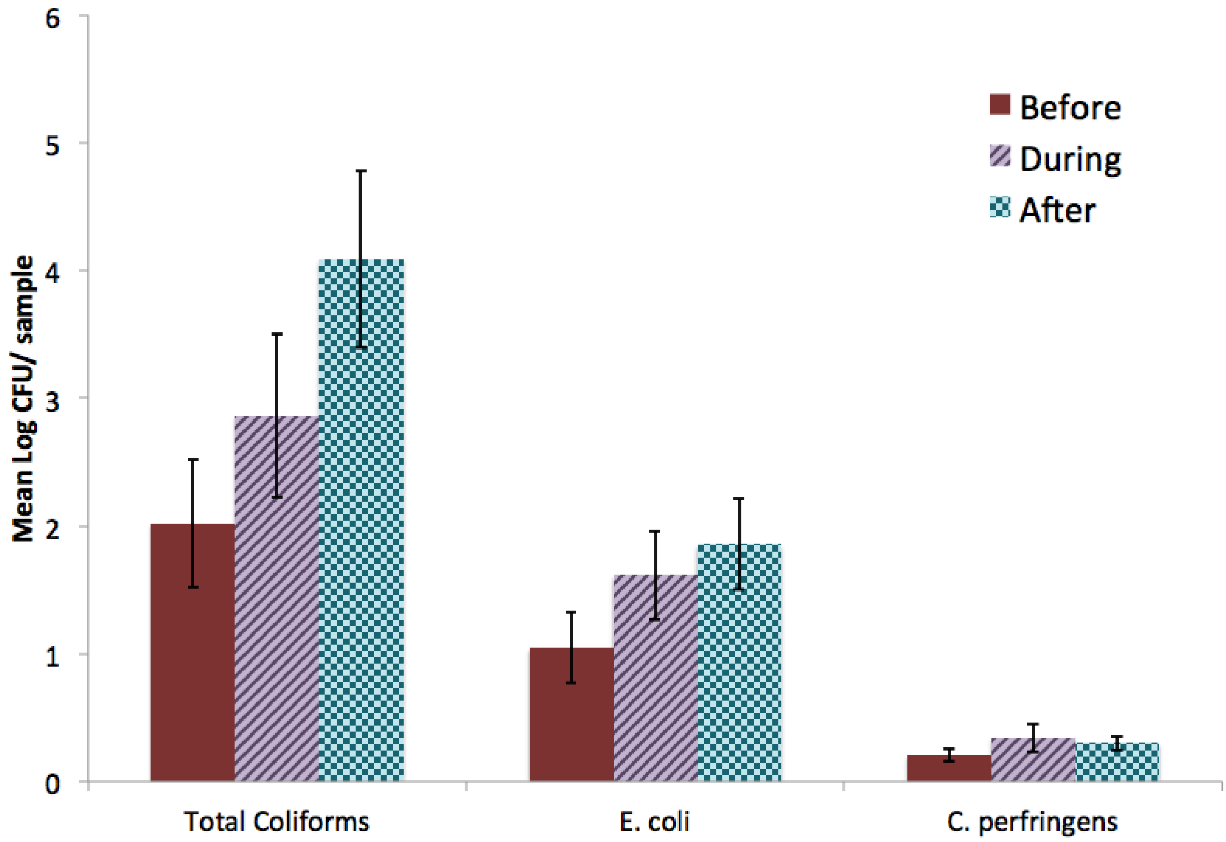

Figure 5.2.12. Cumulative environmental results for digester homes

Table 5.2.5. Summary statistics comparing bacterial load before and after digester installation

Bacteria	Mean Decrease (Log CFU/ sample)	Standard Deviation	95% Confidence Interval	T-statistic	Two-tail p value
E. coli	-0.84	2.62	(-1.57, -0.11)	-2.3	0.025
Total Coliforms	-1.96	4.59	(-3.24, -0.68)	-3.1	0.0033
C. perfringens	-0.090	0.39	(-0.20, 0.017)	-1.7	0.10

Limitations of this study

The results of environmental sampling around the households are limited by a lack of replicates and difficult comparisons between digester and non-digester homes. The non-digester homes were meant to act as controls for the study but were not included in the study until after the digesters were installed. Therefore there is no baseline data available for the non-digester homes to determine if they are comparable to the digester homes or to compare the changes between homes before and after installation. Ideally, the study would include nine homes comparable to the digester homes and include samples from all three phases so that external variables such as weather could be eliminated as possible causes for observed changes.

Conclusions should also be drawn cautiously because each household was only sampled once per time period (before, during, after). Multiple replicates for each time period would lend greater confidence to observed changes. All of the post-installation sampling was also performed within three to five months after the digesters were installed, giving the users little time to adapt to the new technology. Over time, users were observed to alter the feeding process to make it both cleaner and more effective. One example is the installation of a wider basin on the inlet pipe to limit spillage of the feedstock. With more time, the use of digesters may have a greater impact on the concentrations of indicator organisms than was observed in this study.

For the feed and digestate results, the variable retention time should be considered. This study is unique because it draws conclusions from field trials and is more representative of actual results among digester users than studies that strictly control retention times. The exact retention time for each digester was unknown because it was based on available resources and feeding habits of each household.

Conclusion from pathogen measurements

Analysis of feed and digestate revealed that *E. coli* and faecal coliforms were significantly reduced through the digester. *C. perfringens* significantly increased in the digester, and *E. faecalis* showed no significant change. These observations are consistent with literature values from controlled lab studies, indicating that anaerobic digestion behaves similarly under realistic field conditions as under more controlled conditions with regards to bacterial reduction. Future studies should determine whether the levels of *C. perfringens* in the digestate are harmful to human health and if there are post-treatment methods such as composting that could be used to reduce the levels of *C. perfringens* before applying digestate to crops. The impact of anaerobic digestion on other common human pathogens, such as Salmonella and Campylobacter, should also be evaluated.

The environmental samples indicate that sanitation was not improved around households as a result of digester use. The overall *E. coli* and total coliform load significantly increased between the baseline study and the period after installation. Future studies should focus on increasing awareness of sanitation issues and adapting the system to limit transport and spread of pathogens. Such methods may include moving the digester closer to the animals' location and widening the inlet pipe to prevent spillage of feedstock.

That education for better management of the digester could improve sanitation around the household is exemplified by household 24. The householder was enthusiastic about the management of his digester, and it was visually apparent that the area around the digester was clean and tidy. The householder had a separate store for his feedstock and took care not to spill manure when transporting it to the digester. He also attached a basin to the inlet to avoid spillage and washed the area down after feeding. This household had the highest pathogen load before installation and showed the greatest decrease in pathogens following installation.

5.3. Key findings from analysis of household air quality and pathogens

The reduction in particulate matter less than 2.5μm in diameter ($PM_{2.5}$) and carbon monoxide CO due to conversion to biogas were modest (median = 25% and 27% respectively); this was due to only partial conversion to biogas. In order to achieve measureable improvements in human health due to improved air quality, more complete conversion to the technology will be needed.

Sanitation in the wider environment (water courses etc) was expected to be improved by installation of digesters. Aerobic pathogen indicators (*E.coli*) were reduced through the digestion process, although anaerobic indicators (*C. perfringens*) were not. The reduction in total coliform loads in the digestate means that an overall decline would be expected in the wider environment following widespread conversion to application of bioslurry rather than untreated waste. By contrast, the overall *E. coli* and total coliform loads in the local environment (household area, yard etc) significantly increased due to spillage of manure during feeding of the digester; improvement in digester layout and education could counter this observed increase in pathogen loads in the local environment.

6. Socioeconomic analysis, exploring cost/benefits and willingness to pay

6.1. Literature survey

Studies on costs of biogas plant

Walekhwa (2010) studied fixed dome digesters and documented capital, installation, operating and maintenance costs. The cost of land was excluded from the capital cost because the biogas plants were cited on households dwelling. In the GTZ (ISAT, 2007) studies on costs of the biogas plant, manufacturing or acquisition costs (production costs), operation and maintenance costs (running costs) and capital costs have been documented. Understanding of these costs allows comparison of the costs of alternative models (design selection) and provides information to the users and non-users on future financial burdens.

Studies on benefits of biogas plant

Several studies have been carried out on benefits of biogas and a number of benefits have been documented. GTZ (ISAT, 2007) documented benefits of expenditure saved by the substitution of other energy sources with biogas, income from the sale of biogas, expenditure saved by the substitution of mineral fertilizers with bio-fertilizer, increased yield by using bio-fertilizer, savings in the cost of disposal and treatment of substrates (mainly for waste-water treatment), time saved for collecting and preparing previously used fuel materials and time saved for work in the stable and for spreading manure. In the GTZ study the benefits were documented and methods to assign a value to the benefits were attempted but were not successful. Studies carried out by SNV (2009) in Bangladesh shows that 48.6 minutes per day of cooking time is saved by using biogas. Consequently, women have engaged in income generating activities, increased attention to their girls' enrolment in school, and gained greater opportunity in social work. Use of bioslurry is asserted to have improved the physical and biological quality of soil by adding organic manure and has increased crop yields. However, this study did not quantify the benefits. An attempt to quantify some of the benefits has been completed by WHO (2006), especially in terms of energy and some health benefits. Thus there is a need to quantify these benefits as most households would be interested in the potential monetary improvements associated with biogas digesters. Studies carried out in Uganda by Sendegeya and da Silva (2006) show that use of biogas cleans up the home environment. Cows are confined in a small space which results in rapid accumulation of manure, but this can be disposed of regularly in order to keep the animals in good health and to eliminate unpleasant odours. The digestate from the manure is then used as fertilizer.

A study in China by Robert (2005) further explores the potential benefits and suggests that biogas digester systems considerably enhance energy efficiency and agricultural productivity; as a result, a digester can increase a rural household's income and living standards. This is because biogas digester systems provide a reliable renewable energy resource (Hammond, 2007) and can be used for cooking, heating, lighting (SNV, 2009) and powering diesel engines, amenities such as reading lights, heat for schools and cheap fuel for machinery.

Global environmental benefits occur when greenhouse gas emissions are reduced. The burning of fossil fuels in households leads to emission of the greenhouse gas, CO_2 (Hutton *et al*., 2006). Burning of wood fuel may also result in net emission of CO_2 by decreasing the forest area and so reducing standing stock of C in forests (Subedi *et al*., 2012). Biogas digester systems provide an alternative to fossil fuel and wood fuel, thereby potentially reducing CO_2 emissions to the environment.

6.2. Baseline survey

The baseline survey was successfully completed, with a total of 150 households interviewed by MSc1, assisted by three enumerators. Fig. 6.2.1 shows interviews being carried out in Tiribogo by the team. The main objective of the baseline survey was to establish the financial viability before installation of biogas digesters. After installation of nine pilot digesters, these households were resurveyed to determine production and use of the gas, and the changes in financial viability.

Figure 6.2.1 - Baseline interviews for the socioeconomic analysis being carried out by the team in Tiribogo

Description of the study area

The study was conducted in the district of Mpigi, Mudduma Sub-county in Tiribogo village with a total number of households less than 250.The main type of land use is subsistence farming with farmers rearing animals and growing both food and cash crops. The food crops grown include matooke, sweet potatoes, maize, beans and horticultural crops (vegetables).The main cash crop grown is coffee. The animals reared are pigs, goats and cattle, and these are reared on small scale with most households keeping at least one of these animals. The other enterprise common in the village is poultry rearing, with both local and exotic breeds being reared. Most households have 2-4 local birds, while the exotic breeds, especially the layers, are kept by only a few farmers. The village is bordered by the forest and the main energy source for cooking is use of wood fuel, which is collected from the forest. Candles and kerosene lamps are used for lighting.

Preparation for survey

Before conducting the survey the following steps were completed:

- The questionnaire was drafted with inputs and comments gathered from the entire project team;
- The questionnaire was pre-tested and improved based on the pre-test information;
- The local field guide was consulted on the organisation of the survey in order to reduce the respondent burden;
- A meeting was held with area leaders to draw up a village list that would be used to randomly select the respondents;
- The sampling approach was discussed with the field guide to ensure selection criteria were met.

Training of enumerators

Training of enumerators was completed by the socio-economic team at Makerere University to ensure that the enumerators had sufficient knowledge of the data collection tool. Enumerators were also trained on ethical conduct for a survey and establishment of rapport with the community so as to encourage the community in Tiribogo to give appropriate and accurate information.

Sampling methodology

Sampling frame

The sampling frame was developed from a village list that was compiled in consultation with the village local leaders, field guide and the research assistant. This consisted of 270 households from which the sample was drawn. Thirty households were selected within a 100 m radius of each of the nine households chosen for digester installation to generate the full sampling frame of 270 households.

Sample size

A sample of 150 households from the village was randomly selected from the sampling frame. The sampling approach planned to list male and female headed households in separate lists, arranged in alphabetical order, and then select a random sample from each of these numbered lists to meet the total sample size of 150. In practice there were insufficient households to follow this procedure due to unequal numbers of male and female headed households. Therefore, all households were randomly sampled, irrespective of the sex of the household head.

Data collection tool

Primary data were collected by interviewing households using a structured questionnaire. Information was collected on socio-demographic, household composition, perceptions of flexible balloon digesters, land use and livestock possession, energy use, health with focus on diarrheal and respiratory problems, water availability and access. Observations and further interaction with the community were used to obtain extra information and to confirm information given in the questionnaire.

Quality assurance

The field team supervisor from the socio-economic team at Makerere University reviewed all the questionnaires before leaving the village to ensure accuracy and quality of the data collected. A review meeting was held on the completion of the first day of field work to ensure that all the survey teams understood the questionnaire perfectly and carried out the household interviews according to the survey guidelines given to them.

Data coding, entry and processing

This was done to ensure that codes were assigned appropriately. Methods used to clean the data and ensure accuracy included range tests.

Data analysis - Data were analysed using statistical techniques (principally descriptive statistics used to identify the general pattern and trends in the data, frequency tables) with the aid of the Statistical Package for Social Scientists (SPSSv16) computer software.

Variables on which information was collected and analysed

The variables on which information was collected is listed below:

- Household head data, including age, sex and education level;
- Monthly household expenditure with special focus on fuel consumption and expenditure;
- Monthly household income from agriculture, employment, and other income generating sectors;
- Households' knowledge, perceptions about biogas digester and biogas use;

- Number of animals in the household (dairy, non-dairy, sedentary, mobile);
- Current use of animal manure (amount used for burning, fertilizer, composting);
- Crops grown and the use of crop residues;
- Energy sources (firewood, dung patties, agricultural residue, LPG, candles, kerosene and/or electricity) currently used for cooking and lighting
- Origin of different energy sources, frequency of buying or collecting them and the rate at which they are bought
- Operational costs of digester, such as collecting water and cow dung, mixing the feedstock, feeding the digester and collecting and applying slurry to the fields
- Work load analysis (economic & social) of the women and girls in the households; average time per day spent accomplishing various tasks including fuel collection and cooking
- Willingness to pay for a flexible balloon digester, willingness to maintain the digester, willingness to contribute to the digester installation when given free of charge
- Cases of respiratory, digestive and related diseases
- Water access and availability
- Total time taken cooking different meals (breakfast, lunch and supper)
- The factors limiting uptake of biogas technology

Valuation of the costs

Secondary data was used to determine the costs of installing a flexible biogas digester; this data was obtained from the installation work (section 2). Production costs were documented during the construction work. Running and maintenance costs were obtained from the community by asking them how much time was spent carrying out operational activities each day. Market price was used to value the different components.

Valuation of the benefits from flexible biogas installation

Benefits associated with biogas digesters were determined as follows:

i. Savings in the cost of cooking fuel were obtained from the survey conducted in Tiribogo.
ii. Savings in the cost of buying kerosene for lighting were also determined by survey.
iii. Other benefits, such as saved time in cooking, wood fuel collection, improvement in environment, reduction in drudgery of women/children and time required for water collection were determined.
iv. Health benefits were determined qualitatively

Summary of findings

Socio-economic characteristics

Of the 150 households sampled, most are headed by men. In common with many African societies, men predominantly control resources and make household decisions in Tiribogo. Most of the households are headed by a married person, with a lower percentage being headed by a widow/widower or unmarried person. The survey results show that nearly 90% of the household heads attended primary school, although not all completed their education. This suggests a reasonable degree of literacy across the community, which may facilitate the spreading of knowledge within the community compared to communities where many members have never attended school. Agriculture is the dominant income generating activity in Tiribogo, especially from rearing livestock and growing crops. The average number of people in a household is 5, and family members usually provide labour for the various activities and tasks in the households including cooking, collecting fuel wood and water, and any other additional activities that a family may adopt. Household members are also involved in a number of different on- and off-farm activities to generate income to help meet household expenditure. Expenditure varies each month according to the hardships faced by the households, such as sickness. Average monthly household expenditure exceeds average monthly income by over 10 US$; this may be attributed to underestimated incomes, for example by undervaluation of income earned by family labour employed on household activities. Some households fill gaps in expenditure through gifts from friends and relatives. Over 90% of the households interviewed own land; this is good for biogas promotion as farmers will have land for grazing animals. For those who do not own land, there is no incentive to adopt biogas because the digester will be installed on the land owned by others. The average number of livestock owned by households in Tiribogo is one milking cow, two non-milking cows, three pigs, four goats, two sheep, 34 chickens, and two rabbits; this should be sufficient to provide biogas for a family of 5. The main cash crops grown are bananas, maize and coffee. Over 90% of the people surveyed use crop residues for mulching. Further use is made of crop residues as an organic fertiiser and livestock feed. A very small proportion of households use crop residues as a source of energy.

Membership of groups / associations

Less than 25% of the people surveyed in Tiribogo were members of a group. Groups increase information sharing among members as well as providing beneficial information and advice to the community. These people joined the group in order to save money to acquire expensive assets, to access credit, for social networking with others, for collective marketing of products and purchasing of resources, and for general development.

Knowledge about biogas digesters

Most respondents considered they had little or no knowledge about biogas digesters, with less than 5% believing they had good knowledge of the system and benefits. Knowledge of biogas digesters can be attributed to the meeting that was held in Tiribogo to explain the system at the beginning of this project. This is supported by the fact that there is little biogas production and usage in this village.

Respondents' opinions about attributes and benefits of flexible balloon digesters

Most people surveyed believed that biogas would improve family life, save money, and that using bioslurry would help improve crop yields. A significant proportion of people believed that food cooked with biogas would not taste as good as food cooked using wood or charcoal. The monetary saving was expected to arise from reduced need to buy fuel wood and charcoal for cooking and kerosene for lighting.

Use of biogas

Most of the people surveyed reported that they would cook all meals, while others would only partially convert to biogas.

Energy sources and cooking

According to the survey findings, firewood is the most common form of fuel used for cooking in Tiribogo; less than 20% use charcoal, kerosene or agricultural residues. Over 80% of the firewood used is obtained from the natural forest surrounding Tirbogo. Most of the firewood collection is done by women. The average monthly expenditure on energy for cooking per household each month is 26 US$ month^{-1}, nearly 40% of the total household expenditure. Over two hours each meal is spent cooking lunch and supper, whereas breakfast and the evening meal are cooked in under half an hour. Most meals are prepared by women, so women would be expected to suffer most from indoor air pollution.

Energy sources and lighting

The survey results indicate that kerosene is the principal energy source for lighting. Kerosene is used because it is easily accessible. Lighting is used for preparing food, reading, writing, socializing and preparing to sleep. Over 50% of people surveyed stated that they would like to light rooms for longer periods. Expenditure on lighting is nearly 45% of the total expenditure on energy and nearly 20% of the total household expenditure, so householders are likely to be keen to use biogas for lighting.

Use of bioslurry

Most respondents confirmed that they would use bioslurry in their fields. The preferred crops on which slurry would be applied were banana, followed by maize, coffee, other vegetables and tomatoes. Those who would not apply it in the fields suggested that they would sell it to generate income or would give it to the neighbours free of charge.

Health, sanitation and hygiene

Over 50% of the households interviewed were aware of the effects of the biogas digester on sanitation and hygiene. Most people considered these benefits would arise from reduction of waste accumulation around homes and reduction of cholera and diarrheal incidence. Most people were not happy to tolerate any incidences of diarrhea in the household. The majority of households had not faced any diarrheal problems in the past 14 days, and understood that maintaining proper sanitation and hygiene around the home and drinking boiled water would reduce the incidence of infection.

Respiratory problems

Nearly 40% of households in Tiribogo have experienced respiratory problems when using traditional energy sources. Most respondents were not aware that these problems result from using firewood because they have never used an alternative energy source. Of the households surveyed in Tiribogo, almost 75% reported concerns about respiratory problems, suggesting that improvements in indoor air quality following the replacement of firewood by biogas would be welcomed. Nearly 40% of households had experienced respiratory problems in the last 14 days, most reporting symptoms of coughing. The average expenditure on respiratory problems is ~2 US$ month^{-1} (3% of the total household expenditure). This is low compared to severity of the cases reported such as asthma. The low cost may partially be attributed to some medicine being provided by government hospitals/dispensaries free of charge to the community. Most of the households had no knowledge of the cause of respiratory problems or how to avoid them. In addition, some households reported that they had never been exposed to smoke for long periods of time.

Water accessibility

The closest point for accessing water source is an average of only 172 m from the homesteads, but the average time taken for a round trip for collect water is over an hour (note that the average for the nine households where digesters were installed was much higher than this at 633m – Table 3.2.1). This may be due to congestion of people at the water sources, which accounts for a high proportion of the time spent collecting water. Most households collect water two or three times per day. Households collecting water over four times per day are usually located close to the water source. The frequency of water collection in this village is relatively high; this is a good indicator that the increasing water demand after installation of a biogas digester can be met by the households. Women and children collect most of the water used, and water collection usually involves no expense; however a few households pay other people to collect water, pay to repair a faulty borehole, or must cover the costs of water pumping using a generator. A high proportion of households reported problems in sourcing water due to distance from the water source, the gradient of routes to and from water sources, dirty water, and congestion of people at the water source. Installation of a biogas digester is likely to have a negative impact on household labour when households are far from the water source or have to transport the water uphill.

6.3. Follow-up survey

Sampling procedure and sample size

Nine flexible balloon digesters were installed in selected households by MSc2. The criteria for selecting the nine households were based on a scoring system for the necessary requirements for running a biogas digester. A total of 150 households inclusive of those who had installed digesters were included in the follow-up survey.

Costs and benefits associated with a flexible balloon digester

Costs and benefits estimated by householders

Table 6.3.1 shows the costs associated with a flexible balloon digester by householders with a digester. These costs are in two categories; added costs due to increased activities that were not needed before the digester was installed; and saved costs that are costs no longer incurred by households as a result of the digester installation. The costs of gathering and applying slurry were valued at 129 US$ yr^{-1} (36 min day^{-1}) but these costs were omitted as this activity was also done before installation of the digesters.

The operational costs were obtained by asking the householders how much they would be willing to spend on each activity, and assuming that each time the digester was fed, other activities, such as collecting dung, collecting water, mixing the feedstock were also required. The average amount for each activity was scaled up to a yearly value for the nine households. The labour costs obtained from the householders valuation gave a total increase in labour costs of 202 US$ yr^{-1} due to the biogas digester. As a comparison, the costs were also calculated from the time taken for each activity and the rural wage rate for unskilled workers in Uganda of 0.22 US$ hr^{-1} (Winrock International, 2007). The biogas digester increased labour costs estimated from the rural wage rate by only 104 US$ yr^{-1}. This discrepancy suggests that the small sample size of nine householders may have over-valued labour costs, which range from 211% (water collection) to 497% (fuel wood collection) of the costs calculated using the Winrock International wage rate.

Table 6.3.1 – Labour costs associated with a flexible balloon digester in Tiribogo

Cost category	Item/Activity	Costs from household survey (US$ yr^{-1})	Time taken (min day^{-1})	[6]Costs from time US$ yr^{-1})
Added labour costs due the digester	Collecting water	[1]96	34	46
	Collecting substrate	[2]106	28	37
	Mixing of feedstock	[3]80	22	29
	Feeding the digester	[4]67	16	21
	Total	**349**	**100**	134
Labour costs due to the digester (benefit)	Fuel wood for cooking	-147	[5]-22	-29
Total change in labour costs		202	78	104

[1]Households were asked the number of jerry cans used each day to mix feedstock. The market price for each jerry is dependent on the distance from the water source. The annual expenditure for collecting water was obtained from this market price and the number of jerry cans used in a year.
[2]Each household was asked how much they would be prepared to pay for cow dung to be collected. The annual expenditure was then obtained by multiplying this amount by the frequency of feeding the digester.
[3]Each household was asked how much they would be prepared to pay for feedstock to be mixed. The annual expenditure was then obtained by multiplying this amount by the frequency of feeding the digester.
[4]Each household was asked how much they would be prepared to pay to feed the digester. The annual expenditure was then obtained by multiplying this amount by the frequency of feeding the digester.
[5]Average value reported for firewood collection in Table 3.4.1.
[6]Calculated assuming the rural wage rate for unskilled workers in Uganda is 0.22 US$ hr^{-1} (Winrock International, 2007)

Time taken in cooking meals using fuel wood and biogas

The results in the Table 6.3.2 show that cooking using biogas takes more time than cooking using fuel wood for all meals expect breakfast. This result is in contrast to the findings of earlier studies in Bangladesh where 48.6 minutes cooking time were saved every day by converting to biogas (SNV, 2009). When using fuel wood, the intensity of the flame can be increased by adding in more wood to create a hotter flame. This can result in food requiring less time to cook compared to food cooked by biogas, in which the flow of gas to the cooking stove remains constant.

The difference in time taken to cook breakfast is attributed to the small number of people remaining at home in the morning after the children have gone to school; the biogas stove is well suited to cooking using a smaller pan, allowing a smaller volume of water to be boiled.

Table 6.3.2 - Comparison of time taken in preparing meals using fuel wood and biogas

Meals prepared	Average time taken in minutes per day	
	Before installation	After installation
Breakfast	30	24
Lunch	114	120
Dinner	18	24
Supper	108	120
Total	270	288

A study carried out by Winrock International (2007) determined the rural wage rates for unskilled workers. Based on this, an hourly-equivalent agricultural wage rate in Uganda was valued at US$0.22, and was used in this study to value the time saved in cooking. The increase in cooking time was (288-270) = 18 min day^{-1}, equivalent to 110 hours yr^{-1}. Assuming this time is otherwise used in agriculture, at a wage rate of 0.22 US$ hr^{-1}, this is equivalent to 24 US$ yr^{-1}.

Participation of different household members in cooking using fuel wood and biogas

The results in Table 6.3.3 show a shift in the labour demand as a result of using biogas; before installation most of the meal preparation was done by the wife, whereas after installation, cooking was shared more evenly between other members of the household. This is attributed to the convenience of biogas as a cooking fuel and the reduction in unpleasant side-effects of cooking, such as eye irritation and difficulties in breathing. This has increased the interest of all the household members in preparing meals, allowing the wife and children to have more time for other income generating and educational activities.

Table 6.3.3 - Shift in labour demand as result of using biogas versus fuel wood

Meals cooked	**Who cooks? (%)**							
	Wife		**Children**		**Husband**		**Joint responsibility**	
	Before	**After**	**Before**	**After**	**Before**	**After**	**Before**	**After**
Breakfast	93.8	50.0	4.6	-	1.5	-	-	50.0
Lunch	89.7	66.7	3.4	-	6.9	-	-	33.3
Dinner	77.3	-	13.9	-	9.1	-		100
Supper	81.3	100	12.2	-	5.7	-	0.8	-

Impact of biogas on use of fuel wood

With the acquisition of a biogas digester, the frequency of wood collection from the forest changes, and expenditure on fuel wood is reduced by 58% (Table 6.3.4). The reduction in fuel wood collection is due to biogas being used to supplement use of fuel wood. Biogas has in turn reduced expenditure on fuel wood because it has reduced the energy demand of the households that must be met by fuel wood.

Table 6.3.4 - Changes brought in households as result of using biogas

Item	Before	Current	% reduction
Frequency of wood collection per month	6	3	50%
Expenditure per month on fuel wood (US$)	11.4	4.8	58%

This has reduced time spent collecting wood from the forest; this has especially saved time for school-aged childen who are often responsible for this task (Fig. 6.3.1)

Figure 6.3.1 - School children carrying fuel wood from the forest

Figure 6.3.2 - Fuel wood heaped for drying

Impact of biogas on expenditure on compost

Total expenditure on compost and the savings in expenditure predicted in section 7.5 by replacing compost with bioslurry are given in Table 6.3.5. Note the predicted savings are a conservative estimate, being highly dependent on the availability of N in the bioslurry compared to compost. It is anticipated that potential savings will be much greater than reported here.

Table 6.3.5 – Potential savings in compost

Household	H1	H17	H20	H21	H24	H27	H47
Amount of purchased compost expected to be applied (kg yr^{-1})	6000	4500	5000	7000	13000	2000	7500
Price of compost (£ kg^{-1})	0.0153	0.0178	0.0153	0.0153	0.0153	0.0153	0.0127
Expenditure on compost before biogas (£ yr^{-1})	91.80	80.10	76.50	107.10	198.90	30.60	95.25
Predicted saving on compost provided by bioslurry (£ yr^{-1})	53.65	77.94	53.65	44.38	58.00	30.60	51.76

Knowledge level about flexible balloon digesters

Before installation most of the households had a small amount of knowledge about flexible balloon digesters; this was attributed to the start up meeting that was held in Tiribogo and provided some information about the digester.

After installation, knowledge about digesters increased among the householders that did not have a digester. As shown in table 6.3.5, the percentage of householders with partial knowledge of digesters was higher than before; similarly those with a full knowledge also increased. This might be attributed to exposure to biogas digesters from contact with neighbours.

Among householders with a digester, all had a good knowledge of the digester; this is because all householders were working with the digester and so understand the system better than before.

Table 6.3.5 - Knowledge level

Level of knowledge	Percent of interviewed households		
	Before installation (n=150)	After installation	
		Households without digesters (n=141)	Households with digesters (n=9)
Knowing nothing at all	24.7	8.5	-
Know little	62.0	42.1	-
Partial knowledge	8.7	39.3	-
Full knowledge	4.7	10.0	100

Willingness to pay for a flexible balloon digester

This was the main component of the follow-up survey and different scenarios were used to explore willingness to pay, depending on whether a household had a digester or not.

In households without digesters, householders were surveyed on their willingness to maintain the digester, willingness to contribute to the installation of a flexible balloon digester when given free of charge, and willingness to purchase a new flexible balloon digester.

In the nine households with digesters, householders were surveyed on willingness to pay for the digester not to be taken away (since it was given to them free of charge by the project) and willingness to replace or purchase a new digester in case the original digester was worn out or damaged.

Table 6.3.6 shows the amount individuals were willing to pay.

Table 6.3.6 - Willingness to pay for a flexible balloon digester

Willingness to category	Percentage	Amount prepared to pay (US$)
Households without digester (n=141)		
Willingness to maintain	87.1	17.4
Willingness to contribute	87.8	20.8
Willingness to purchase a digester	81.6	38.2-47.7
Households with digesters (n=9)		
Willingness to pay for a digester not to be taken away	100	97.5
Willingness to replace a digester	100	38.2-104

The results show that householders are generally willing to pay for the digester but the amount they are prepared to pay is very low compared to the actual cost of the digester. The results further show that households with digesters are willing to pay more compared to those without; this is because important life-style benefits derived from the digester are being realised. However, the willingness to pay for a digester is under ~$100, even in households that have experienced these benefits; this suggests to be taken up by householders, the cost of digesters must be reduced to around this level.

Factors limiting uptake of flexible balloon biogas digesters

Householders with flexible balloon digesters were surveyed to determine factors limiting uptake. A number of different factors were identified.

Lack of sufficient substrate

Lack of sufficient substrate compared to the size of the household leads to biogas production that cannot fully satisfy the need for fuel for cooking. Closely related to this (as cited by Nasery (2011) and Gitonga (1995)) is the installation of too large a capacity plant resulting in under feeding, and eventual failure of the plant to produce enough biogas. Underfeeding was also attributed to low collection of cow dung or substrate.

Lack of capital for investment

Lack of sufficient capital for investment in a biogas digester is likely to be a significant barrier to uptake. This is supported by the analysis of the amount a household is willing to pay for a new digester; this is not even half the cost of an imported, pre-manufactured flexible balloon digester. This finding is in line with a study conducted by Perumal and Muthukrishnan (2013) in India, where the majority of respondents reported that the cost of installation decided whether to reject or adopt the technology.

Leaking digesters

Leaking digesters due to punctures with an unknown cause may dissuade some householders from taking up this technology. Faulty digesters were reported by four households. This is similar to the findings of Nasery (2011), who reported many plants are faulty in their construction, or develop problems that leads to a non-functioning plant.

Lack of equipment for using biogas for lighting

Lack of equipment to enable biogas to be used for lighting created a negative image, suggesting to householders that biogas could only be used for cooking. The technical expertise was not available to advise on purchase of equipment for lighting, and so householders were not motivated to buy such equipment themselves.

Size of cook-stoves

The small size of the cooking stoves compared to the household size limited cooking being done on biogas in large households. Because households prefer to cook a meal in one go and not be limited by the size of stoves and pans, this would limit the value of biogas for large households.

Hygiene

Poorly positioned slurry inlets and outlets, too close to the kitchen entrance, creates fear of disease spreading. Positioning of digesters should be more carefully planned with consideration of the impact on pathogens.

Type of food cooked

Householders perceive that biogas can only be used to cook softer foods; this will limit uptake as most African traditions include foods that require an extended period of cooking. Such foods include dried beans and other foods that require a long cooking period, such as banana which is cooked for 3-4 hours in some cultures in Uganda. This limits biogas uptake as gas flow to the cooking stove will not be maintained for such a long period. This is similar to the findings of Nasery (2011), where respondents reported that the staple bread, chapatti, could not properly be roasted using a biogas burner.

Number of livestock

The number of cows owned by the households limited uptake. Farmers who had very few cows were not able to produce enough biogas to satisfy their cooking needs. This is in line with the findings of a survey conducted by Gitonga (1995) who reported that a family of eight with only one cow was unable to find enough dung to feed the plant, and so produced very little gas, resulting in the family switching back to fuel wood to meet their energy needs. This was also supported by the study of Walekhwa et al. (2009), where the number of livestock influenced the adoption of biogas.

Water supply

The water supply in Tiribogo limits uptake of biogas technology. Water is essential for mixing with dung to create a semi-liquid that will flow freely in the digester and provide a suitable medium for the anaerobic decomposition. This is in agreement with the findings Gitonga (1995) in Kenya, where biogas plants were no longer operational after the source of water broke down.

Perceived factors limiting uptake in households without digesters

Factors perceived to be limiting uptake in households without digesters include lack of cows to provide the substrate; the perception that the digester increases workload; the perception that the technology is complicated; and the perception that biogas is dangerous if it leaks and will catch fire and destroy household property.

Comparison of male and female headed household use of digesters

The results from the limited survey of the households where biogas digeters were installed (n=9) show that there is no significant difference between households headed by men and women in the amount they are willing to pay for the digester, the net present value or the time taken to prepare meals (Table 6.3.7). This finding is an important factor for development; most literature shows that households headed by women are more vulnerable to external factors, which predisposes them to poverty and under-development. The results show that there is a significant difference in reduction in the costs of fuel wood between households headed by men and women. A biogas digester saves male headed households more money than female headed households. This may suggest a more effective substitution of fuel wood by male headed households, although further evidence is needed to be able to generalise this result.

Table 6.3.7 – Comparison of responses from male and female headed households

Variable	Mean		P-value
	Male headed (n=7)	Female headed (n=2)	
Willingness to pay - amount (‘000 Ugshs)	361	525	0.63
Net Present value (‘000 Ugshs)	-1,195	-1,214	0.82
Fuel wood costs (‘000 Ugshs)	11.1	18	0.02
Time taken cook meals (minutes)			
Breakfast	25	12.5	0.23
Lunch	104	136	0.35
Dinner	22	26	0.59
Supper	115	125	0.63

6.4. Key findings from socioeconomic analysis

The results from the socioeconomic analysis are summarised in Table 6.4.1. The analysis of what householders are prepared to pay for tasks suggests an increase in the net labour costs equivalent to 226 US$ yr^{-1}, requiring extra labour of 96 min day^{-1}. This finding is consistent with the analysis done in section 3.4, where labour in the nine households studied was found to increase between 20 and 70 minutes every day, but is in contrast to the assertion of previous studies where it has been suggested that installation of digesters will reduce household labour, leaving more time for activities such as education (ISAT, 2007). This discrepancy is due to the balance of activities in individual households; for instance, households that are situated further from the forest will spend more time collecting wood and so save more time by converting to biogas, which could result in an overall labour saving rather than a cost. Note that the small sample size might have resulted in tasks being overvalued, as demonstrated by comparison against costs calculated using the rural wage rates for unskilled workers (Winrock International, 2007) which gives net labour costs of only 128 US$ yr^{-1}. The results in Table 6.3.3 illustrate that the person doing the work changes; for instance cooking activities shift from being primarily the responsibility of women in the household, to being shared more equally with other household members. Therefore, time available for individuals to do other activities may increase as total labour is shared more equally between the household. Further analysis is needed to investigate the impact of distribution of labour between individuals on the time available for other profitable activities.

Expenditure on fuel wood was found to decrease from 11.4 to 4.8 US$ $month^{-1}$ (Table 6.3.4). This amounts to decrease in expenditure of 79 US$ yr^{-1}. As shown in Table 6.3.5, the average expenditure on compost before introduction of a biogas digester (64 US$ yr^{-1}) was reduced by an average of 53 $US yr^{-1} (a conservative estimate). Therefore, the total savings in actual expenditure are at least 131 US$ yr^{-1}. Assuming a cost of the digester of $512 (Table 2.3.1 using an exchange rate of 1.53 £ $(US\$)^{-1}$), the payback time would be just under 4 years. Assuming a digester cost of ~$100, the amount that a householder familiar with the benefits of a digester is willing to pay (Table 6.3.6), payback time would be under one year.

Table 6.4.1. Summary of changes in household costs with installation of a biogas digester

Item/Activity	Change in costs according to what householders are prepared to pay (US$ yr^{-1})	Change in costs calculated from time of activities by household survey (US$ yr^{-1})
Labour		
Collecting water	96	46
Collecting substrate	106	37
Mixing of the feed stock	80	29
Feeding the digester	67	21
Cooking	24	24
Collection of fuel wood	-147	-30
Net cost of labour	226	128
Household expenditure		
Woodfuel savings	-79	
Compost / fertiliser	-53	
Total saving in expenditure	-131	
Payback time for digester with respect to savings in household expenditure		
Cost of digester	513	
Payback time (yr)	3.9	

7. Systems modelling to optimise return of agricultural products and energy from biogas digester / farming system

A systems model was developed to describe the value of a biogas digester to the householder. This model used simple calculations to estimate the value to the household of replacing cooking fuel with biogas and any purchased fertilisers or composts with bioslurry. The value to human health was also considered, but as yet there is insufficient evidence to develop a coherent and generally applicable model of these factors. This model is designed to provide a tool to help demonstrate to householders the likely impacts of installing a digester. Further work is needed to fully evaluate the accuracy of the simulations provided by the model.

7.1. The value of replacing cooking fuel with biogas

Household energy requirement

In SSA, 90-100% of the household energy demand is for cooking fuel (Davidson and Sokona, 2001), and the percentage of the cooking fuel obtained from fuel wood is between 75 and 100%, depending on country (Omer and Fadalla, 2003; World Bank, 2000). If fuel wood is in short supply, labour requirements for fuel collection can be very high, and alternatives, such as charcoal, can introduce a high economic burden to the household. Recycling of organic waste has potential to supply a high proportion of the household energy demand.

Omer and Fadalla (2003) presented estimates for the biogas required for different purposes in Sudan. Cooking in Sudan requires approximately 0.425 m^3 biogas $capita^{-1}$ day^{-1}, and a 2 mantle burner for lighting will require 0.14 m^3 biogas $capita^{-1}$ day^{-1}. Therefore, depending on the requirements for lighting, the biogas requirement might be expected to be in the region of ~0.5 m^3 $capita^{-1}$ day^{-1}. The per capita energy requirement varies across countries. The typical rural energy requirement can be obtained for example using values provided by the African Development Bank (1996) assuming 45 GJ (t oil equivalent)$^{-1}$ and ranges from 7650 MJ $capita^{-1}$ $year^{-1}$ in Senegal to 17550 MJ $capita^{-1}$ $year^{-1}$ in Botswana, equivalent to 1.0 to 2.1 m^3 $capita^{-1}$ day^{-1} assuming an energy content of ~22 MJ m^{-3} biogas (Omer and Fadalla 2003; Cornejo and Wilkie, 2010). The energy use depends on the time taken for cooking, which differs across countries due to different cooking traditions. Assuming 0.67 m^3 biogas is required for each kWh energy requirement (Austin, 2003), if a single gas plate, typically equivalent to 0.75 kWh electrical energy (Austin, 2003) is used to cook food for 1 hour, the biogas requirement will be ~0.5 m^3. If the cooking tradition is for slow cooking stews, requiring 2-3 hours of cooking, biogas requirement will clearly be much greater than where cooking uses rapid techniques such as stir fry that may be completed in a few minutes.

Calculation by household data

The household biogas requirement, $V_{household}$ (m^3 yr^{-1}) is calculated from household data specifying the number of hours cooking required, t_{cook} (hrs day^{-1}), and the number of gas plates (each assumed to be equivalent to 0.75 kWh electrical energy), n_{plates},

$$V_{\text{household}} = 365.25 \times 0.75 \times t_{\text{cook}} \times n_{\text{plates}} \times V_{\text{elec-gas}} \quad \text{Eqn. 7.1.1}$$

where $V_{elec\text{-}gas}$ (m^3 kWh^{-1}) is the volume of gas required to replace each kWh of electrical electricity (assumed to be 0.67 m^3 kWh^{-1}). This can be translated into the total household energy requirement from the biogas, $E_{household}$ (MJ yr^{-1}) using the heat of combustion of the gas, (MJ $m^{-3)}$,

$$E_{\text{household}} = \Delta H_{\text{c,biogas}} \times V_{\text{household}} \quad \text{Eqn. 7.1.2}$$

If the CH_4 content of biogas is 65%, the heat of combustion of the gas, $\Delta H_{\text{c,biogas}}$ (MJ $m^{-3)}$, will be 21.25 - 22.21 MJ m^{-3} (Cornejo & Wilkie, 2010).

Calculation by national statistics

For larger scale calculations, or if the specific values for the household are unknown, the household requirement for biogas, $E_{household}$ can be estimated from national statistics on the typical per capita energy requirement, $E_{req,cap}$ (MJ yr^{-1}) and the number of people in the household, n_{people},

$$E_{household} = E_{req.cap} \times n_{people} \quad \text{Eqn. 7.1.3}$$

National statistics on the per capita energy requirement can be obtained from the figures for energy consumption given by the African development bank (1996) assuming 45 GJ (t oil equivalent)$^{-1}$ (http://bioenergy.ornl.gov/papers/misc/energy_conv.html).

Amount of feedstock

For small farmers in SSA, the feedstock for biogas production is mainly manure from livestock e.g. cattle, sheep, goats, horses, donkeys, rabbits and chickens but also from humans if culturally acceptable (Jewitt, 2011). If animals are stall fed, manure is easily collected for biogas. If the cattle are grazing for part of the day, manure can be collected from the fields, but this requires extra labour.

Assuming optimum conditions for biogas production (temperature 30-35 °C; pH 6.8-7.5; C to N ratio 20-30; solid content 7-9% and retention time 20-40 days (Gutser et al., 2005)), biogas production is dependent on the proportion of volatile solids in the organic waste (Polprasert, 2007). Cow manure, rice straw and water hyacinth all yield high amounts of biogas, producing over 0.1 m^3 (kg fresh waste)$^{-1}$. The amount of biogas produced per head also depends on food intake and the size and breed of the animal. Housed dairy and beef cattle are estimated to produce more manure than feedlot cattle, which results in a higher potential for biogas production from dairy and beef cattle (over 2 m^3 $head^{-1}$ day^{-1}) than from feedlot beef (less than 1.7 m^3 $head^{-1}$ day^{-1}). Brown (2006) suggested that 1-2 cows or 5-8 pigs would supply adequate feedstock for a single 4 person household biogas digester. Orskov et al (2013) estimated biogas production to equate to 0.83 to 1.4 m^3 $head^{-1}$ day^{-1} from 2 cows (or 0.16 m^3 $head^{-1}$ day^{-1} from cattle in Sudan), and only 0.37 m^3 $head^{-1}$ day^{-1} from 8 pigs, suggesting consistency with Brown's estimate of the number of cows needed, but that a higher number of some breeds of pigs might be needed to provide a more appropriate biogas yield for a 4 person household.

From the results of nationally representative household surveys in Ethiopia, Kenya, Rwanda, Mozambique and Zambia, Jayne et al. (2003) concluded that farm sizes in Africa are declining over time, with approximately 25% of agricultural households being virtually landless, controlling less than 0.1 ha $capita^{-1}$, the largest part of the variation in farm sizes occurring within, rather than between villages. Households controlling such a low area of land may be limited in the livestock they can manage, which may in turn limit their potential to run a biogas digester. A system based on human faeces alone would produce only 0.02 m^3 biogas $capita^{-1}$ day^{-1}, which is not enough biogas. The system could be supplemented by vegetable material; for instance, sufficient biogas could be produced from 1.5 – 6.3 kg $capita^{-1}$ day^{-1} rice straw or 2.6 – 11.0 kg $capita^{-1}$ day^{-1} water hyacinth. In households controlling such small areas of land, consideration would also need to be given to the possibilities for productive use of the bioslurry produced.

Livestock numbers may also fluctuate within the year due to the annual cycle of animals reproducing and being sold or slaughtered. This may constrain the functioning of the digester in some periods of the year due to inadequate feedstock. The household energy demand will then need to be met, either from other sources, or by collecting vegetable material to feed the digester. The numbers of livestock may also change over time due to changes in the financial circumstances of the household. This can introduce problems with adequate sanitation if numbers increase, or problems with maintaining digester functioning if numbers fall. If livestock numbers are likely to change, the cheaper and less long-lasting balloon digester might allow the household to better respond to changes in feedstock availability.

Feedstocks are included in the systems model from animal sources and from crop residues. The amount of feedstock, M_{feed} (t fresh weight yr^{-1}), can either be entered directly, or can be estimated from the number of each of the different types of animals on the farm (n_{animal}), the area of the different types of crops grown (A_{crop}, ha) and the percentage of the available waste of each type that is used in the digester (P_{used}, %). For animal wastes, the amount of feedstock is given by

$$M_{feed} = 365.25 \times \frac{P_{used}}{100} \times \frac{P_{waste}}{100} \times n_{animal} \times M_{animal} \quad \text{Eqn. 7.1.4}$$

where P_{waste} is the wet waste produced per animal as a percentage of its live weight (kg fresh waste day^{-1} (100 kg live weight)$^{-1}$) and M_{animal} is the typical live weight for the type of animal specified (t live weight).

These values were obtained from Gotaas (1996), Taiganides (1978), Volger (1981), Omer and Fadalla (2003), Rey et al. (1992) and Lohani and Rajagopal (1981).

For crop waste, the amount of feedstock is given by

$$M_{\text{feed}} = \frac{P_{\text{use}}}{100} \times A_{\text{crop}} \times D_{\text{crop}} \qquad \text{Eqn. 7.1.5}$$

where D_{crop} is the amount of organic waste produced by the crop (t fresh waste ha^{-1} yr^{-1}). Default values for D_{crop} are published for a range of crops in different publications. Work continues to collect this data and extend the number of crop residues included in the biogas calculator.

Biogas production

A number of detailed models have been published to calculate the amount of biogas produced during anaerobic digestion (Donoso-Bravo et al., 2011). Each component of the organic waste (carbohydrates, proteins and lipids) goes through three stages of decomposition; hydrolysis, fermentation and CH_4 production. When considering solid waste digestion, hydrolysis of the complex polymeric substances is often considered to be the rate-limiting step (Mata-Alvarez et al., 1977). Fermentation of amino acids, sugars and fatty acids is done by fermentative or acid-forming bacteria, which use extra-cellular enzymes to break down the carbohydrates, proteins and lipids into soluble sugars, amino acids and fatty acids, respectively, forming organic acids, hydrogen and CO_2 (Gaudy and Gaudy, 1980). Hydrogen producing acetogenic bacteria complete the fermentation by oxidizing fatty acids to produce acetic acid, hydrogen and CO_2 (Zinder,1984). Approximately 75% of CH_4 production is done by acetoclastic methanogens, which transform acetic acid to CH_4 and CO_2, and 25% by H_2 utilizing methanogens, which reduce CO_2 to CH_4 (Mah et al., 1980). Early modeling approaches attempted to simplify the description of this complex set of processes by describing only the rate limiting step (Hill and Barth, 1977). The limiting factors can, however, be different under different operating conditions (Speece, 1996), resulting in different authors focusing on different rate limiting steps; CH_4 production from acetic acid, conversion of fatty acids into acetic acid, and hydrolysis of suspended solids (Eastman and Ferguson, 1981). The concentration of volatile fatty acids soon emerged as a key parameter (Andrews and Graef, 1971), with formation of volatile fatty acids and their conversion to acetic acid being described separately (Hill, 1982). The influence of NH_4^+-N on CH_4 production (Hill and Barth, 1977) and the controlling inhibiting role of hydrogen gas in the formation of volatile fatty acids and subsequent conversion into acetic acid (Mosey, 1983; Harper and Pohland, 1986) were also included in models. This gave rise to models that predict the change in individual volatile fatty acid species, pH, partial pressure of hydrogen gas, and biogas production and composition as a function of time (Massé and Droste, 200; Rozzi et al., 1985; Jones and Hall, 1989; Costello et al., 1991). In an attempt to produce a generic model and reach a common basis for further development, Batstone et al. (2002) included descriptions of the dynamics of 24 species and 19 bioconversion processes. Such complexity makes the model very difficult to use, and an additional step would be required to translate the values simulated into a description of decomposability of bioslurry.

These models are too complex to be used as a simple tool for small scale application of biogas digesters. Therefore, here we have used a simple, static approach based on the approach suggested by Polprasert (2007). The volume of biogas produced, V_{biogas} (m^3 yr^{-1}), was calculated according to standard values for the amount of each type of feedstock, and the amount of feedstock produced, M_{feed} (t fresh weight yr^{-1}) (given in Eqns 7.1.4 and 7.1.5),

$$V_{\text{biogas}} = (P_{\text{VS}} \times P_{\text{DW}} \times p_{\text{CH4:VS}} \times M_{\text{feed}}) \Big/ (100 \times P_{\text{CH4:biogas}}) \qquad \text{Eqn. 7.1.6}$$

where P_{VS} is the percentage of the total solids in the specified feedstock that are volatile, and P_{DW} is the percentage dry weight in the feedstock, $p_{\text{CH4:VS}}$ is the amount of biogas produced for each unit weight of volatile solids, (m^3 CH_4 t^{-1}), and $P_{\text{CH4:biogas}}$ is the percentage of CH_4 in the biogas (assumed to be 65% after Cornejo and Wilkie (2010). This is then converted into the energy provided by the biogas, E_{biogas} (MJ yr^{-1}), according to the energy content of biogas, $p_{\text{E:biogas}}$ (MJ m^{-3}), which assuming a CH_4 content of 65%, is 21.245 - 22.207 MJ m^{-3} (Cornejo & Wilkie, 2010).

$$E_{\text{biogas}} = V_{\text{biogas}} \times p_{\text{E:biogas}} \qquad \text{Eqn. 7.1.7}$$

If the C:N ratio of the feedstock is outside the range 20:30, the N content is assumed to limit biogas production, and the use of available feedstocks is adjusted to ensure the total feedstock composition provides a C:N ratio within the optimum range.

Future work should increase the reliability of the simple modelling approach, following the principles developed by Batstone et al. (2002), but maintaining the requirement for only simple input data. An important variable that should be considered in a revised model is the hydraulic retention time; a factor that has an important impact on gas production, shows marked differences between households and is easily calculated from the feed-rate.

Reduction in carbon loss due to forest clearance

By providing an alternative energy source that would otherwise be obtained from fuelwood or charcoal, it is widely assumed that biogas digesters could help to reduce the rate of deforestation in SSA (e.g. Felix and Gheewala, 2011). At global level, the link between deforestation and the use of fuelwood and charcoal is weak because fire wood is often obtained from fallen wood or from sources that would already be felled for construction or land clearance (Maes and Verbist, 2012). However, at the household level, the reduction in potential wood clearance attributable to replacement by biogas digesters can be determined from household calculations.

Calculation by species

Potential reduction in carbon loss

For household scale calculations, the potential reduction in C loss due to forest clearance, ΔC_{loss} (t C yr^{-1}) is estimated for the four major wood species collected for firewood by the household from the energy in wood derived fuel needed to replace the energy in the biogas that could be generated by the household, E_{fuel} (MJ yr^{-1}), the percentage of each species used in the wood derived fuel, P_{species} (%), and the energy to C ratio, $p_{\text{E:C}}$ (MJ/tC)

$$\Delta C_{\text{loss}} = \left(\frac{P_{\text{species}}}{100}\right) \times \left(\frac{E_{\text{fuel}}}{p_{\text{E:C}}}\right) \qquad \text{Eqn. 7.1.8}$$

The two unknown factors in this equation are the energy to C ratio of wood derived fuel, and the energy in the wood derived fuel replaced by generated biogas.

Energy to carbon ratio of wood derived fuel

The energy to C ratio, $p_{\text{E:C}}$, is given by the density of energy production of the wood derived fuel, D_{energy} (MJ ha^{-1}), and the density of C production, $D_{\text{C,wood}}$ (t C ha^{-1}),

$$p_{\text{E:C}} = \left(\frac{D_{\text{energy}}}{D_{\text{C,wood}}}\right) \qquad \text{Eqn. 7.1.9}$$

The density of energy production of wood, $D_{\text{energy,wood}}$ (MJ ha^{-1}), is obtained from the gross heat of combustion for the wood, $\Delta H_{\text{c,wood}}$ (MJ (t wood)$^{-1}$), and the density of biomass production, $D_{\text{biomass,wood}}$ (t wood ha^{-1}),

$$D_{\text{energy ,wood}} = \Delta H_{\text{c,wood}} \times D_{\text{biomass ,wood}} \qquad \text{Eqn.7.1.10}$$

The density of energy production of charcoal, $D_{\text{energy,char}}$ (MJ ha^{-1}), must also account for the losses during charcoal production, expressed as the percentage yield of charcoal obtained from the wood, P_{char} (t charcoal (100 t wood)$^{-1}$),

$$D_{\text{energy ,char}} = \Delta H_{\text{c,char}} \times D_{\text{biomass ,wood}} \times \frac{P_{\text{char}}}{100} \qquad \text{Eqn.7.1.11}$$

where $\Delta H_{\text{c,char}}$ is the gross heat of combustion for the charcoal (MJ (t charcoal)$^{-1}$).

The density of C production is given for both wood fuel and charcoal by the density of C production in the forest, calculated from biomass production, $D_{biomass,wood}$, and the percentage of C in the wood, $P_{C,wood}$ (t C (100 t wood)$^{-1}$); this approach assesses energy production according to the primary source of C and accounts for losses in C occurring during the charcoal production,

$$D_{C,wood} = D_{biomass,wood} \times \frac{P_{C,wood}}{100} \qquad \text{Eqn.7.1.12}$$

Energy in wood derived fuel replaced by generated biogas

For charcoal, the energy in the fuel, $E_{fuel,char}$ (MJ yr^{-1}), used in Eqn.7.1.8, is given by the ratio of the efficiency of the biogas stove, $P_{stove,biogas}$ (%), and the efficiency of the selected design of wood stove, $P_{stove,wood}$ (%),

$$E_{fuel,char} = E_{biogas} \times \left(\frac{P_{stove,biogas}}{P_{stove,wood}}\right) \qquad \text{Eqn.7.1.13}$$

For wood, the equation must also account for the energy needed to drive off the moisture content of the wood, $E_{moisture}$ (MJ yr^{-1})

$$E_{fuel,wood} = \left(E_{biogas} \times \left(\frac{P_{stove,biogas}}{P_{stove,wood}}\right)\right) + E_{moisture} \qquad \text{Eqn.7.1.14}$$

where $E_{fuel,wood}$ is the energy in wood fuel needed to replace biogas generated (MJ yr^{-1}).

The energy needed to drive off the moisture content of the wood is given by the energy needed to evaporate the water content of the wood, $\Delta H_{evap,wood}$ (MJ (t wood)$^{-1}$), the mass of wood used each year, M_{wood} (t yr^{-1}), and the percentage moisture content of the wood ($P_{moisture}$ (t water (100 t wood)$^{-1}$)

$$E_{moisture} = \Delta H_{evap,wood} \times M_{wood} \times \frac{P_{moisture}}{100} \qquad \text{Eqn.7.1.15}$$

The mass of wood, M_{wood}, is obtained from the potential reduction in C loss due to forest clearance, ΔC_{loss}, and the C content of the wood, P_c,

$$M_{wood} = \Delta C_{loss} \times \frac{100}{P_C} \qquad \text{Eqn.7.1.16}$$

Substituting M_{wood} into Eqn.7.1.15, $E_{moisture}$ into Eqn.7.1.16 and rearranging gives an equation for $E_{fuel,wood}$ in terms of known values only,

$$E_{fuel,wood} = \left(E_{biogas} \times \left(\frac{P_{stove,biogas}}{P_{stove,wood}}\right)\right) \Bigg/ \left(1 - \left(\frac{\Delta H_{evap,wood} \times P_{species} \times P_{moisture}}{100 \times p_{E:C} \times P_C}\right)\right) \qquad \text{Eqn.7.1.17}$$

Potential area saved from clearance

The potential reduction in C loss, ΔC_{loss} (tC yr^{-1}), is translated into the potential area saved from clearance, ΔA_{loss} (ha yr^{-1}), by dividing by the density of C in the stand, $D_{C,wood}$ (t C ha^{-1}) (Eqn.7.1.12),

$$\Delta A_{loss} = \frac{\Delta C_{loss}}{D_{C,wood}} \qquad \text{Eqn.7.1.18}$$

Calculation by biome

For larger scale calculations, similar equations are used to calculate the potential reduction in C loss due to forest clearance, but using less detailed input data. The potential area saved from clearance is calculated from the ratio of the energy required to replace the biogas generated, $E_{fuel,}$ (MJ yr^{-1}), and the energy released per unit area of biome combusted, $E_{c,biome}$ (MJ ha^{-1}),

$$\Delta A_{loss} = \frac{E_{fuel}}{E_{c,biome}} \quad \text{Eqn.7.1.19}$$

The energy released per unit area of biome combusted, $E_{c,biome}$, is obtained from the density of biomass in the stand, $D_{biomass,biome}$ (t wood ha^{-1}), assuming a gross heat of combustion of $\Delta H_{c,biome}$ =19000 MJ t^{-1},

$$E_{c,biome} = \Delta H_{c,biome} \times D_{biomass,biome} \quad \text{Eqn.7.1.20}$$

The area saved from clearance is then translated into a potential reduction in C loss, ΔC_{loss} (t C yr^{-1}), using the density of C held in the biome, $D_{C,biome}$ (t C ha^{-1}),

$$\Delta C_{loss} = \Delta A_{loss} \times D_{C,biome} \quad \text{Eqn.7.1.21}$$

Household value of the biogas

The household value of the biogas arises from the replacement of purchased fuel by biogas, and the change in labour required to produce biogas compared to the labour needed to collect fuelwood. The changes in labour are, as yet, not well established and are likely to change as the recommended methods of biogas production are refined. Furthermore, if profitable uses for household labour are not available, householders may not consider savings in time to be a real monetary saving. Therefore, the model currently accounts for only replacement of purchased fuel. The value of the biogas to the household, S_{biogas} (£ yr^{-1}), is given by the amount spent on fuel each year, S_{fuel} (£ yr^{-1}), and the proportion of the purchased fuel that could be replaced by biogas, $p_{biogas:purchased}$, as

$$S_{biogas} = p_{biogas:purchased} \times S_{fuel} \quad \text{Eqn.7.1.22}$$

The proportion of the purchased fuel that can be replaced by biogas is worked out from the energy provided by biogas, E_{biogas} (MJ yr^{-1}), the household energy requirement, $E_{household}$ (MJ yr^{-1}) and the percentage of the household energy requirement that is provided by purchased fuel, $P_{purchase\ fuel}$ (%),

$$p_{biogas:purchased} = \frac{E_{biogas} \times 100}{E_{household} \times P_{purchased\ fuel}} \quad \text{Eqn.7.1.23}$$

If $p_{biogas:purchased} > 1$, it is set to a value of 1.

7.2. Value of bioslurry as an organic fertiliser

Amount of bioslurry produced

The conversion of organic C to CH_4 is a very efficient process. As a result, the reduction in total C on anaerobic digestion was observed to be 71% by Massé et al. (2007), 69-80% in a series of experiments by Schievano et al. (2011), and 94% by Perez et al. (2006), although the latter used thermophilic digestion so may not be relevant here. The 20-31% of the total organic C that is not lost (Massé et al., 2007; Schievano et al., 2011) remains in the bioslurry and is usually composed of material that is not readily available to biological degradation (Messner et al., 1987).

The amount of bioslurry remaining after the anaerobic digestion is calculated from the C in the feedstock less the C emitted as CH_4 and CO_2. The C in the feedstock, C_{feed} (t C yr^{-1}), is given by the weight of feedstock used each year, M_{feed} (t fresh weight yr^{-1}), the percentage dry matter in the feedstock, P_{DW} (%total solids / fresh weight), and the percentage organic C, P_C (% weight C / weight total solids),

$$C_{feed} = \frac{M_{feed} \times P_{DW} \times P_C}{10^4} \quad \text{Eqn.7.2.1}$$

The C content of the biogas, C_{biogas} (t C yr^{-1}) is calculated from the percentage of the gas that is CH_4 and CO_2, $P_{CH4+CO2}$, using the Ideal Gas Law;

$$C_{\text{biogas}} = \frac{P_{\text{atm}} \times P_{\text{CH 4+CO 2}} \times V_{\text{biog as}} \times 12}{10^5 \times RT} \qquad \text{Eqn.7.2.2}$$

where P_{atm} is the atmospheric pressure, assumed to be 101325 Pa, R is the gas constant = 8.314472 J K^{-1} mol^{-1} and T is the air temperature in Kelvin.

Assuming that the system is closed (ie no leaks) so that all losses of C from the feedstock occur in the biogas, the C remaining in the digestate, $C_{\text{bioslurry}}$ (t C yr^{-1}) can be calculated by difference,

$$C_{\text{bioslurry}} = C_{\text{feed}} - C_{\text{biogas}} \qquad \text{Eqn.7.2.3}$$

This typically results in 20-35% of the feedstock remaining in the digestate, which is in agreement with the range observed in measurements (e.g. Massé et al., 2007; Schievano et al., 2011).

Amount of nutrients available to the crop

The nutrients held in organic wastes can be categorized as immediately available, rapidly released, slowly released or unavailable (Zhang et al., 2012). Nutrients that are immediately available to the plant are in the form of a small mobile ion, such as NH_4^+ that can readily be taken up by the plant without the need for further chemical or biological conversion. Rapidly released nutrients will be released to the plant by the soil micro-organisms in the first years following application. Ammonium, NO_3^-, phosphates (HPO_4^{2-} and $H_2PO_4^-$), and sulfate (SO_4^{2-}) are the main forms of nutrients provided by this microbial conversion of organic compounds into inorganic compounds. Slowly released nutrients will become available to the plant over a much longer period. Unavailable nutrients are in a form that cannot be accessed by the soil micro-organisms, either due to being in a recalcitrant form or due to physical protection by other recalcitrant materials. The release characteristics of nutrients from the treated and untreated organic wastes depend on the amount of nutrients held in each of these forms.

Different treatment processes have distinctive impacts on the different categories of nutrients (Kirchmann and Witter, 1992). Anaerobic digestion tends to concentrate the nutrients that are initially in rapidly and slowly released forms by release of C during decomposition. The stability of organic matter is increased, but the C:nutrient ratio decreases, resulting in a product with a high content of rapidly released nutrients (Gutser et al., 2005). In contrast to aerobic composting, because oxygen rather than nutrients limit decomposition, anaerobic digestion tends to increase the content of immediately available N, in the form of NH_4^+ (Möller and Müller, 2012; Gutser et al., 2005). Kirchmann and Witter (1992) measured NH_4^+-N concentrations in anaerobically digested materials of 50-75% of the total N. Similar results were reported by Schievano et al. (2011). Precipitation of insoluble inorganic P during anaerobic digestion tends to reduce the concentration of immediately available P and micronutrients (Möller and Müller, 2012), although this does not usually result in P deficiency in crops (Loria and Sawyer, 2005; Möller and Stinner, 2010), perhaps because the N:P ratio in the untreated manure is higher than the N:P requirement of most plants (Eghball and Power, 1999). Volatile fatty acids and other labile organic compounds are formed as intermediates in the anaerobic digestion process (Cysneiros et al., 2008; Jacobi et al., 2009). If these compounds are still present when bioslurry is applied to the soil, they provide a readily available source of C, which could result in the available nutrients being immobilized or lost from the soil (Bateman and Baggs, 2005). However, if care is taken to avoid too rapid a throughput of the organic waste, so circumventing a high content of these intermediate compounds, bioslurry provides an excellent source of immediately available nutrients that can be applied directly to crops when the crop needs additional nutrients, and a rapid crop response to the applied bioslurry will result.

Losses of nutrients during the digestion process may be expected to be less from anaerobic digesters than from compost heaps due to the use of an airtight vessel. Biogas is generally composed of 48–65% CH_4, 36–41% CO_2, up to 17% nitrogen gas, <1% oxygen gas, 32–169 ppm hydrogen sulphide and traces of other gases (Ward et al., 2008). Therefore losses of nutrients other than N during this process can be expected to be small. In measuring nutrient losses in large centralized biogas plants in Europe, Möller et al. (2010) found that P and K losses during digestion were negligible and N losses occurred mainly as gaseous losses of ammonia during storage. Losses of N are reported by many authors to be very small, with most of the N being conserved in the bioslurry (Field et al., 1984; Larsen, 1986; Messner and Amberger, 1987; Plaixats et al., 1988). Schievano et al. (2011) reported net losses of 5-10% of the total N. Strik et al. (2005) suggested losses could occur as migration of NH_3 with the biogas flux. However, Schievano et al. (2011) reported that less than 1% of the N loss occurred by this mechanism, suggesting that the remaining loss occurred by partial organic / inorganic matter sedimentation and subsequent retention in the digester. In experiments with batch reactors reported by Massé et al. (2007), loss of N by sedimentation was observed to approach 30%. Similar proportions (2-9%) of P and K loss were observed during anaerobic digestion by Schievano et al. (2011), again suggested to be due to sedimentation. These nutrients are removed from the bioslurry, but not entirely lost from the system as they can be returned to the soil when the digester is cleaned out, providing a potential slow release organic fertilizer. In a flexible balloon digester, the positioning of the inlets and outlets means that sedimentation is much lss than in other designs of digesters. Therefore, these losses can be assumed to be negligible.

Because the N content of the digestate is the nutrient most often limiting crop production, the model presented here focuses on the availability of N. The available (NH_4^+) N in the digestate, $N_{NH4,bioslurry}$ (t N yr^{-1}), is calculated from the N available in the feedstock, N_{feed} (t N yr^{-1}), the percentage losses during treatment, P_{Nloss} (%), and the proportion of the total N in the feedstock that is in the form of NH_4^+, $p_{NH4:totalN}$,

$$N_{\mathrm{NH\,4,bioslurry}} = N_{\mathrm{feed}} \times \left(1 - \frac{P_{\mathrm{Nloss}}}{100}\right) \times p_{\mathrm{NH\,4:totalN}} \qquad \text{Eqn.7.2.4}$$

The nature of the bioslurry produced by biogas digesters in SSA is impacted by the nature of the feedstock and the temperature of digestion (Yadvika et al., 2004). Boadzo et al (2011) reported that gas production from anaerobic digestion was highest from fats (1.27 m^3 kg^{-1} total solids), followed by carbohydrates (0.79 m^3 kg^{-1} total solids) and proteins (0.7 m^3 kg^{-1} total solids), suggesting that the increase in concentration of nutrients in the bioslurry is highest in a fatty feedstock. However, the gas yield from the different types of feedstocks available in SSA varies over a very small range (municipal solid wastes = 0.1-0.2, household waste = 0.2-0.3, sewage sludge = 0.2-0.4 and manure = 0.1-0.3 m^3 kg^{-1} total solids (Boadzo et al., 2011)), and so the nutrient content of the feedstock is likely to have a greater impact than the amount of gas produced on the nutrient concentration in the bioslurry. Animals provided with a low nutrient feed produce manure with a lower nutrient content (Salcedo et al., 2010). Digestates from feedstocks with a high degradability, such as cereal grains, poultry and pig manures with a diet high in concentrates, are characterized by a high NH_4^+:total N ratio and low C:N ratios (Möller and Müller 2012; Emmerling and Barton, 2007, de Boer, 2008). Cattle manures or fibrous feedstocks low in N lead to a low NH_4^+-N : total N ratio (Möller and Müller 2012; Möller and Stinner, 2010). The low nutrient contents of animal feeds commonly used in SSA, therefore, tend to reduce the immediately available nutrient content of the bioslurry. Therefore, the NH_4^+-N : total N ratio in the digestate ($p_{NH4:totalN}$) might be expected have a NH_4^+-N : total N ratio at the lower end of the 50-75% range presented by Kirchmann and Witter (1992), and the N losses during digestion (P_{Nloss}) are likely to be at the lower end of the 5-10% losses presented by Schievano et al. (2011). In the simple approach presented here, $p_{NH4:totalN}$ is assumed to be 0.5 and P_{Nloss} is assumed to be 5%. A more sophisticated approach would calculate these values according to the nature of the feedstock and the conditions of the digestion. However, further research is needed to provide the data needed to do these calculations. Therefore, the simple robust approach using fixed values is used here.

Carbon sequestered in the soil

The amount of C sequestered in the soil each year is a balance between the annual C input and the annual emissions from the decomposing organic matter. Models that are used to estimate C sequestration differ in the ways they simulate these two factors.

Annual carbon inputs to the soil

The annual C input depends on the plant inputs and organic amendments to the soil, but annual plant inputs, especially from dead roots and root exudates, are difficult to measure. Some authors use estimates of plant productivity to determine plant inputs (e.g. Parton et al., 1988); others use the measured C content of the soil at steady state to infer the plant inputs needed to achieve the measured amount of soil C (e.g. Smith et al., 2005). The amount of C added to the soil in organic waste depends on the treatment process used. Different treatments retain different quantities of C from the same quantity and quality of starting material. The percentage C remaining after treatment of the organic waste is a key parameter that must be determined to allow the amounts of C sequestered by the different treatments to be compared.

Annual carbon emissions from the soil

The annual emissions of C from decomposing organic matter depend on the total amount and decomposability of organic matter already present in the soil, the amount and decomposability of any added plant material and organic wastes, and the microbial activity, which is dependent of the added organic matter and environmental characteristics (including temperature, water and clay content) of the soil. Some models define decomposability using the decomposition profile for the particular type of organic matter (e.g. Bosatta and Ågren, 1991); but this approach can become unwieldy when many different types of organic materials are added to the soil on numerous occasions. Other models define decomposability by quantifying the proportions of "decomposable" and "resistant" fresh plant material, and "rapidly" and "slowly" decomposing organic material for the organic matter already present in the soil and the organic matter added as plant inputs and organic amendments (e.g. Coleman and Jenkinson 1996). The rate constants set for these different pools allow the proportions of the different pools to define the decomposition profile without the need to keep track of each different amendment of organic material.

Decomposability of organic wastes

The decomposability of the organic waste following treatment is another key parameter that must be determined to allow the potential for C sequestration by different treatments to be compared. Treatment of organic wastes by anaerobic digestion stabilizes the organic matter and reduces the rate of CO_2 emissions when the wastes are applied to soils. In soil incubation studies with anaerobic digests of pig slurry, Marcato et al. (2009) observed a significantly higher C mineralization rate after 49 days in soils receiving untreated slurry compared to the treated slurry (17.6 g and 12.0 g CO_2-C 100 g^{-1} organic C supplied respectively). These rates were similar to those reported by Garćia- Gómez et al. (2003) for untreated and composted pig slurry (22.5 g and 12.0 g CO_2-C 100 g^{-1} organic C supplied respectively), suggesting that the decomposability of organic matter following 7 weeks of anaerobic digestion is similar to the decomposability following 4 weeks of composting.

Messner and Amberger (1987) suggested that C not transformed into biogas during anaerobic digestion is mainly composed of materials that are less available for biological degradation. Fourier transform infrared spectroscopy was used by Marcato et al. (2009) to characterize the functional groups in the raw and digested slurry. The raw and digested slurry contained similar functional groups, but showed a marked decrease in aliphatic structures and lipids, amides and polysaccharides, representing the biodegradation of the labile fraction into biogas with a relative increase in the more resistant and stable compounds (Smidt et al., 2002). This is consistent with the initial decomposition of lipids, proteins and carbohydrates observed during aerobic composting by Amír et al. (2005). An increase in carbonates was observed, and Marcato et al. (2009) suggested this was due to mineralization of organic matter during digestion. Comparison of the stabilization of organic matter during biological treatment of municipal organic wastes using combined mechanical, anaerobic and composting treatments suggested that stabilization was greatest during the anaerobic digestion (Ponsá et al., 2008).

Changes in carbon sequestration following anaerobic digestion of organic wastes

A representation of the RothC model (Coleman and Jenkinson, 1996) using an annual timestep is used to determine the soil C sequestration that might be expected when the same amount of starting material is incorporated in the soil, either as untreated organic waste, or following anaerobic digestion.

The decomposability of the incorporated organic waste was defined using the proportion of decomposable plant material (DPM) to stabilized material (HUM) in the organic waste. Decomposable and stabilized material are defined as having decomposition rate constants of 10 $year^{-1}$ and 0.02 $year^{-1}$ (Coleman and Jenkinson, 1996). Therefore, the ratio of DPM to HUM determines the rate of organic waste decomposition in the soil.

The proportion of C in the DPM pool, C_{DPM} (t C ha^{-1}), that is lost by decomposition, $C_{\mathrm{DPM,loss}}$ (t CO_2-C ha^{-1} $timestep^{-1}$) is given by an exponential equation for first order decomposition (Coleman and Jenkinson, 1996),

$$p_{\mathrm{DPM,loss}} = \frac{C_{\mathrm{DPM,loss}}}{C_{\mathrm{DPM}}} = 1 - e^{-abc\, k_{\mathrm{DPM}}\, t} \qquad \text{Eqn.7.2.5}$$

where a, b and c are rate modifying factors for temperature, moisture and plant cover respectively, k_{DPM} is decomposition rate constant for DPM (k_{DPM} = 10 $years^{-1}$, as given by Coleman and Jenkinson, 1996), and t is a factor to convert the annual time step of the rate constant to actual period of incubation ($t = \frac{d}{365}$, where *d* (days) is the duration of the incubation).

The temperature rate modifier is given by Coleman and Jenkinson (1996),

$$a = \frac{47.9}{1+\exp\left(\frac{106}{T+18.3}\right)} \quad \text{Eqn.7.2.6}$$

where *T* is the average air temperature over the period of the timestep, *t* (°C).

The moisture rate modifier (*b*) is also given by Coleman and Jenkinson (1996),

$$b = 0.2 + (1.0 - 0.2) \times \frac{D_{\max} - D}{D_{\max}\ (1-0.444)} \quad \text{Eqn.7.2.7}$$

where D_{max} is the maximum soil moisture deficit (mm) and *D* is the actual soil moisture deficit (mm).

The plant cover rate modifier (*c*) accounts for the impact of factors due to the presence of the plant, such as shading of the soil, on the rate of decomposition. The plant cover rate modifier is set to 0.6 when the plant is present and 1.0 when it is not (Coleman and Jenkinson, 1996).

Similarly, the proportion of C in the HUM pool, C_{HUM} (t C ha^{-1}) that is lost by decomposition, $C_{HUM,loss}$ (t CO_2-C ha^{-1}) is given by

$$p_{\text{HUM,loss}} = \frac{C_{\text{HUM,loss}}}{C_{\text{HUM}}} = 1 - e^{-abc\, k_{\text{HUM}}\, t} \quad \text{Eqn.7.2.8}$$

where the rate constant, k_{HUM}, for decomposition of the HUM pool is 0.02 $years^{-1}$ (Coleman and Jenkinson, 1996).

Assuming that all of the C in the incorporated organic waste can be described as C in either the DPM or HUM pools, the measured percentage loss of incorporated organic waste, P_{loss} (%), can be related to the proportions of C in the DPM and HUM pools lost by decomposition

$$P_{\text{loss}} = \left(p_{\text{DPM,loss}} + p_{\text{HUM,loss}}\right) \times P_{\text{input}} \quad \text{Eqn.7.2.9}$$

Substituting the equations for $p_{DPM,loss}$, $p_{HUM,loss}$ and P_{input} into the above equation and rearranging allows the proportion of DPM and HUM in the incorporated organic waste (p_{DPM} and p_{HUM}) to be determined

$$p_{\text{DPM}} = \frac{\left(P_{\text{loss}}/100\right) + p_{\text{HUM,loss}}}{p_{\text{DPM,loss}} - p_{\text{HUM,loss}}} \quad \text{Eqn.7.2.10}$$

and

$$p_{\text{HUM}} = 1 - p_{\text{DPM}} \quad \text{Eqn.7.2.11}$$

The DPM/HUM ratios were obtained from p_{DPM}/p_{HUM} calculated from data presented by Marcato et al. (2009); for untreated waste DPM/HUM = 0.20 and for digestate DPM/HUM = 0.14. More research is needed to establish the consistency of the values of these ratios for untreated waste and digestate, and to determine which the characteristics of the digestion process determine the DPM/HUM ratio of the bioslurry. However, in this preliminary version of model, the amount of C sequestered in the soil is calculated using the DPM.HUM ratio is set to 0.20 for untreated waste and 0.14 for bioslurry.

Household value of the bioslurry

Replacement of inorganic fertilizers

Because the highest demand in most crops is for N and P, these nutrients most commonly limit crop growth (Williams et al., 1976). Fertilizer applications, particularly of N and P, can therefore significantly increase crop yields in SSA. In a meta-analysis of 90 peer-reviewed papers from journals and conference proceedings with information on control yields, yields after N fertilizer application, and fertilizer N rates in maize-based cropping systems in SSA, Vanlauwe et al. (2011) noted increases in yields of up to 40 kg per kg of applied N. Phosphorus limitations are also widespread (Bationo et al., 1991a) and can be alleviated by application of mineral or organic fertilizers. Tests conducted by farmers in P deficient fields at Sadore in Niger showed that millet yields could be increased by more than 250% by the use of P fertilizers (Bationo et al., 1991b). In three soils in the northern highlands of Ethiopia, Assefa Abegaz (2008) observed increases in barley yields of up to 90, 69 and 90 kg per kg of applied N, P and potassium (K) respectively.

Increased recycling of nutrients and replacement of expensive inorganic fertilizers through application of the bioslurry output from biogas digesters could impact the nutritional status of crops and so greatly improve yields. Although the potential economic benefits of increased crop yields through application of bioslurry are high, it is difficult to quantify the likely improvement in yields at a specific site without detailed dynamic simulation modeling and analysis of the nutrient status of the soils and crops. However, the value to the farmer can be partially estimated from the potential savings to the farmer of applying bioslurry instead of any planned applications of purchased inorganic fertilizer. This can be quantified from input values of the amount of fertilizer expected to be applied, M_{fert} (t fertilizer yr^{-1}), the price of the fertilizer, S_{fert} (£ (t fertilizer)$^{-1}$). Because the amounts of N in the organic wastes most often limits yield, the calculations currently use the , and the proportion of the proportion of the N required in fertilizer that is available in the bioslurry, $p_{\mathrm{Nfert,bioslurry}}$ to estimate how much inorganic fertilizer could be replaced by the bioslurry,

$$S_{\mathrm{bioslurry}} = p_{\mathrm{Nfert,bioslurry}} \times M_{\mathrm{fert}} \times S_{\mathrm{fert}} \qquad \text{Eqn.7.2.12}$$

The proportion of N required in fertilizer that is available in bioslurry s calculated as

$$p_{\mathrm{Nfert,bioslurry}} = \frac{N_{\mathrm{NH4,bioslurry}} \times 100}{M_{\mathrm{fert}} \times P_{\mathrm{Nfert}}} \qquad \text{Eqn.7.2.13}$$

where $N_{\mathrm{NH4,bioslurry}}$ is the amount of available N in the bioslurry (t N yr^{-1} Eqn 7.2.4) and P_{Nfert} is the percent N in the fertilizer. If $p_{\mathrm{Nfert,bioslurry}}$ >1, $p_{\mathrm{Nfert,bioslurry}}$ is set to 1.

Other benefits

Incorporation of bioslurry to crops has a number of other monetary benefits, but these are highly uncertain and difficult to quantify and so have not yet been included in the calculations of value of the bioslurry to the householder.

Crop productivity is intimately linked to the soil organic matter content (Pan et al., 2009), which influences soil physical, chemical and biological properties, as well as indigenous soil nutrient supply (Bessam and Mrabet, 2003; de Ridder and van Keulen, 1990). Soil organic matter influences the long term losses of nutrients by erosion, leaching and gaseous emissions, and when decomposed by micro-organisms can also provide a slow release source of nutrients to plants. Lal (2004) estimated that 1 t of C sequestered as soil organic matter will hold on average 80 kg N, 20 kg P and 15 kg K, and observed that an increase in arable soils of 1 t ha^{-1} could increase crop yields by 20 to 40 kg ha^{-1} for wheat, 10 to 20 kg ha^{-1} for maize, and 0.5 to 1 kg ha^{-1} for cowpeas. As well as the direct effect of improved nutrient supply, increases in yield associated with organic applications are due to the action of soil organic matter on aggregate structure, so influencing the water holding capacity and aeration of the soil, and affecting root development down the soil profile, which determines the amount of nutrients and water available to the growing plant. Significant improvements in crop yields were observed when fertilizer was applied in conjunction with crop residue mulch (Yamoah et al., 2002), trees (Sanchez, 2002) or with manure or compost (Vanlauwe et al., 2011), suggesting that additional factors to nutrient supply determine the impact of soil organic matter on crop yields. Assefa Abegaz (2008) reported that increases in the agronomic efficiencies of applied P and K fertilizers were much greater in fields with higher soil organic C contents. In long term experiments at Kabete, Kenya, Janssen (2011) observed an increase in yield of 0.85 t ha^{-1} for each g soil organic C added per kg of soil. Farm demonstrations in different countries in SSA suggest that with good management of soil organic matter, it is possible to increase yields by up to five times (World Bank, 2008).

The soils of SSA are often deficient in soil organic matter and have great potential to sequester C. Lal (2004) identified SSA as a global hotspot of soil degradation with a high priority for soil restoration and C sequestration. It has been suggested that a critical limit for soil organic C concentration in most soils of the tropics is 1.1% (Aune and Lal, 1997), but Nyamangara et al. (2003) indicated that on average in SSA, the organic C content of soils is less than 1%. Different local studies reveal similar results. For instance, Assefa and van Keulen (2009) reported organic C contents between 0.9 and 1.1% on continuously cultivated soil of the north highlands of Ethiopia. Increasing or changing the decomposability of organic amendments to the soil has the potential to sequester more C in the soil. In the long term, this may provide additional value to the household through C trading mechanisms. As yet, however, these benefits are not realized. Therefore, the potential monetary value of C sequestration in the soil has not yet been included in these calculations.

7.3. Value of reduction in pathogens

The work presented in section 5 has attempted to quantify the impact of installing a biogas digester on exposure of the members of a household to pathogens. The results are not easily used to generate a general rule for the impact on pathogens. *E.coli* and total coliforms show a significant decrease between feedstock and digestate, whereas *Clostridia perfringens* show a significant increase. In the environment around the digester, *E.coli* and total coliforms show a significant increase overall areas tested, perhaps due to the management and positioning of the digester, whereas *Clostridia perfringens* shows no significant change. The impact of this on the health of people in the household has yet to be established. Further work is needed to examine the significance of these results in terms of likely change in human health, and what how this can be valued for the household.

7.4. Value of improved indoor air quality

The work presented in section 5 shows that levels of CO and $PM_{2.5}$ in the household cooking area decreased significantly with the use of biogas for cooking, with an average percent decrease for $PM_{2.5}$ and CO of 32%. However, the levels of CO and $PM_{2.5}$ remained above EPA and WHO guidelines due to continued use of fuelwood for cooking. These results are based on a limited number of samplings. Further measurements are needed to improve the reliability of results. Further analysis is also needed to translate this improvement in household air quality into a likely improvement in human health.

The relationship between household air quality and firewood use is highly variable, depending on ventilation in the cooking area and positioning of the stove. The average rate of emissions from the households in Tiribogo, where firewood use was also measured was 26 (standard error = 7) $\mu g\ PM_{2.5}\ m^{-3}$ and 0.56 (standard error = 0.26) ppm CO per (kg day^{-1}) firewood used (Table 7.4.1). At these rates of emissions, even assuming no emissions from biogas, to reduce the average concentration of $PM_{2.5}$ to within the EPA limit of 250 $\mu g\ m^{-3}$ would require firewood use to be less than 10 (range = 6-19) kg day^{-1}; and to reduce the average concentration of CO to within the WHO limit of 6 ppm would require firewood use to be less than 11 (range = 7-20) kg day^{-1}. This would require the households tested in Tiribogo to reduce their firewood consumption from pre-biogas levels by an average of 51% for $PM_{2.5}$ and 46% for CO.

Table 7.4.1 – Rate of particulate and carbon monoxide emissions with firewood use

Household		Average firewood use (kg day^{-1})	Average 24 hour $PM_{2.5}$ concentration ($\mu g\ m^{-3}$)	Rate of $PM_{2.5}$ emissions ($\mu g\ m^{-3}$) per (kg wood day^{-1})	Average 24 hour CO concentration (ppm)	Rate of CO emissions (ppm) per (kg wood day^{-1})
Before installation	H17	19	187	10	4.8	0.25
	H20	24	350	15	24	1.00
	H24	19	722	38	10	0.53
After installation	H17	22	234	11	4.9	0.23
	H20	6	261	47	5.1	0.91
	H24	16	562	35	7.3	0.46
Average value		18	386	26	9	0.56
Standard error		3	86	7	3	0.13

7.5. Example calculations for households in Tiribogo

The data collected for the nine households in Tiribogo were used to estimate the value of biogas to these households. The data entered are given in Table 7.5.1. From the soil and climate measurements reported in section 4.3, the site was described with an average annual air temperature of 30 °C, an average soil water content of 20 mm $(25cm)^{-1}$, soil C content of 21 t C ha^{-1}, clay content of 13%, field capacity of 80 mm $(25cm)^{-1}$, wilting point of 20 mm $(25cm)^{-1}$, and pH of 6.2.The fuel replaced was calculated by biome, assuming dry miombo woodland, and the biogas stove was assumed to replace a three-stone open fire. From the results of the socio-economic survey (section 6.3), it was assumed that the amount spent on fuel was the average reported in the baseline survey, £204 yr^{-1} (assuming an exchange rate of 1.53 £ $(US\$)^{-1}$), and that this provided 20% of the fuel requirement. The amount of compost expected to be applied and the cost of compost were obtained from the socioeconomic survey (section 6.3). The N content of the compost was obtained from the analysis of compost given in section 4.1 (2%). Collated evidence describing the N content of organic wastes used in the UK (Defra, 2011) suggests that the percentage of the N that is readily available ranges from 20 to 26% in farmyard manures, 35 to 50% in poultry manure, and 46 to 69% in slurries. As the organic waste in SSA are likely to be nutrient poor, it was assumed that less than 35% of the total N was available to the crop in the first year following application.

The results of the analysis are given in Table 7.5.2. The percentage of the household energy requirement met by the biogas is predicted to range from 57% – 100% This is over the 46% to 51% reduction in firewood use needed to bring household air quality to within EPA limits for $PM_{2.5}$ and WHO limits for CO. As only 20% of the total fuel requirement is purchased, the full cost of purchased fuel (£204 yr^{-1}) is provided by the biogas. The potential reduction in C emissions due to reduced fuelwood collection is estimated to range from 1.0 – 3.0 t C yr^{-1}, equivalent to an area of forest of 0.03 – 0.09 ha yr^{-1}. The C in the bioslurry produced each year ranged from 0.222 – 0.392 t, potentially sequestering 0.58 – 1.02 t C ha^{-1} over the long term if applied annually to the soil, and providing 20 – 45 kg N ha^{-1} yr^{-1}. This represents a significant potential improvement to soil fertility but this was not valued as householders did not report purchasing fertilisers.

Table 7.5.1 – Input data used to estimate value of biogas to households in Tiribogo

Household	H1	H11	H13	H17	H20	H21	H24	H27	H47
Number of people using biogas	17	4	3	8	6	10	9	9	10
Number of hours cooking required	5	4	4	5	4	4	4	4	4
Number of gas plates (each equiv. 0.75 kWh electrical energy)	1	1	1	1	1	1	1	1	1
Feedstock 1									
Type	Cow (African)								
Number of individuals contributing to feedstock	5	17	4	6	5	3	5	5	5
Percentage of organic waste used in digester	100	65	100	100	100	100	100	100	100
Feedstock 2									
Type	Pork pigs								
Number of individuals contributing to feedstock	2	0	4	3	1	2	3	7	4
Percentage of organic waste used in digester	50	0	100	50	100	100	50	50	50
Amount spent on fuel for cooking (£ $year^{-1}$)	204	204	204	204	204	204	204	204	204
Percentage of fuel requirement provided by purchased fuel (%)	20	20	20	20	20	20	20	20	20
Amount of purchased compost expected to be applied (kg $year^{-1}$)	6000			4500	5000	7000	13000	2000	7500
Price of compost (£ kg^{-1})	0.0153			0.0178	0.0153	0.0153	0.0153	0.0153	0.0127
N available from compost (%)	0.7			0.7	0.7	0.7	0.7	0.7	0.7

Table 7.5.2. Results of systems analysis estimate value of biogas to households in Tiribogo

Household	H1	H11	H13	H17	H20	H21	H24	H27	H47
Household energy requirement (MJ yr^{-1})	19839	15871	15871	19839	15871	15871	15871	15871	15871
Organic waste produced (t fresh waste yr^{-1})	19.1	40.3	17.9	23.1	19.1	12.6	19.5	21.2	19.9
Biogas produced (MJ yr^{-1})	13398	27900	13195	16310	13398	9123	13785	15333	14172
Percentage household requirement met	68%	100%	83%	82%	84%	57%	87%	97%	89%
Potential reduction in C emissions due to reduced fuelwood collection (t C yr^{-1})	1.4	3.0	1.4	1.7	1.4	1.0	1.5	1.6	1.5
Potential area of forest saved from logging (ha yr^{-1})	0.04	0.09	0.04	0.05	0.04	0.03	0.05	0.05	0.05
Economic value to household as a fuel (£ yr^{-1})	204	204	204	204	204	204	204	204	204
Carbon in bioslurry (t C yr^{-1})	0.222	0.344	0.392	0.287	0.222	0.227	0.256	0.389	0.289
Nitrogen in bioslurry (kg N yr^{-1})	25	45	32	31	25	20	27	35	29
Potential carbon sequestered in soil (t C ha^{-1})	0.58	0.90	1.02	0.75	0.58	0.59	0.67	1.02	0.76
Economic value to household as a fertilizer (£ yr^{-1})	54	-	-	78	54	44	58	31	52
Total economic value (£ yr^{-1})	258	204	204	282	258	248	262	235	256

7.6. Identification of regions where digesters are likely to be of value

Feedstock availability

The amount of biogas that can be produced is dependent on the volatile solids in the manure, which is determined by the livestock type, the livestock body mass, livestock management system and the availability of manure for collection. The technical potential for biogas production in Ethiopia, Malawi, Uganda and Zambia was calculated from National Statistics. Below is a summary of the data used to estimate biogas potential in these countries. These figures were calculated from the number of livestock in each country multiplied by a conservative estimate of the quantity of organic waste produced by each animal type. From experience in the field, this was assumed to be 4 kg manure cow^{-1} day^{-1}, 0.75 kg manure pig^{-1} day^{-1}, 0.2 kg manure $goat^{-1}$ day^{-1}, 0.2 kg manure $sheep^{-1}$ day^{-1}. The calculation assumed that all livestock in SSA are grazed during the day and penned at night for security reasons (40% manure available for collection). Ethiopia had the potential to collect over 206 x 10^6 kg of manure day^{-1}, followed by Uganda, Zambia and Malawi with 51 x 10^6 kg of manure day^{-1}, 9 x 10^6 kg of manure day^{-1} and 4 x 10^6 kg of manure day^{-1} respectively.

Table 7.6.1 – Manure available for biogas production

	Uganda[1]	**Malawi**[2]	**Ethiopia**[3]	**Zambia**[4]
Cow manure (kg day^{-1})	45,739,180	3,536,528	197,191,592	8,649,428
Pig manure (kg day^{-1})	2,388,223	594,272	0	706,762
Goat manure (kg day^{-1})	2,468,881	524,603	4,376,845	414,699
Sheep manure (kg day^{-1})	682,074	15,322	5,003,443	11,006
Total of wet manure (kg day^{-1})	**51,278,358**	**4,670,726**	**206,571,883**	**9,781,897**

[1] Uganda National Bureau of Statistics (2010).
[2] Malawi National Statistical Office, Livestock Report (2008).
[3] The Federal government of Ethiopia. Agriculture Sample Survey (2007/2008).
[4] Lubungu M, Mofya MR (2012).

Water availability

The availability and distribution of water may limit biogas production in many countries in the SSA. A wet anaerobic process is largely dependent on water for its operation; semi-arid regions of SSA are most likely to face operational challenges due to scarcity of the water resource. The success of a biogas digester is therefore sensitive to the distance to water source and seasonality in the rainfall. For biogas to be successful in SSA, the maximum distance to and from the water source should be within 400 m or should take 30 minutes (Batzias et al., 2005). Here we have assumed that the distance to water source is not limiting to production of biogas. Assuming the dry matter content of the manure is 10%, the water needed to run a biogas digester can be estimated by multiplying the amount of feedstock available by a factor of two as given (see Eqn. 2.1.2 and 2.1.3). To produce biogas from all the available manure would require 413 x 10^6 dm^3 water day^{-1} in Ethiopia, 102 x 10^6 dm^3 water day^{-1} in Uganda, and 19.5 x 10^6 and 9.3 x 10^6 dm^3 water day^{-1} in Zambia and Malawi respectively (Table 7.6.2). This amounts to (10.5 x 10^{-3}) % of the annual rainfall in Ethiopia, (8.6 x 10^{-3}) % in Uganda, (1.8 x 10^{-3}) % in Malawi and (1.1 x 10^{-3}) % in Malawi, suggesting biogas production is more limited by availability of water in Ethiopia and Uganda than in Malawi and Zambia. Note that this simple calculation takes no account of the geographical distribution or the seasonal patterns. A more sophisticated analysis should be done in future work to account for both of these factors.

Table 7.6.2 – Water required for biogas production

	Uganda	Malawi	Ethiopia	Zambia
Quantity of organic waste (kg day^{-1})	51,278,358	4,670,726	206,571,883	9,781,897
Water needed for biogas production (dm^3 day^{-1})	102,556,717	9,341,452	413,143,766	19,563,794
[1]Annual rainfall (dm^3 yr^{-1})	437 x 10^{12}	191 x 10^{12}	1,430 x 10^{12}	669 x 10^{12}
Percentage of annual rainfall required for biogas production x 10^{-3}	8.6	1.8	10.5	1.1

[1] Annual rainfall obtained from Uganda National Bureau of Statistics, 2010.

Uganda: Area = 236.04x 10^3 km^2
Annual rainfall = 700 – 3000 mm; average annual rainfall = 1850mm
Total rainfall = 236.04 x 10^3 x 1850 = 436.674 x 10^6 dm^3 yr^{-1}.

Malawi: Area = 118.484 x 10^3 km^2
Annual rainfall = 725 – 2500 mm; average annual rainfall = 1612.5mm
Total rainfall= 118.484 x 10^3 x 1612.5 = 191.06 x 106 dm^3 yr^{-1}.

Ethiopia: Area = 1.104 x 10^6 km^2
Annual rainfall = 91-2500 mm; average annual rainfall = 1295.5mm
Total rainfall = 1.104 x 10^6 x 1295.5 = 1,430.232 x 10^6 dm^3 yr^{-1}.2

Zambia: Area = 752.618 x 10^3 km^2
Annual rainfall = 508 – 1270 mm; average annual rainfall = 889 mm
Total rainfall= 752.618 x 10^3 x 889 = 669.077 x 10^6 dm^3 yr^{-1}.

Biogas yield

The potential for biogas production from manure was estimated using Eqn. 2.1.4 and 2.1.5 (Table 7.6.3). Omer and Fadalla (2003) presented estimates for the biogas required for different purposes in Sudan. Cooking in Sudan requires approximately 0.425 m^3 biogas $capita^{-1}$ day^{-1}, and a 2 mantle burner for lighting will require 0.14 m^3 biogas $capita^{-1}$ day^{-1}. However, the per capita energy requirement varies across countries. Assuming a conservative estimate of 0.6 m^3 biogas required $capita^{-1}$ day^{-1} and that water is not limiting biogas production, the biogas produced might be expected used to be sufficient for over 10 million, 2.6 million, 0.7 million and 0.2 million people in Ethiopia, Uganda, Zambia and Malawi respectively. This amounts to 15.4 % of the rural population in Ethiopia, 9.5 % in Uganda, 8.2 % in Zambia and 2.1 % in Malawi.

Table 7.6.3 – Potential biogas production

Potential biogas production (dm^3 day^{-1})	**Uganda**	**Malawi**	**Ethiopia**	**Zambia**
Cow manure	1,372,175,400	106,095,840	5,915,747,760	345,977,120
Pig manure	119,411,138	29,713,613		42,405,705
Goat manure	49,377,628	10,492,068	86,776,300	6,995,864
Sheep manure	13,641,484	306,448	84,453,304	51,928
Total	**1,554,605,650**	**146,607,969**	**6,086,978,114**	**395,431,367**
Number of people potentially supplied with biogas x 10^6	2.59	0.24	10.14	0.66
[1]Population x 10^6	34.55	15.27	84.54	13.45
Percentage of the total population potentially supplied with biogas	7.5	1.6	12.0	4.9
[2]Rural population x 10^6	27.27	11.37	65.94	7.99
Percentage of the rural population potentially supplied with biogas	**9.5**	**2.1**	**15.4**	**8.2**

[1]Source - Ethiopia: http://www.csa.gov.et/; Malawi: http://www.nsomalawi.mw/; Uganda: http://www.ubos.org/; Zambia: http://www.parliament.gov.zm/

[2]Source - http://www.tradingeconomics.com/

7.7. Recommendations for conversion to biogas

Number of livestock required

The systems model described above can be used to estimate the number of livestock required to meet biogas requirements as shown in Table 7.7.1. Omer and Fadalla (2003) estimated that cooking in Sudan requires ~0.425 m^3 biogas $capita^{-1}$ day^{-1}, but a stove testing project at CREEC indicated that the stoves in Uganda are less efficient, tending to consume more gas, so a higher gas requirement of 0.6 m^3 biogas $capita^{-1}$ day^{-1} is assumed (Tumwesige, et al., 2013). For housed animals, the calculations in Table 7.7.1 suggest that the household requires 0.5 cows, 2 pigs or 5 goats or sheep per capita; i.e. a four person household would require two cows, four pigs or ten goats or sheep in order to produce sufficient biogas to meet the family's requirements for cooking. Conversion to biogas is only recommended if manure is available to the household from at least this number of livestock.

Table 7.7.1 – Number of livestock needed to meet biogas requirements

	[a]Manure M (kg head^{-1} day^{-1})	Volatile Solids, P_{VS} (% total solids)	[d]Weight of volatile solids, W_{VS} (kg head^{-1} day^{-1})	Biogas production per unit weight of volatile solids, V_{VS} (m^3 kg^{-1})	Biogas produced, V_{head} (m^3 head^{-1} day^{-1})	[g]Livestock required (head capita^{-1})
Cow	[b] 10	[b] 85	8.50	[b] 0.15	1.28	0.5
Pig	[c] 2.3	[b] 85	1.96	[d] 0.20	0.39	2
Goat	[c] 0.9	[b] 85	0.77	[e] 0.17	0.13	5
Sheep	[c] 0.9	[b] 85	0.77	[e] 0.17	0.13	5

Notes

a Assumes animals are housed so 100% manure is available for biogas production

b Omer & Fadalla, 2003

c Adapted from Lohani and Rajagopal (1981) by Polprasert, 2007. p. 30.

d Calculated as $W_{VS} = M \times P_{VS}/100$

e Austin, 2007

f Calculated as $V_{head} = W_{VS} \times V_{VS}$

g Calculated as V_{req} / V_{head} , assuming biogas required (V_{req}) = 0.6 m^3 capita^{-1} day^{-1}

Availability of water

The water needed to mix with the feedstock can be calculated from the manure required for adequate biogas production and the dry matter content of the manure. Assuming the optimal dry matter content for anaerobic fermentation is between 2 and 5% (Preston, 2011), for each 10 kg of dry matter, ~200 dm^3 of water is needed, so the water that must be added can be calculated from the required feedstock and the dry matter content of the feedstock by multiplying by a factor of 0.2 (Eqn. 2.1.2 and 2.1.3). As shown in Table 7.7.2, this suggests that to be suitable for conversion biogas, households should have access to 20-30 dm^3 water capita^{-1} day^{-1}.

Table 7.7.2 – Amount of water needed to meet biogas requirements

[a]Livestock required, L (head capita^{-1})		[b]Manure, M (kg head^{-1} day^{-1})	Manure required for biogas production, R (kg capita^{-1} day^{-1})	[f]Dry matter content, DM (%)	[g]Water required to mix with feedstock (dm^3 capita^{-1} day^{-1})
Cow	0.5	[c] 10	5.0	27.5	27.5
Pig	2	[d] 2.3	4.6	22.5	20.7
Goat	5	[d] 0.9	4.5	21.5	19.4
Sheep	5	[d] 0.9	4.5	21.5	19.4

Notes

a From Table 7.7.1

b Assumes animals are housed so 100% manure is available for biogas production

c Omer & Fadalla, 2003

d Adapted from Lohani and Rajagopal (1981) by Polprasert, 2007. p. 30.

e Calculated as $R = L \times M$

f Daublein and Steinhauser, 2008; Al Seadi et al, 2008; Nijaguna, 2002

g Calculated as $W = 0.2 \times DM \times R$ (Eqn 2.1.2)

Some of the additional water required could be recycled from household use. Water is used in SSA households for drinking, cooking, hygiene (bathing, laundry, washing hands, food and dishes) and irrigation (Rosen and Vincent, 1999). The amount of water used by a household depends on the availability of the water source; whereas WaterAid (2012) suggested that the average person in the “developing world” uses 10 dm^3 day^{-1} for drinking, washing and cooking, Cairncross and Cliff (1987) reported that households in Mozambique with a centrally-located water source used an average of 11.1 dm^3 capita^{-1} day^{-1}, and those relying on a distant source averaged only 4.1 dm^3 capita^{-1} day^{-1}. The minimum water intake required for survival in tropical areas is estimated at 1.8-3.0 dm^3 capita^{-1} day^{-1} (White et al., 1972), so in households relying on a distant source, this would amount to waste and irrigation water of less than 2 dm^3 capita^{-1} day^{-1}, whereas in households with a centrally-located water source, waste and irrigation water would increase to nearly 10 dm^3 capita^{-1} day^{-1}. By diligent reuse of waste water in the digester, the need for additional water collection could be reduced by as much as 50%. Household rainwater harvesting may also help to alleviate the labour needed to collect additional water (Rockström, 2000; Fox et al., 2005; Kahinda et al., 2007). Storage tanks or ponds can collect rainwater from roofs and other large surfaces (Moges et al., 2011), and can be used to provide an additional source of income in the form of fish ponds, as often seen for example in Vietnam (Vu et al., 2007).

Distance to water and woodfuel

The results reported in Table 3.4.1 showed that with the current design of digester, households surveyed required on average an extra 55 minutes day^{-1} to handle the organic waste. Before deciding to convert to biogas, households should consider the impact of the digester on household labour; for some households, the benefits provided by the digester would make additional household labour acceptable, but for others this might not be a good option. The household would incur no additional labour if the additional time required to collect water, $\Delta T_{\mathrm{water}}$ (min day^{-1}), and handle manure, $\Delta T_{\mathrm{manure}}$ = 55 min day^{-1}, is balanced by the reduction in time required to collect firewood, ΔT_{wood} (min day^{-1}),

$$-\Delta T_{\mathrm{wood}} > \Delta T_{\mathrm{manure}} + \Delta T_{\mathrm{water}} \qquad \text{Eqn. 7.7.1}$$

The values of ΔT_{wood} and $\Delta T_{\mathrm{water}}$ are dependent on the change in the number of trips needed to collect wood and water, $\Delta n_{\mathrm{trip,wood}}$ and $\Delta n_{\mathrm{trip,water}}$, and the distance to wood and water, d_{wood} and d_{water} (m).

Assuming a worst case where no household water is reused in the digester, the change in the number of trips to collect water, $\Delta n_{\mathrm{trip,water}}$, is obtained from the volume of water needed for the digester; this can be estimated from the volume of substrate used. By rearranging Eqn. 2.2.4, the volume of substrate, V_{s} (dm^3 day^{-1}), can be obtained from the chosen retention time, T_{R} (days), and the ratio of the volume of substrate to gas $p_{\mathrm{S:G}}$ as

$$V_{\mathrm{s}} = \frac{p_{\mathrm{S:G}}}{T_{\mathrm{R}}(1+p_{\mathrm{S:G}})} \times 1000 \qquad \text{Eqn. 7.7.2}$$

For a simple digester design such as the flexible balloon digester, to ensure complete digestion, the retention time, T_{R}, should be at least 40 days (Price, 1981). For a typical agricultural biogas plant, the ratio $p_{\mathrm{S:G}}$ is between 3:1 and 10:1, with the ratio most frequently being 5:1 - 6:1. Using T_{R} = 40 days and $p_{\mathrm{S:G}}$ = 5, this gives V_{s} = 19 dm^3 day^{-1} for every 1 m^3 of digester.

From the results in Table 7.7.2, the added water makes up 80 – 85% of the total substrate. Therefore, the largest volume of water needed for each 1m^3 of digester, V_{W} (dm^3 day^{-1}), is given by 85% of V_{s}, which is 16 dm^3 day^{-1}.

According to WSSCC (2004), the average weight that women in low income countries carry on their heads is approximately 20 kg. Depending on the weight of the water container, this is equivalent to 15-20 dm^3 water, so 0.8-1.0 extra trips would be required each day for each 1m^3 of digester. This can also be calculated directly from the water required to mix feedstock given in Table 7.7.2 and expressed as an extra 1.0-1.4 trips each day to collect water for each person in the household.

The change in the number of trips to collect wood, $\Delta n_{\mathrm{trip,wood}}$, can be estimated from the energy value of the biogas generated. The volume of biogas produced can be estimated from the volume of water needed, V_{W} (dm^3 day^{-1}), using the ratio of water to manure in the digestate, $p_{\mathrm{W:M}}$, and the ratio of digestate to gas, $p_{\mathrm{S:G}}$,

$$V_{\mathrm{G}} = V_{\mathrm{W}} \times \frac{(1+p_{\mathrm{W:M}})}{(p_{\mathrm{W:M}} \times p_{\mathrm{S:G}})}$$ Eqn. 7.7.3

Depending on the dry matter content of the manure, the value of $p_{\mathrm{W:M}}$ is between 4.3 and 5.5 (Table 7.7.2), and so the volume of gas produced is ~4 dm^3 day^{-1} for each $1m^3$ of digester. Cornejo and Wilkie (2010) give the energy content of biogas as 22 MJ m^{-3}. Therefore, the energy potentially replaced by biogas is ~88 MJ day^{-1} for each 1 m^3 digester. Using a higher heating value for the woodfuel of 20 MJ kg^{-1} (CREEC, pers.comm.), the woodfuel potentially replaced by biogas is (88 MJ day^{-1} / 20 MJ kg^{-1}) = 4.4 kg m^{-3} day^{-1}. Assuming 20 kg wood is carried in each trip (WSSCC, 2004), the change in the number of trips to collect woodfuel, $\Delta n_{\mathrm{trip,wood}}$ = -0.22 trips each day for each $1m^3$ of digester. This can also be calculated directly from the biogas requirement (0.6 m^3 $capita^{-1}$ day^{-1}, Tumwesige et al., 2013) and the energy content of biogas (22 MJ m^{-3}, Cornejo and Wilkie, 2010) to be -0.66 trips each day to collect wood for each person in the household.

Assuming the same speed of walking when carrying wood or water, v_{walking} = 88 m min^{-1} (Table 3.1.2), and the time required to gather wood or queue for water is negligible, the conditions where labour will be reduced by the biogas digester can be defined from the ratio of the change in the number of trips required to collect water and wood, x, and the volume of the digester, V_t (m^3), as

$$d_{\mathrm{wood}} \geq x d_{\mathrm{water}} + \frac{4840\,x}{\Delta n_{\mathrm{trip,water}} \times V_t}$$ Eqn. 7.7.5

Using the change in the number of trips calculated for wood and water estimated above gives a range of values of x from 1.5 to 4.5, averaging 2.0, and a range of value of $\Delta n_{\mathrm{trip,water}}$ from 0.8 to 1.4, averaging 1.0, which gives conditions for when labour will be reduced as follows:

$d_{\mathrm{wood}} \geq 2d_{\mathrm{water}} + 1000$ m (for $10m^3$ digester)
$d_{\mathrm{wood}} \geq 2d_{\mathrm{water}} + 1200$ m (for $8m^3$ digester)
$d_{\mathrm{wood}} \geq 2d_{\mathrm{water}} + 1600$ m (for $6m^3$ digester)
$d_{\mathrm{wood}} \geq 2d_{\mathrm{water}} + 2400$ m (for $4m^3$ digester) Eqn. 7.7.6

8. Communication and User Engagement

8.1. Information booklets and posters for local communities

The project worked with the community at Tiribogo, throughout the period of installation, startup and full operation of the biogas digesters. The value of the biogas digesters to each household was presented to in an accessible way, focussing on the benefits to household energy, crop production and human health. This information was summarised in a graphical booklet and a series of posters, allowing a booklet to be provided with each digester for use by the householder, and information boards to be produced that explain to local people the advantages of the digesters.

Information sheets were developed in consultation with a graphic designer with previous experience of working on similar biogas initiatives in Uganda (see Appendix E). These were developed to be primarily visual, as a tool to help facilitate future community-to-community engagement sessions to enable expansion in the uptake of the balloon digester technology.

Developed initially in English, these information sheets were translated into the local Bantu language, Luganda (Appendix F) and into Swahili (Appendix G).

Community members in Tiribogo were given the opportunity to comment and adapt these to their needs through a series of participatory sessions with group members (Fig. 8.1.1). Feedback was collated and the relevant revisions were incorporated into a second draft.

The training and communication materials were made available in a number of formats including, printed A4 booklets, A0 laminated sheets for use in community workshop settings and as printed sheets for use in local schools. Digital copies will also be placed on the dedicated project website that has been created http://www.abdn.ac.uk/sustainable-international-development/research/networks/digesters-p/.

Figure 8.1.1 – Participatory sessions to adapt communication materials

Project partner, the Centre for Research in Energy and Energy Conservation (CREEC), has also used the information sheets as part of the SENRMCAM project. SENRMCAM (Strengthening Sustainable Environment and Natural Resource Management, Climate Change Adaptation and Mitigation in Uganda) is a Government of Uganda project that is being implemented by WWF Uganda Country Office and is funded by UNDP Uganda Country Office. The project is focusing on strengthening the efforts and capacities of local governments, civil society organizations and communities to sustainably manage natural resources. In an effort to popularise efficient energy utilisation especially in climate change hot spots, biogas production will be started at selected schools. The biogas component of the program is being implemented by CREEC. It seeks to promote biogas technology at an institutional level. Full recognition of DFID's funding of the information sheets has been made as part of this initiative.

8.2. Summary report for government departments

In order for biogas digesters to become economically feasible, the Ugandan government should take action to remove existing policy barriers and make renewable energy developers eligible for tax and import duty exemptions and special tax deductions. A summary report is currently being produced and will be used to provide information to appropriate government departments

8.3. Information sheets for rural financial institutions

There is a need to help rural financial institutions in understanding and appraising biogas digesters and develop a sound capacity to evaluate the viability of biogas projects for financing, monitor their performance, and debt collection. An information sheet is currently being produced aimed at rural financial institutions. This will be sent to Ugandan institutions that might have an interest in funding biogas digesters and made available on the web.

8.4. Information sheet for manufacturers

An information sheet is currently being produced aimed at local manufacturing businesses. This will be sent to a number of Ugandan businesses, identified as having an interest in manufacturing parts for biogas digesters. It will also be made available on the web.

8.5. Project website

The project website is being further developed to incorporate research results.

8.6. Local businesses

During this project we have explored the potential for local business and private sector to play a role in supporting or funding biogas digesters in design or deployment projects.

Biogas digesters were sourced from the Q-Energy (info@changeitfoundation.com), a new Ugandan company importing flexible balloon biogas digesters from China. Other local companies importing digesters to Uganda include Biogas International (http://www.biogas.co.ke/index.php?option=com_contact&view=contact&id=1&Itemid=63). In response to our finding that the cost of digesters is more than farmers are willing to pay, Q-Energy have indicated that they are willing to explore approaches to reducing costs. Local manufacturing companies were approached to investigate the potential for manufacturing digesters in Uganda. Difficulties with obtaining the equipment needed to weld the different joints in the digesters prevented this from being taken further in the time available.

Installation of digesters was completed by Green Heat Uganda, a partner on the project. Green Heat is committed to installation of biogas digesters in Uganda, and has many successful and ongoing projects (http://greenheatug.wordpress.com/page/2/). The University of Aberdeen has established an initial revolving fund of £5000 with Green Heat Uganda to provide upfront purchase of up to 10 digesters at a time. Digesters will be provided through a local “Biogas Association” consisting of interested householders, also including elders from the village. Membership of the Association will be subject to the selection criteria that indicate feasibility of maintaining the digester (water, feedstock etc). The selection of the householders to receive the digesters in each round will be made by the people of the Association. The digesters will be “rented” to the householders up to the time when the cost of the digester has been covered by the rent; after this time, the ownership of the digester will be passed to the householder, and sufficient repayment will have been made to allow an additional digester to be made available to the Association. Householders receiving digesters will be asked to pay back the cost of the digester at an agreed rate that reflects the savings the householder expects to achieve through reduced expenditure on fuel and fertiliser. If the digester does not achieve this rate of saving, the repayments may be reduced to reflect the actual savings. If no savings are made, the digester will be reclaimed as it will not be providing the expected benefits to the household. It is hoped that this will provide a demonstration for an approach to funding digesters that is free from risk for the householder, and will encourage other organisations to provide more funding of this kind.

8.7. Scientific Publications

Dissemination of information to the scientific community will be achieved through publication of 3 MSc theses. It is also anticipated that the following papers will be published in open access, international, peer-reviewed journals over the coming months (Table 8.6.1). The publications involve input from 18 African researchers.

Table 8.6.1 – Anticipated publications from the project

Authors	Title	Journal
J. Smith, A. Abegaz, R. Matthews, M. Subedi, R.E. Orskov, V. Tumwesige, P. Smith	What is the potential for biogas digesters to improve soil fertility and crop production in Sub-Saharan Africa?	Biomass and Bioenergy (submitted)
M. Subedi, R. Matthews, M. Pogson, A. Abegaz, B. Balana, J. Oyesiku-Blakemore, J. Smith	Can biogas digesters help to reduce deforestation in Africa?	Biomass and Bioenergy (submitted)
J. Smith, A. Abegaz, R. Matthews, M. Subedi, R.E. Orskov, V. Tumwesige, P. Smith	What is the potential for biogas digesters to improve soil carbon sequestration in Sub-Saharan Africa?	Biomass and Bioenergy (submitted)
R.E. Orskov, K. Yongabi, M. Subedi, J. Smith	Overview of Holistic Application of Biogas for Small Scale Farmers in Africa and Asia	Biomass and Bioenergy (submitted)
K. Yongabi, L. Avery, A. Pertiwiningrum, J. Mwirigi, S. Semple	Review of occupational diseases due to Agricultural practices in Sub-Saharan Africa	Biomass and Bioenergy (submitted)
S. Semple, A. Apsley, A. Wushishi, J. Smith	Commentary: Switching to biogas – what effect could it have on indoor air quality and human health?	Biomass and Bioenergy (submitted)
L. Avery, K. Yongabi, V. Tumsweige, N. Strachan, P. J Goude	Potential for Pathogen Reduction in Anaerobic Digestion and Biogas Generation in Sub-Saharan Africa	Biomass and Bioenergy (submitted)
J Mwirigi, B. Balana, J. Mugisha, P. Walekhwa, R Melamu, S. Nakami, P. Makenzi	Socio-economic hurdles to widespread adoption of small-scale biogas digesters in Sub-Saharan Africa: a review	Biomass and Bioenergy (submitted)
Z. Gebreegziabher, L. Naik, B. Balana, R. Melamu	Prospects and challenges for urban application of biogas installations in Sub-Saharan Africa	Biomass and Bioenergy (submitted)
P. Walekhwa, L. Drake, J. Mugisha	Economic viability of biogas energy production from family-sized digesters in Uganda	Biomass and Bioenergy (submitted)
L. Naik, Z. Gebreegziabher, V. Tumwesige, B. Balana, J. Mwigiri, G Austin	Factors determining the stability and productivity of small scale anaerobic digesters	Biomass and Bioenergy (submitted)
V. Tumwesige, G. Davidson, D. Fulford	Biogas appliances in Sub-Sahara Africa	Biomass and Bioenergy (submitted)
M. Kabyanga, J. Mugisha, B. Balana, K. Glenk, P. Walekhwa	Cost benefit analysis of a flexible balloon digester in Uganda	Unknown
M. Kabyanga, J. Mugisha, B. Balana, K. Glenk, P. Walekhwa	Willingness to pay for a flexible balloon digesters in Uganda	Unknown
V. Tumwesige, L. Haroff, A. Apsley, S. Semple	Impact of biogas cooking on indoor air quality in rural Uganda	Unknown
L. Haroff, V. Tumwesige, A. Apsley, N. Strachan, L. Avery	Reduction of pathogenic bacteria in organic waste and impact on environmental pathogens through production of biogas	Unknown
S. Semiyaga, N. Morley, J. Tumuhairwe, C. Niwagaba, E. Sabiiti	Impact of anaerobic digestion on carbon and nitrogen dynamics in the soil / crop system	Unknown
Tumwesige V, Smith JU	Systems modelling of the value of small scale biogas digesters in Sub-Saharan Africa	Unknown

8.8. Media coverage

The University of Aberdeen's press office, CREEC's communication team, and Makerere University have all attempted to promote the project in media in the UK and Uganda (Appendix H). This has lead to some misunderstandings, but has overall had a positive impact on the publicity for the project.

9. Conclusions

9.1. What is the potential of flexible-balloon digesters to alleviate poverty?

Poverty is a multidimensional portrayal of human deprivation that encompasses not only low income or consumption but also low achievements in health, education, nutrition and other areas of human development. It can be depicted by lack of opportunities (material deprivation), lack of capabilities (low achievement in education and health, malnutrition), and vulnerability (low level of security).

Access to affordable domestic energy sources is one the major problems faced by poor households in SSA. Traditional biomass covers 70-90% of the primary energy supply and up to 95% of the total energy consumed in Africa (World Energy Council, 2005), but the availability of traditional cooking fuels such as wood, agricultural residue, dried dung and charcoal is declining. Commercial fuels are often too expensive for the rural poor, and their availability is unreliable, particularly in rural/remote areas. In many places, the collection of traditional fuels and the production of charcoal are exhausting natural resources and damaging the very environment on which people rely. By opening up opportunities for poor households to obtain energy in a sustainable way, biogas technology has the potential to alleviate multiple dimensions of poverty;

- Households may spend less time in collecting wood leaving more time for generating income, providing potential for households to tackle their income poverty
- Switching to cleaner fuels can reduce health risks, providing potential for households to tackle health risks and improve their life expectancy
- Biogas may enhance opportunities for education of children, providing the potential for them to address illiteracy and enhance production of human capital
- Biogas may improve the environment, providing the potential for degraded environments to be rehabilitated which in turn increases in the productivity of natural capital and improves living standards

Therefore, in principle, biogas has great potential to play a big role in alleviating poverty in SSA. However, despite this, uptake of biogas digesters in SSA has been less successful than in other parts of the world. It was proposed that the lack of uptake might be due to the high upfront cost of the fixed dome design of biogas digester, and that the cheaper flexible balloon digester might provide a more affordable alternative.

Based on this background, the socio-economic analysis presented in this report attempted to generate empirical evidence to quantify the role of biogas in poverty alleviation. This has been approached by carefully identifying household specific costs and benefits[1] of flexible-balloon digesters and evaluating the net household welfare (gain/loss).

A key finding from this project has been that flexible balloon digesters are not as cheap to install in Uganda as has been reported to be the case in Asia. The flexible balloon digesters were purchased for the project at a cost of £335 each, which was £275 more than the reported cost of £60 each (Smith et al., 2011). The household survey revealed householders who were familiar with the benefits of biogas digesters were willing to pay only £65 / digester (Table 2.6.4). Therefore, unless the cost of the flexible balloon digesters can be reduced, the potential for poverty alleviation provided by biogas digesters may be limited in Uganda. Costs might be reduced by better matching the size of the digester to the requirements of the household; in the current project 8m^3 digesters were installed in all households for consistency in the experimental methods; these digesters were too big for some households and so costs could have been reduced by installing smaller digesters. Further technical and political measures that could be used to reduce the upfront cost of digesters are discussed in section 9.3.

Savings in household expenditure on wood fuel and compost amount to an average of 131 US\$ yr^{-1} (202 £ yr^{-1}). At this rate of saving, the cost of the digesters purchased for the current project would be repaid within 4 years. If more benefits can be derived from the digester, a shorter payback period would be achieved. Factors such as the impact of the digester on human health have not been accounted for here, as these are still highly uncertain. They nevertheless represent a significant potential saving in expenditure and should be included in the calculation of payback time when more research has been done to quantify these benefits.

[1] Costs and benefits should be understood broadly, not only in terms of money, but also in terms of the household welfare.

The activities required to operate a flexible balloon digester are collecting of water for mixing with feedstock, collecting cow dung or other feedstocks, mixing the feedstocks with water, feeding the feedstock into the digester and changes in cooking time. If the costs of labour were to be factored in, these tasks would cost the household a total of 373 US\$ yr^{-1} (571 £ yr^{-1}) in terms of household labour, while the cost of labour for collecting fuel wood would be reduced by only 147 US\$ yr^{-1} (225 £ yr^{-1}) resulting in a net additional labour requirement of 226 US\$ yr^{-1} (346 £ yr^{-1}) (Table 6.4.1). This additional burden reflects a loss in household welfare, although it may be somewhat allayed by better distribution of tasks around the household. The saving in expenditure may also be more apparent to the household as it represents an actual reduction in expenditure, whereas the cost of labour is not apparent if alternative employment is not available.

What is the potential of flexible-balloon digesters to alleviate poverty?

Advantages

- **Payback time in Uganda is under 4 years**; this estimate only accounts for reductions in wood fuel and compost use
- Households may also spend less time collecting wood, leaving more time for generating income
- Bioslurry may also improve crop productivity
- Including health impacts (household air quality and sanitation) could further reduce payback time
- Biogas may also enhance opportunities for education

Problems

- **Digesters are too expensive**; cost of flexible balloon digesters in Uganda is over 5 times the cost reported in Asia, which is more than farmers are willing to pay
- **Labour is increased by conversion to biogas**; this is due to extra work needed for mixing and handling organic wastes

Key issues needing further research

- How can we reduce the cost of digesters to less than £65 / digester?
- How should we adapt the design / layout to minimise handling of organic wastes?

9.2. What is the value of a flexible balloon biogas digester to a household?

Energy

Despite a marked shift in the type of energy use in developing countries from biomass-based fuel to more sophisticated energy delivery, such as gas and electricity (Arnold and Jogma, 1977), the majority of people in developing countries still rely on traditional fuels such as fuelwood, charcoal and dung cakes (Mwampamba, 2007). Historical trends indicate that the use of both fuelwood and charcoal for cooking is increasing (Broadhead et al., 2001; FAO, 2010). Population increase in recent years has contributed to the increased demand for energy, including woodfuel, which is evidenced by collection of woodfuel remaining one of the most important and time consuming household chores in SSA (Munasinghe and Shearer, 1995; Walmsley, 2002). After the development of the use of fossil fuels and electrical energy, people with high income, mainly living in and around cities, are increasingly attracted towards using these more sophisticated, but expensive, energy types (Barnes et al., 2004). Charcoal is also very popular and widely used for cooking in most African cities ((Mwampamba, 2007; Mercer et al., 2011). However, for people with low income and living in rural areas, fuelwood is still the primary source of heat energy. Biogas energy could be a suitable alternative for cooking and heating energy and therefore is proposed as one of the approaches to reduce deforestation, particularly deforestation resulting from woodfuel consumption. By providing an alternative energy source that would otherwise be obtained from fuelwood or charcoal, it is widely assumed that biogas digesters could help to reduce the rate of deforestation in SSA (e.g. Felix and Gheewala, 2011). At global level, the link between deforestation and the use of fuelwood and charcoal is weak because fire wood is often obtained from fallen wood or from sources that would already be felled for construction or land clearance (Maes and

Verbist, 2012). However, at the household level, the reduction in potential wood clearance attributable to replacement by biogas digesters can be determined from household calculations.

The savings in firewood consumption observed in the nine households in Tiribogo where biogas digesters were installed averaged 6 kg day^{-1} = 2.190 t yr^{-1} (Table 3.1.1). An average of 204 £ yr^{-1} was spent on cooking fuel, providing 20% of the fuel for cooking (Table 7.5.1). Systems analysis suggested that all of this expenditure could be saved by cooking with biogas. The remaining cooking fuel was collected from the forests. This amounts to a labour cost of 225 £ yr^{-1}. The average percentage of the household energy requirement that could be replaced by biogas in the nine households studied was 83% and ranged from 57% to 100%.

Organic fertiliser

Food requirements across SSA are expected to increase over the next 50 years with increases in the population. Recent global projections indicate that the population of SSA will double from today's level, reaching close to 2 billion by the year 2050, with half of this number being under 25 years of age (UN, 2008). If SSA is to meet the hunger-related Millennium Development Goals, FAO (2009) estimates that it will need adequate food supplies for 18 million additional people each year, and to improve the nutritional status of 94 million people. This is the equivalent of achieving a 4.6% annual growth in food supplies (Conceição et al., 2011). Added to this, the increasing demand for livestock products in SSA and the lower efficiency of food production by livestock compared to direct cropping (Smith et al., 2007), are likely to further increase pressure on land used to grow food. Tilman et al. (2011) forecast a 100-110% increase in global crop production by 2050, with much of this expansion occurring in poorer nations. If the required growth in food supplies is to be achieved, all resources that impact crop production must be targeted and recycled to avoid any waste or loss to the wider environment (Smith et al., 2011).

Factors that control crop production include uptake of nutrients, water and oxygen, light interception, and temperature. The environmental constraints that directly impact these factors include availability of nutrients, organic matter content of the soil and water availability. The widespread introduction of biogas digesters is likely to have an impact on all of these environmental constraints.

Analysis of the field trials conducted in this project suggests that when the same quantity of N is applied in bioslurry, chicken manure compost and urea, the yields of crops treated with bioslurry are significantly higher than the control, and there is no significant difference between the yield and N content of bioslurry treated crops compared to those treated with urea or chicken manure. This result demonstrates that bioslurry is an effective organic fertilizer. Emissions of the greenhouse gas, nitrous oxide, were significantly lower from crops treated with bioslurry than from those treated with urea. Future work should include comprehensive crop trials to determine the optimum application rate for the bioslurry. Further analysis of the impact of the digestion process on the composition of the bioslurry is also needed so that the impact of the feedstock and the digestion conditions on the availability of nutrients to the crop and to loss processes in the soil can be better understood.

Sanitation

Current burdens of faecally derived pathogens entering the environment through untreated human and animal faeces can lead to disease, through direct handling and through contamination of water supplies used for drinking and washing. Excreta from humans and livestock, applied fresh, semi-dried or composted (Yongabi et al., 2009) or directly deposited by animals or humans, presents a source of faecally-contaminated run-off. Health is compromised when pathogens contaminate drinking water at source, through seepage of contaminated run-off water, or within the piped distribution system where this exists (WHO, 2007). Microbiologically unsafe drinking water and inadequate sanitation represent a major source of infectious disease in SSA, particularly in rural areas, with as little as 15% of households (equating to more than 325 million people) being connected to an improved water supply (WHO/UNICEF, 2006, 2009). The lowest coverage of sanitation is in SSA (37% in 2004; WHO/UNICEF, 2006) and coverage has been declining rther than increasing over the last few years. It is estimated that five million people lose their lives due to water-related disease each year. It has been well documented that immune-compromised people, babies and the elderly are the most susceptible to bacterial infections (Momba et al., 2008). Anaerobic digestion for biogas generation in rural households in SSA has the potential to reduce pathogen loadings to the environment through treatment of livestock manures and effluent from pit latrines.

A diverse range of pathogens is present in organic wastes and manures of both human and animal origin. These include enterobacteria, enteroviruses, parasites, yeasts and fungi. Key human and animal pathogens include *Vibrio cholera*, *Salmonella spp., Escherichia coli* (including toxigenic forms), *Campylobacter spp., Listeria monocytogenes*, *Yersinia enterocolitica*, *Staphylococcus spp*, *Clostridium spp., Mycobacteria spp. Hepatitis viruses*, *Rotavirus*, Adenovirus, *Aspergillus spp*, *Candida spp*, *Trichophyton spp.*, *Cryptosporidium, Giardia* and T*oxoplasma.* Many of these are zoonoses, meaning that they can be passed between animal and human populations. They are particularly prevalent among human and animal populations in developing countries and are therefore frequently found in faecal material (Yongabi et al., 2004, 2009; WHO, 2007; Clarsen et al., 2007). Their persistence in the environment is affected by local climate, soil type, animal host prevalence, topography, land cover and management, organic waste applications and hydrology (Gagliardi & Karns, 2000; Jamieson et al., 2002; Hutchison et al., 2004; Tyrell & Quinton, 2003; Tate et al., 2006). Human exposure to pathogens can be linked to contamination levels around the home, on the farmstead and in local water courses.

In the current work, changes in indicator organisms, *E.coli* and *C. perfringens* were measured. The data shows that aerobic pathogen indicators (*E.coli*) were reduced through the digestion process but that anaerobic indicators (*C. perfringens*) were not. So what does this tell us about the impact on human health?

Pepper et al. (2010) warned that pathogen occurrence may not correlate well with indicator organisms. This is corroborated by a trend in the literature data (Avery et al., 2013) which indicates that the inactivation of different microbial groups such as viruses, fungi, and protozoa is likely to differ significantly from that of Gram negative enteric bacteria (within which category the faecal indicator organisms (FIOs) fall). Olsen and Larsen (1987) also reported a relationship between decimal reduction times and different pathogens. Even among the bacterial pathogens, some species are more or less likely to tolerate the conditions of the digester due to their differing structures and physiology. Furthermore, many species are made up of a spectrum of pathogenic and non-pathogenic sub-types, and there is a range in their ability to persist under different physiological conditions. These factors can complicate the straight-forward use of indicator organisms.

Nevertheless, the changes in pathogens observed, follows patterns predicted in the literature. Pathogen die-off is strongly time-temperature dependent and isothermal death generally follows an exponential pattern with increasing temperature leading to more rapid die-off (Olsen & Larsen, 1987). For example, in a liquid raw sewage, three strains each of *E. coli* and *Salmonella* were subjected to a range of time-temperature treatments. At 70 °C, all strains were inactivated within ten seconds and at 55 °C, inactivation occurred within an hour. At 35 °C, a 1.5-2 log decrease was achieved within 20 days (Smith et al., 2005). Operating in the mesophilic temperature range (20-35°C), anaerobic digesters in SSA might be expected to achieve a 1.5-2 log decrease within 20 days. There is substantial variation in removal efficiencies of the anaerobic digestion processes even among indicator organisms, and this does not always seem to correlate with the digestion conditions. For example, for total coliforms in mesophilic systems, the die-off ranges from less than one log, despite a relatively long digestion period (20 days; Chauret et al., 1999) to greater than 4 log (Poudel et al., 2011).

Spore formers and anaerobes or facultative anaerobes (*Clostridium* species fulfil both of these criteria), are expected to evade destruction more readily and potentially grow during the digestion process, as illustrated by Massé et al. (2011) and Chauret et al. (1999). *Clostridia* are, in fact, thought to play a role in acidogenesis (Chen et al., 2005) and Sahlstrom et al. (2008) found that *Clostridia* survived thermophilic temperatures of 70 °C for 60 minutes, demonstrating their potentially high Z-values (temperatures required to reduce the decimal reduction time by one log unit), although there is strain dependent variability in heat resistance (Wijnands et al., 2009). *Clostridia, Mycobacteria,* and *Bacillus* species along with fungi and protozoa can survive for particularly long periods of time in the environment due to their ability to resist environmental stresses and form spores or resistant forms. Interestingly, even other Gram negative species such as *Campylobacter* and *Yersinia* appeared to have lower log reductions in some cases than coliforms Massé et al., 2011). There is, however, a substantial amount of variability which inevitably relates to an array of interacting factors. Therefore it is particularly important to understand whether this will lead to a proliferation of the pathogenic members of the genus which could become concentrated in the environment through application of digestate to land. Whether treatment of the feedstock in a biogas digester has lead to reduced risks to human health requires further research into the impacts of digestion on the specific pathogenic members of the genus, but a clear and significant reduction in the indicator organisms *E.coli* has been observed during digestion.

By contrast, the environmental analysis suggested that sanitation was not improved around the households as a result of digester use. The overall *E. coli* and total coliform loads significantly increased between the baseline study and the period after installation. Note that although loads in the local environment were observed to increase, the reduction in loads in the digestate means that an overall decline is expected in the wider environment following widespread application of bioslurry rather than untreated waste. Future studies should focus on increasing awareness of sanitation issues and adapting the system to limit transport and spread of pathogens. Such methods may include moving the digester closer to the location of animals and widening the inlet pipe to prevent spillage of feedstock. For example, in one household, it was observed that carrying organic waste from the animal enclosure to the digester inlet resulted in the organic wastes being dropped in the household area; rotating the digester by 180° so that the inlet was closer to the animal enclosure while retaining the position of the gas pipe (and so maintaining gas pressure to the kitchen) could significantly reduce environmental contamination (Fig.9.2.1).

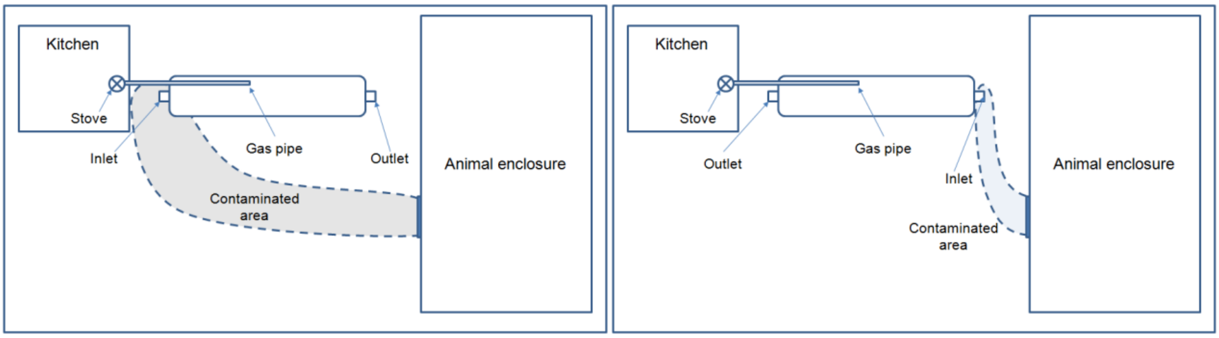

Fig. 9.2.1. Illustration of how positioning of the digester could be used to reduce pathogen contamination in the local environment, while maintaining gas pressure in the gas stove.

Much of the research to date has been carried out in laboratory or pilot scale digesters. There is little data available from small scale systems operating in the environmental and social conditions of SSA and installation and monitoring of these systems is essential to learn important lessons about process control for pathogen reduction. From the work presented here, we can say that pathogen reduction in small scale ambient temperature digesters in SSA is likely to lead to significant reductions in the burden of enteric pathogens in human and animal wastes. This is consistent with the prediction by Avery et al. (2013) that reductions for coliforms are likely to be in the order of 2-3 log units, but that some organisms, including Gram positive species, particularly spore formers and also anaerobes or microaerophiles (*Clostridia* and possibly *Campylobacter*) are likely to withstand the mesophilic treatment temperatures and undergo only limited reduction during the process. Therefore while reducing the overall pathogen burden, it is unclear whether the digestion could promote the proliferation of these organisms and ultimately lead to increased incidence in the environment. *Clostridia* are common in the environment but pathogenic types exist that can cause gastrointestinal illnesses (e.g. botulism) in addition to a range of wound infections (gas gangrene) and neurological illness (tetanus). This could be pertinent to occupational exposure of farmers. *Campylobacter* species also cause diarrhoeal disease, but, as a non-spore-former, is likely to be less resilient than *Clostridia*, and so may be more likely to decline over time once applied to land. Process failure in terms of pathogen reduction within small scale digesters in SSA may occur due to poor reactor sizing or design, inconsistent loading rates, short circuiting and limited mixing of wastes. However, where post-process composting is applied, this will further contribute to pathogen reduction, ameliorating some of these issues.

Future research should focus on the efficacy of small scale systems in reducing pathogen loadings under SSA conditions, understanding the behavior of specific pathogens during treatment and post-processing application to land in order to recommend appropriate hygienic measures to protect people and the environment while maximizing the use of digestate as an organic fertilizer. Based on available data, the following recommendations would promote reduced risk to farmers and their families in SSA who are using anaerobic digesters and applying digestate to land:

- Post-digestion composting of bioslurry to promote further pathogen die-off
- Minimum direct skin contact and handling of organic wastes pre and post digestion and composting.
- Good personal hygiene and handwashing with soap and clean water
- No application of bioslurry to foods grown close to the ground, unlikely to be peeled and to be consumed raw within 3 months of harvest

- Thorough cooking of bioslurry-fertilised food crops
- Training in operation of digester and handling of feedstocks and effluent for farmers and their families.

The importance of different rates of throughput, different types of digester, and different types of organic wastes will underpin this form of combined waste management and energy generation for SSA. Health risks associated with handling of feedstock materials at the household level should also be explored.

Household air quality

The health effects of exposure to air pollution from incomplete combustion are substantial both in terms of acute and chronic effects, and have been quantified as being responsible for approximately 2 million early deaths per annum and producing a global health burden of about 4% of total healthy life years lost (Bruce et al., 2000). The PM and CO generated from incomplete combustion of biomass fuels having been shown to produce a range of respiratory (Po et al., 2011), cardiovascular, eye and perhaps even neurological health effects. These effects can occur across the life-course from low-birth weight and reduced lung function due to neo-natal exposure, and increased risk of pneumonia in childhood (Rehfeuss et al., 2009) through to chronic obstructive pulmonary disease (Kurmi et al., 2010), lung cancer (Kurmi et al., 2012), elevated blood pressure (Baumgartner et al., 2011) and cataracts in later life (Fullerton et al., 2008).

A review of the scientific and grey literature for data describing exposure reductions from interventions that introduced household biogas digesters produced no results, suggesting the need for real-world research to quantify the actual changes in personal exposure of householders who move from solid biomass fuels to biogas. Cross-sectional studies on homes using Liquified Petroleum Gas (LPG) compared to biomass fuel suggest that improvements in indoor air quality may be of the order of 66-99% (Titcombe & Simcik, 2011; Kurmi et al., 2008; Dutta et al., 2011). Such improvements in households taking up this technology could bring respiratory and cardiovascular health benefits of the order of 20-25% reduction in risk of a wide range of diseases (Semple et al., 2013). There is a need for well-designed longitudinal studies to examine the impact of introducing biogas digesters to communities on both exposure to indoor air pollution and the health effects this may bring.

The concentrations of $PM_{2.5}$ measured prior to the installation of the biogas digesters in this group of homes were approximately sixteen times higher than the WHO guidance value for indoor $PM_{2.5}$. While the installation produced some limited reduction in measured levels, the size of the effect was modest, with significant improvements seen in only 6 of the 9 homes and the median reduction being approximately 25%, resulting in average household concentrations being 367 micrograms m^{-3}. This value is still some fourteen times greater than the WHO guideline. Even after biogas installation all 9 homes recorded at least 40% of measurement time (over 9.5 hours from the 24 hour sampling period) exceeding the WHO guideline. A similar pattern was seen for CO (median reduction = 27%).

The modest reductions in air pollution seen within this pilot study are unlikely to produce measurable improvements in human health for this group of householders. The small effects can be explained by incomplete conversion of households to biogas. In order to achieve measureable improvements in human health due to improved air quality associated with conversion to biogas, more complete conversion to the technology will be needed. It should also be noted, however, that biogas use may lead to greater reductions in personal exposure than is suggested by the measured air quality in the cooking area; women may have to spend much less time working at the stove because it is a more controllable energy source than wood fuel, so reducing exposure due to cooking. In future studies exposure should be measured using personal monitoring techniques rather than the static or area sampling methods used in this study.

What is the value of a flexible balloon biogas digester to a household?

Energy

- The **savings in firewood consumption** averaged 6 kg day^{-1} = 2.190 t yr^{-1}
- An average of 204 £ yr^{-1} was spent on cooking fuel, providing 20% of the fuel for cooking
- All of this expenditure could be saved by cooking with biogas
- Collecting remaining fuel amounts to a labour cost of 225 £ yr^{-1}
- The average household energy requirement that could be replaced by biogas was 83% and ranged from 57% to 100%.

Organic fertiliser

- **Bioslurry is an effective fertiliser**; yields of crops treated with bioslurry are significantly higher than the control and not significantly different to crops treated with urea or compost.
- **Bioslurry reduces greenhouse gas emissions**; losses of nitrous oxide from crops treated with bioslurry are significantly lower that from crops treated with urea

Sanitation

- **Aerobic pathogens in bioslurry are significantly reduced by anaerobic digestion**; the mean reduction in total coliforms in the digestate was 4.58 log CFU / g sample
- **Anaerobic pathogens in bioslurry are not significantly reduced during anaerobic digestion**
- **Both anaerobic and aerobic pathogens are increased in the local environment**; this is due to spillage during handling of organic wastes to feed the digesters
- Spillage and excessive handling of manures should be avoided when feeding the digester

Household air quality

- **Household air quality is improved on conversion to biogas**; in the households trialled, carbon monoxide and particulate matter with a diameter of less than 2.5μm were reduced by an average of 25% on conversion from woody biomass fuel to biogas
- To bring household air quality within safe limits for CO (WHO = 6 ppm) and $PM_{2.5}$ (EPA = 250 μg m^{-3}), biogas use should be sufficient to **reduce firewood use to less than 10 kg day^{-1}**.

Key issues needing further research

- How should we adapt the design / layout to minimise handling of organic wastes?
- What is the optimum rate of bioslurry application to different crops?
- How does composition of bioslurry change with different treatment conditions and feedstocks?
- Can combining anaerobic digestion and composting further reduce pathogens in organic wastes?

9.3. What changes are needed to make flexible balloon digesters more successful?

The main changes needed to make flexible balloon digesters more successful are associated with cost, damage to the flexible tube, manual handling of feedstock, and maintaining gas pressure.

Cost

The socioeconomic analysis summarised in Table 6.3.6 suggests that even householders who are familiar with the benefits of digesters are only willing to pay ~US$100 (£65) for a biogas digester. A cost of ~£335 / digester is clearly too high for most rural householders. Technical and political means of bringing this cost down should be explored in future work. These could include improved tax incentives, local manufacturing of components, establishment of funding mechanisms to facilitate purchase of digesters, and use of cheaper materials and simpler manufacturing methods in producing digesters.

Revolving fund to facilitate purchase

A revolving fund of £5000 has been established with Green Heat Uganda by the University of Aberdeen. This will provide upfront purchase of 10 digesters at a time. Householders wishing to purchase digesters will be asked to pay back the cost of the digester at an agreed rate that reflects the savings the householder expects to achieve through reduced expenditure on fuel and fertiliser. If the digester does not achieve this rate of saving, the repayments will be reduced to reflect the actual savings. If no savings are made, the digester will be reclaimed as it will not be providing the expected benefits to the household. From the calculations presented in section 6, it is anticipated that a typical household will repay the cost of the digester within 3 years. Therefore, sufficient repayments should have been made to allow purchase of another digester every 3/10 years, i.e. within every 4 months. It is hoped that this will provide a demonstration for an approach to funding digesters that will encourage other organisations to provide more funding of this kind.

Potential to reduce the cost by simpler manufacturing methods – the folded plastic digester

K.Yongabi (PRF) demonstrated the construction of a biogas digester by folding a tube of plastic. The tube produced was 3m x 1m and cost less than $35 for plastic, 2 x PVC drain pipe and hosepipe. The size of digester can be adapted to requirements by using larger pieces of plastic.

The plastic tube was folded 4 times (Fig. 9.2.1) and the ends were fed through the 2 PVC drain pipes (Fig.9.2.2). The end of the plastic were folded over the drainpipe and fixed with tape.

Figure 9.2.1 – Laying out the plastic tube, ready to construct a folded plastic digester

Figure 9.2.2 – Attaching the inlet and outlet to the folded plastic digester

A hosepipe is attached to the top side of the plastic tube using glue or hosepipe connectors. Gas is not stored in the digester, but comes out immediately and is stored in separate bags. This allows gas to be used or distributed to others as needed. It also reduces pressure within the digester tube.

There is some disagreement over the cost of these digesters. This needs to be further investigated in future work. The costs of labour, gas storage bags, stoves, gas hoses and fittings could add significantly to the total costs. In Uganda, total costs were estimated to be between US$ 200 (K.Yongabi, PRF, pers.comm.) and US$ 350 (A.Coenradie, Q-Energy, pers.comm.) (i.e. £130 - £230); this is still more than the £65 the socioeconomic survey suggested householders are willing to spend on a biogas digester. In Ethiopia, costs may be less; costs were estimated to be US$ 170 (£110) (S.Edwards, Institute of Sustainable Development, pers.comm.)

A digester constructed by folding plastic is expected to be significantly less robust than the pre-manufactured flexible balloon digesters used in the current project. A householder should not expect the plastic in the digester to last more than 1 year, whereas the manufacturers suggest that the pre-manufactured digesters could last more than 10 years. However, the cost of the plastic is a small proportion of the total cost including stoves and other fittings, and so could be easily replaced on an annual basis. Increased longevity could be achieved by using more robust plastic or providing better protection for the plastic by constructing a stick fence or lining the pit containing the digester with mud bricks. However, we should beware of introducing a technology that might reduce user confidence in digesters as failures of these systems could also reduce uptake of other designs.

Because of the position of the outlet pipe, these systems tend to collect sediment from the slurry and need to be emptied three times a year. This requires additional labour, but this could be coordinated with composting or cropping activities to provide additional organic fertilizer when needed.

Damage of flexible tube

During the current project, damage of the flexible tube by sharp objects either during or after installation has been a common cause of system failure. These faults can easily be mended using a plastic patch and glue. Future installations should include a repair kit and instructions on repair so householders can get their system working again without having to wait for the installers to visit.

The plastic in the tube can be degraded by prolonged exposure to UV light. Instructions for construction of a shelter to protect the digester from sunlight should also be included with the digester.

Manual handling of feedstock

The results in section 5 show that, while total coliforms are decreased in the digestate compared to the feedstock, increases are observed in the environment due to manual handling and spillage of manure around the kitchen area. This effect is dependent on the design and layout of the system within the household; it is anticipated that significant reductions in pathogens in the environment could be achieve by redesigning the system to reduce handling. An education package for improving sanitation should be provided before installation (for instance hand washing after handling wastes). Information should be given to advise on the position of digesters (close to the animals, away from the kitchen). This may require development of hand pumps to maintain gas pressure. Issues of household sanitation are likely to differ between countries; in Ethiopia, many people live with animals inside the house, whereas in Cameroon, it is taboo in some areas to have animals near the house. Future work should focus on the layout and design of the system to minimize handling. This would also have the advantage of reducing the labour needed to run the digester.

Gas Pressure

Flexible tube digesters have a constant volume, which means that the biogas produced has a variable pressure, depending on the volume of gas in the digester. After prolonged periods of cooking, the gas pressure can drop. The gas pressure and activity of the micro-organisms decomposing the organic waste are also more affected by changes ambient temperatures than in designs with better insulation, such as fixed dome digesters, that are constructed underground. This can be addressed by ***a***pplying weights to the balloon when the gas pressure drops.

Problems were observed during this project with the pipe that transports the gas from the digester to the kitchen bending, causing the gas line to block. An improved design should include a pipe that is resistant to bending at this point.

What changes are needed to make flexible balloon digesters more successful?

Flexible tube digesters

- **Installation of a flexible balloon digester is simple**; installation takes only a few days and is easily learnt by householders
- **Digesters are susceptible to damage**; protection is needed from sharp objects and sunlight
- **Gas pressure** is variable – problem can be overcome by applying weights

Cost

- **Digesters are too expensive**; cost of flexible balloon digesters in Uganda is over 5 times the cost reported in Asia, which is more than farmers are willing to pay
- **Revolving fund** could provide upfront costs of digesters
- **Simpler manufacturing methods** could bring cost down
- **Research is needed to reduce costs of digesters**

Manual handling of feedstock

- **Labour is increased by conversion to biogas**; this is due to extra work needed for mixing and handling organic wastes
- **Both anaerobic and aerobic pathogens are increased in the local environment**; this is due to spillage during handling of organic wastes to feed the digesters
- **Research is needed to reduce manual handling of feedstock**

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Appendix A – Project work plan

	Organisations
GHU	Green Heat Uganda
JHI	James Hutton Institute
MU	Makerere University
ORS	Orskov
UoA	University of Aberdeen

	MSc students
MSc1	MSc registered at MU with JM & PW - input from KG & BB = Moris Kabyanga
MSc2	MSc registered at UoA with JS - input from GD, BO & KB = Vianney Tumwesige
MSc3	MSc registered at MU with ES, JBT & CN - input from EB, NM, JS, RM & MS = Swaib Semiyaga
RA1	RA registered at UoA with SS & NS - input from ES, KY & LA = Andrew Apsley

Personnel					
AA	Andrew	Apsley	BO	Bob	Orskov
LA	Lisa	Avery	ES	Elly	Sabiiti
BB	Bedru	Balana	SS	Sean	Semple
EB	Liz	Baggs	JS	Jo	Smith
KB	Karsten	Bechtel	NS	Norval	Strachan
GD	Grant	Davidson	MS	Madhu	Subedi
KG	Klaus	Glenk	JBT	John Baptist	Tumuhairwe
RM	Robin	Matthews	VT	Vianney	Tumwesige
NM	Nick	Morley	PW	Peter	Walekhwa
JM	Johnny	Mugisha	KY	Kenneth	Yongabi
CN	Charles	Niwagaba			

	Milestone	Start date	Delivery date	Organisation responsible	Main person doing work	Additional input
1	**What is the potential of flexible-balloon digesters in SSA?**					
1.1	Sociological and economic research to identify villages in regions where implementation of flexible-balloon digesters will be piloted	01/03/2012	31/05/2012	MU	MSc1	JM, PW, BB, KG
1.2	Socioeconomic analysis, exploring cost/benefits and willingness to pay	01/06/2012	19/02/2012	MU	MSc1	JM, PW, BB, KG
2	**What changes are needed in design of equipment and farming systems?**					
2.1	Installation of flexible-balloon digesters at 10 selected sites	01/06/2012	30/06/2012	GHU	VT	
2.2	Provide training to local people on installation of flexible-balloon biogas digesters	01/06/2012	30/06/2012	GHU	VT	GD
2.3	Document engineering problems associated with technical implementation	01/06/2012	30/06/2012	MU	MSc2	KB, GD, MSc3, RA1
2.4	Establish trials to identify optimum return of agricultural products from applied nutrients	01/07/2012	31/07/2012	UoA	MSc2	MSc3,RA1
2.5	Comprehensive time-management analysis to determine potential labour savings and improved designs of cooking equipment and farm layout	01/08/2012	30/09/2012	JHI	MSc2	GD, JS, KB
2.6	Integrate results from measurements in (3) into systems model	01/10/2012	31/12/2012	UoA	MSc2	JS
2.7	Provide an estimate of the potential regional improvement in water quality, crop production and carbon sequestration	01/01/2013	31/01/2013	UoA	MSc2	JS
2.8	Identify regions where digesters are likely to be most beneficial to the rural community.	01/02/2013	20/02/2013	UoA	MSc2	JS
3	**What is the value of a biogas digester?**					
3.1	Training in measurement techniques for measurement of carbon, nutrients, energy and water flows	01/03/2012	31/05/2012	UoA (1,2) / MU (3)	MSc3	NM, EB, ES, JBT
3.2	Measurement of carbon, nutrients, energy and water flows before installation	01/05/2012	31/05/2012	MU	MSc3	JBT, ES, NM, EB
3.3	Measurement of carbon, nutrients, energy and water flows in trials	01/06/2012	31/07/2012	MU	MSc3	JBT, ES, NM, EB
3.4	Measurement of carbon, nutrients, energy and water flows after installation	01/06/2012	20/02/2013	MU	MSc3	JBT, ES, NM, EB
3.5	Training in measurement techniques for measurement of pathogen distribution and household air quality	01/03/2012	31/05/2012	UoA & JHI (1,2) / MU (3)	RA1	NS, LA, SS, ES, JBT, KY
3.6	Measurement of pathogen distribution and household air quality before installation	01/05/2012	31/05/2012	UoA	RA1	NS, LA, SS, ES, JBT, KY
3.7	Measurement of pathogen distribution and household air quality in trials	01/06/2012	31/07/2012	UoA	RA1	NS, LA, SS, ES, JBT, KY
3.8	Measurement of pathogen distribution and household air quality after installation	01/06/2012	20/02/2013	UoA	RA1	NS, LA, SS, ES, JBT, KY
3.9	Documentation of diseases contracted	01/01/2013	20/02/2013	JHI	RA1	NS, LA, SS, ES, JBT, KY
3.10	Presentation of results on information boards	01/01/2013	20/02/2013	JHI	MSc3, RA1	GD
4	**User Engagement**					
4.1	Identify social and economic barriers to uptake	01/03/2012	31/05/2012	MU	MSc1	GD, JM, PW, BB, KG
4.2	Try out approaches to overcome barriers	01/06/2012	30/06/2012	JHI	MSc1	GD
4.3	Address engineering problems associated with technical implementation	01/06/2012	30/06/2012	JHI	MSc2	GD
4.4	Present results of research to local people and downstream users in an accessible way	01/01/2013	20/02/2013	JHI	GD	MSc1, MSc2, MSc3, MSc4

Date	MSc1	MSc2	MSc3	RA1
05/03/2012	Literature survey; Household selection for socio-economic survey	Source digesters & literature review; Design baseline survey with MSc1, MSc2 and RA1; Documentation of engineering problems and time management analysis	Prepare for trip to UoA; Design baseline survey with MSc1, MSc2 and RA1	Training in microbial techniques at JHI; Questionnaire design, Ethics application, Equipment and reagents ordering, Visa, Excel risk assessment training, Risk assessment and insurance
12/03/2012			Training at the UoA	
19/03/2012				
26/03/2012				
02/04/2012	Design of questionnaire for the socio-economic baseline survey	Selection of farmers		
09/04/2012				
16/04/2012				
23/04/2012			Exams and further training at MU	
30/04/2012				Arrange delivery of consumables and equipment
07/05/2012				
14/05/2012				
21/05/2012				
28/05/2012				
04/06/2012	Field survey; Questionnaire pre-testing, Baseline survey		Interview farmers at selected sites to find out how they want to use bioslurry	First visit and consent; Dry run micro.sampling; Dry run air sampling
11/06/2012				Visit A - sites 1-2; Air sampling
18/06/2012		Installation of digester at Kabanyolo		- sites 3-4
25/06/2012				- sites 5-6
02/07/2012		Collect together data and information for use in systems modelling; Setup trials at Kabanyolo with MSc3	Decide on experimental design	- sites 7-8
09/07/2012				- sites 9-10
16/07/2012				Holiday
23/07/2012				
30/07/2012			Baseline measures at sites before sowing	
06/08/2012	Cost items identified and quantified; Benefit items identified and approaches to quantification outlined; Description of the study area (farming systems, perception,...) via talking to people, visits, secondary data	Setup trials with MSc3; Training in microbial and household air quality techniques	Setup trials with MSc2; Baseline measures for trials at MU experimental site	Setup lab
13/08/2012				
20/08/2012				Visit A - sites 1-5 Micro.sampling - before digester installed
27/08/2012		Installation of biogas digesters at selected sites; Training of farmers in installation, maintenance and value of digesters		- sites 6-9
03/09/2012			September measurements at sites	- sites 10-14 Micro.sampling
10/09/2012			September measurements on trails	- sites 15-18 - no installation
17/09/2012				Visit B - sites 1-5 Micro.sampling - after digester installed; Air sampling (2 homes / week)
24/09/2012				- sites 6-9
01/10/2012	Entry and analysis of baseline data, completion of report on baseline survey and preparation of data collection tools for follow-up survey	Setup trials at Tiribogo with MSc3	October measurements at sites	- sites 10-14 Micro.sampling
08/10/2012			October measurements at sites	Ugandan public holiday
15/10/2012				- sites 15-18 - no installation; Air sampling (2 homes / week)
22/10/2012				
29/10/2012		Visit C - sites 1-5 Micro.sampling - after installation; Air sampling (2 homes / week)		Complete training of MSc2 in microbial and air quality measurement
05/11/2012		- sites 6-9	November measurements at sites	Write-up papers and report
12/11/2012		- sites 10-14 Micro.sampling	November measurements on trials	
19/11/2012		- sites 15-18 - no installation		
26/11/2012				
03/12/2012	Second round survey	Data analysis	December measurements at sites	
10/12/2012			December measurements on trails	
17/12/2012				
24/12/2012		Debrief and clean-up		
31/12/2012		Prepare for trip to Aberdeen		
07/01/2013	Analysis and write-up	Training and application of systems analysis at UoA.; Analysis and write-up; Final thesis	January measurements at sites	
14/01/2013			January measurements on trials	
21/01/2013				
28/01/2013				
04/02/2013	Final thesis		Analysis and writeup. Final thesis	
11/02/2013				
18/02/2013				

Appendix B – List of 54 households surveyed for installation of biogas digesters

Code	Contact person	GPS data
H1	Kasule Godfrey	N00°21.488' ; E032°18.285'
H2	Godfrey Semakula/Rose Nakasi	N00°21.418' ; E032°18.261'
H3	Godfrey Kanakulya	N00°22.036' ; E032°18.262'
H4	Hadija Nakijjoba	N00°22.332' ; E032°18.501'
H5	Regina Nabuyigo	N00°21.944' ; E032°18.242'
H6	Jane Kagimu	N00°21.586' ; E032°18.136'
H7	Kyeyune Hussein	N00°21.586' ; E032°18.136'
H8	Paul Twase	N00°21.586' ; E032°18.136'
H9	Kiwanuka Harriet	N00°21.586' ; E032°18.136'
H10	Ssemambo Christopher	N00°21.364' ; E032°18.393'
H11	Nakato Betty	N00°26.485' ; E032°18.285'
H12	Ssemazi Mugaga	N00°22.182' ; E032°18.398'
H13	Francis Sseruwagi Gitta	N00°22.602' ; E032°18.726'
H14	Ndagire Kevin	N00°22.810' ; E032°18.816'
H15	Kavuma Richard	N00°22.810' ; E032°18.816'
H16	Nailubulwa	N00°22.810' ; E032°18.816'
H17	Masembe Joseph	N00°22.810' ; E032°18.816'
H18	Namagembe Milly	N00°22.768' ; E032°18.657'
H19	Kibirige Henry	N00°22.768' ; E032°18.657'
H20	Jane Kisero	N00°22.421' ; E032°18.608'
H21	Hajji Lukyamizi	N00°22.025' ; E032°18.625'
H22	Nakaggwa Nasta	
H23	Joseph Kaboggoza	
H24	Kaloli Kimuli	
H25	Narwadda Mariam	N00°22.532' ; E032°15.656'
H26	Muteesi Mariam	

Code	Contact person	GPS data
H27	Kasaago Jacob	N00°22.148' ; E032°18.135'
H28	Muzuni Samuel	
H29	Tim Godfrey	
H30	Atugonza Stella	
H31	Dungu Bendicto	
H32	Mannjeli Nabawesi	
H33	Anette Nabukenya	N00°22.240' ; E032°18.577'
H34	Petero Bakina	
H35	Christine Nakilanda and Kasibante	
H36	Mathias Lukwago	
H37	Alex Ssemanda	
H38	Grace Nakabiri	
H39	Nagawa Christine	
H40	Joyce Nakirijja	
H41	Ssalongo Lujja	
H42	Harriet Bukirwa	N00°22.209' ; E032°18.424'
H43	Paul Ssekiwanda	N00°22.146' ; E032°18.398'
H44	Ida Najjumbwe	N00°22.088' ; E032°18.288'
H45	Gerald Mukasa	N00°22.828' ; E032°18.236'
H46	Rose Namatove	N00°22.130' ; E032°18.143'
H47	Ruth Nakampi	
H48	Mukuye Amos	
H49	Nankabirirwa Aisha	
H50	Nkwenge Stephen	
H51	Tinka Ibrahim	
H52	Katabarwa Sudaice	
H53	Nantume Sheila	
H54	Ssenkandwa Moses	

Appendix C – Questionnaire used in household survey for suitability for installation of flexible balloon biogas digesters

Interviewer data:

1.1 Name of the respondent: ____
1.2 Contact: ____
1.3 Date of assessment: ____
1.4 District: ____________________Sub-county: ________________Parish: __________________
1.5 Village: ____________________GPS data: ____
1.6 How many people are hosted in your household? _______________________________________

Demand assessment:

2.1 How many meals are prepared per day (incl. Breakfast, lunch and dinner)? __________________
2.2 How many minutes or hours do you spend cooking per meal? Breakfast____ lunch ____ and dinner ____
2.3 How many pieces of fire-wood does your household use every day to cook? _______________________________________
2.4 Do you boil drinking water? YES/NO
2.5 How much water does your household's boil in a week?
a) 5L ____ b) 10L____ c) 20L____
2.6 How big are your cooking pots?
Between 1L and 2L_______ between 3L and 5L_______ over 5L_______
2.7 How big is your household's water collecting vessel?
a) 5L ____ b) 10L____ c) 20L____ d) Both b and c____
2.8 How often does your household collect water?
a) Once a day____ b) Twice a day____ c) Thrice a day____ d) Others (specify) ____
2.9 How much water does your household need per day?
a) 10L to15L_______b) 16L to 25L_______ c) 25L_______
2.10 How much (minutes/hours) does your household spend collecting water?

a) 15 to 30 minutes_______ b) 31 to 59minutes_______ c) Over minutes_______

2.11 Who is in charge of water collection? ______________

2.12 How far is the water source from the home? ______________

2.13 What is the source of water used in this village? ____________

2.14 How many rooms do you light during night? ____

2.15 How many hours do you light these rooms?____

2.16 Do you currently use solar lamp? YES/NO

2.17 Energy usage and cost

Energy source	Usage (units / time)	Unit Cost (UGX / unit)	Cost each transport (UGX)	Purpose e.g. cooking, lighting, boiling, e.t.c
Kerosene				
Candles				
Charcoal				
Firewood				
Cow dung				
Alternative energy source (specify)				

2.18 Household fuel supply

Fuel source	Where does your household get fuel?	Distance from your household to supplier	Difficulties in energy supply	How does your household store the fuel?
Kerosene				
Candles				
Charcoal				
Firewood				
Cow dung				
Alternative energy source (specify)				

Possible alternative fuels

3.1 Nature of organic waste in your household

Organic waste source	Tick the waste generated in your household.	Describe the organic waste produced by your household?	What is the quantity of your waste?	How much waste does your household generate per day?
Cow dung				
Pig dung				
Kitchen peels				
Goat/sheep dung				
Others				

3.2 Does your household keep animals around the house?
a) Yes b) No

3.3 Does your household grow crops around the house?
a) Yes b) No

3.3 Does your household graze more animals away from the house?
a) Yes b) No

3.4 Does your household grow crops away from the house?
a) Yes b) No

3.5 What does your household currently do with this waste?
a) Compositing b) Mulching c) Animal feed d) burning as fuel e) Burning as waste f) Dumping

3.6 Household farm

	What is the area of land used around the house for farming?	What is the area of additional land used	Does your household keep more animals or grow crops away from the house?
Cultivated land			
Pig			
Cow			
Goat/sheep			
Others			

Appendix D – Responses on how to use bioslurry

Note: Presented are the responses from interviewed farmers who were selected to receive biogas digesters. Chicken Manure means chicken droppings mixed with coffee husks which are used as a bedding layer for poultry.

Code	Crops grown	Fertilizers currently used	Crops currently fertilized	How Fertilizers are currently used	Crops desired to be fertilized with slurry	How to use the slurry	Any comment
H21	Banana Maize Beans Sweet potato	Chicken manure Crop wastes	Maize Banana Beans	Maize – Manure applied on a plant shoot. Banana – Garden covered with crop waste ~ mainly from maize stalks.	Maize	I think applying it directly may burn the crops. It needs to first be stored for about 2 weeks and then applied to the garden before planting.	We keep more than 800 heads of chicken. This can produce enough manure that we need in gardens.
H17	Banana Maize G. Nuts Beans Cabbages Yams Sweet potato Coffee	Chicken manure Animal dung (composited)	Maize Beans Cabbages	Maize – A hole is dug + manure + seed + soil cover. Beans + Cabbages – Plant shoot surrounded by manure.	Cabbages	I would need to compost it first, and then apply it in the entire garden before planting.	Chicken manure we use is bought. We have a few chickens which are reared in a free range system.
H47	Tomatoes Banana Greens Maize cabbages	Chicken manure UREA and NPK SUPERGROW	Tomatoes Banana Greens Maize	Maize first planted, fertilizer applied when the shoot comes out. NPK – Spread in the entire garden before planting SUPERGROW – Spraying on the leafy vegetables	Tomatoes Green paper Maize Cabbages Greens	Stored for some time and then sprayed to crops.	Chemical fertilizers are usually applied on Greens (Nakatti) and Cabbages. For Tomatoes and Maize – Chicken manure is used. Chicken manure is bought from

				UREA- Mixed with water and sprayed on the crops			Kampala at 2000 – 3000/= per bag before transportation.
H27	Banana Maize Pumpkins Beans	Chicken manure Animal dung	Maize Banana Pumpkins	Maize – A hole is dug + manure + seed + soil cover. Banana – A hole is dug aside of plant ~ 100cm + Manure + soil cover. Cow dung is used when dry.	1. Maize 2. Banana 3. Pumpkins	Need to be trained. Its something new and I have never used it.	Chicken manure is bought from Kampala at ~ 7000/= per bag (transport inclusive)
H1	Banana Maize Cassava Beans Sweet potato Coffee	Chicken manure Animal dung Crop wastes	Maize Banana Coffee	Maize – A hole is dug + manure + seed + soil cover. Banana – A hole is dug + Manure + plant shoot + soil.	1. Maize 2. Banana 3. Coffee	Need to be trained in different possible ways. I would like to apply it per hole dug to avoid over growth of weeds.	We can produce the required fertilizers locally.
H24	Banana Maize Beans Cassava Sweet potato Irish potato	Chicken manure Crop wastes	Maize Banana	Maize – Dig a hole + maize seed + soil cover. When the shoot comes out, it is surrounded by manure. Crop wastes – remains like maize stalks are laid in Banana gardens.	Maize	When its from the digester, we need to leave it for a few days and then applied to crops.	
H13	Maize	Chicken manure	Maize	Maize – Dig a hole +	Maize	Store it for some	Animal dung is

	Banana Beans Sweet potato Yams	Animal dung	Banana	Manure + seed + soil cover	Banana	time and then spraying the entire area before planting.	rarely used on a large scale due to its scarcity and cannot be bought unlike chicken manure. Chicken manure is bought at 3500 to 4000/= per bag
H11	Maize Banana Sweet potato Vegetables	Chicken manure	Maize Banana Sweet potato Vegetables	Maize – Dig a hole + seed + soil cover + manure on top Banana – Put in a hole before planting. For the grown plants, manure is laid in trenches dug parallel to planted rows. Sweet potato – Manure spread over the entire area. Vegetables – Manure spread over the garden and seeds are added.	Vegetables Banana	Spreading it in the trenches for fertilizing Banana	Chicken Manure costs 2500 to 3000/= per bag before transportation.
H20	Maize Banana Beans Sweet potato Jackfruit Passion fruit G. Nuts Pumpkin Tomatoes	Chicken manure	Maize Banana Vegetatables	Maize – Dig a hole + Manure + seed + soil cover. Banana – Manure is spread around the plant. Vegetable – Coffee husks + seed + Manure.	Maize Banana	That's the information to be provided by the researchers.	Animal dung is dispersed in different locations; we need to know when installation is to begin so that we can start to pile it up. We keep poultry so we don't buy Manure.

Appendix E – Biogas information sheets

DIGESTERS

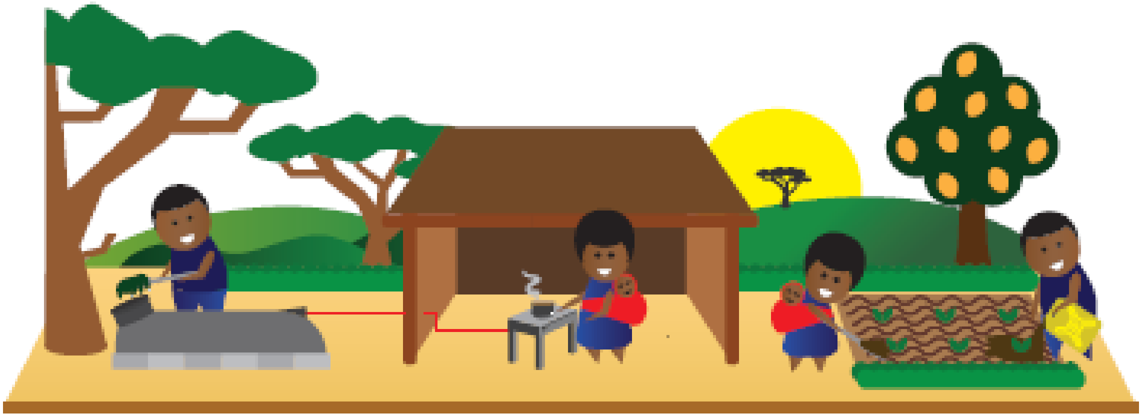
Developing Innovative Green Energy Systems to Enhance Rural Sustainability

UKaid

from the British people

How Biogas Works

Biogas is produced from the decomposition of organic waste such as animal waste, human waste and dead plants. There are many benefits to using biogas fuel, which make it a lot better to use than traditional charcoal and wood fuel cooking stoves. Biogas can also be used for lighting and electricity generation.



Wet dead plants and human and animal waste are fed into the biogas digester, where they are broken down into a gas.

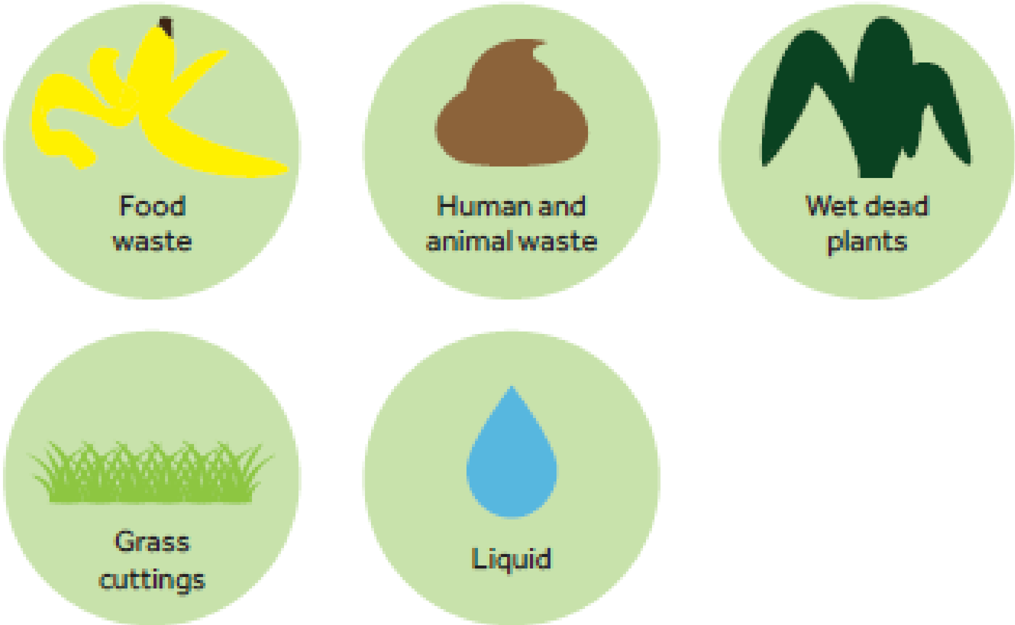
This gas is piped through to a connecting stove where it can be used as a clean, safe and quick cooking fuel.

Leftover waste from the digester can be used as a natural and efficient fertiliser for crops and plants or in aquaculture.

What Must Not Be Put In It

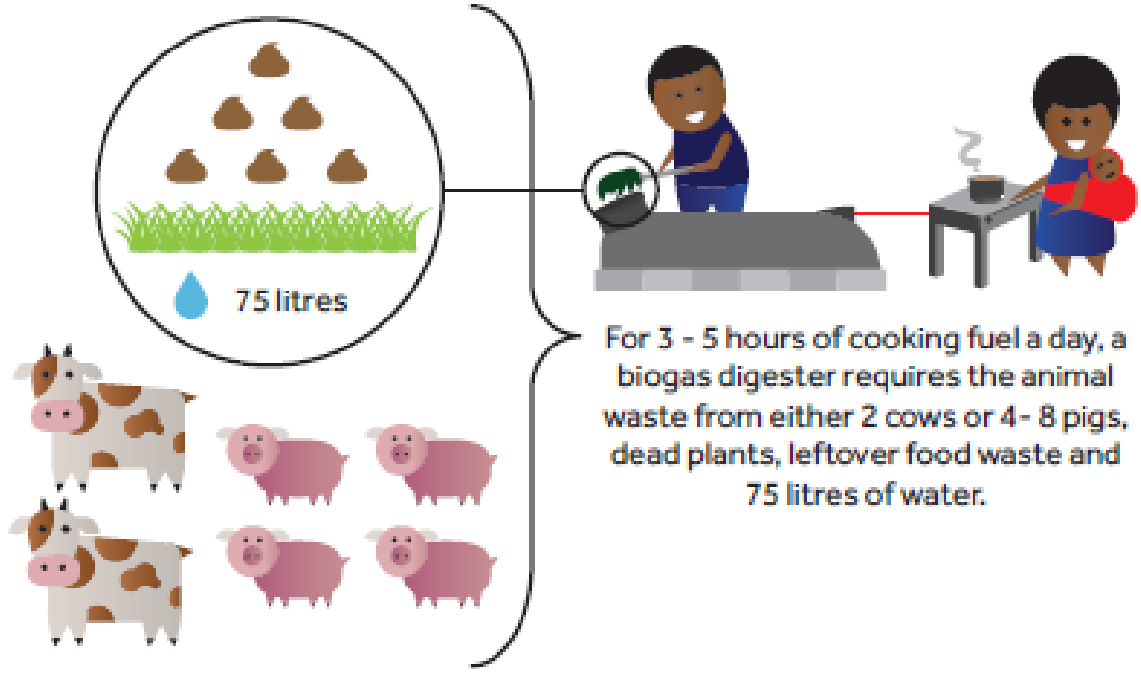
For biogas to work properly it is important to feed it correctly.
Organic waste and water should be fed into the digester daily.
Never put waste such as plastic and glass into the digester.

What Can Be Put In It

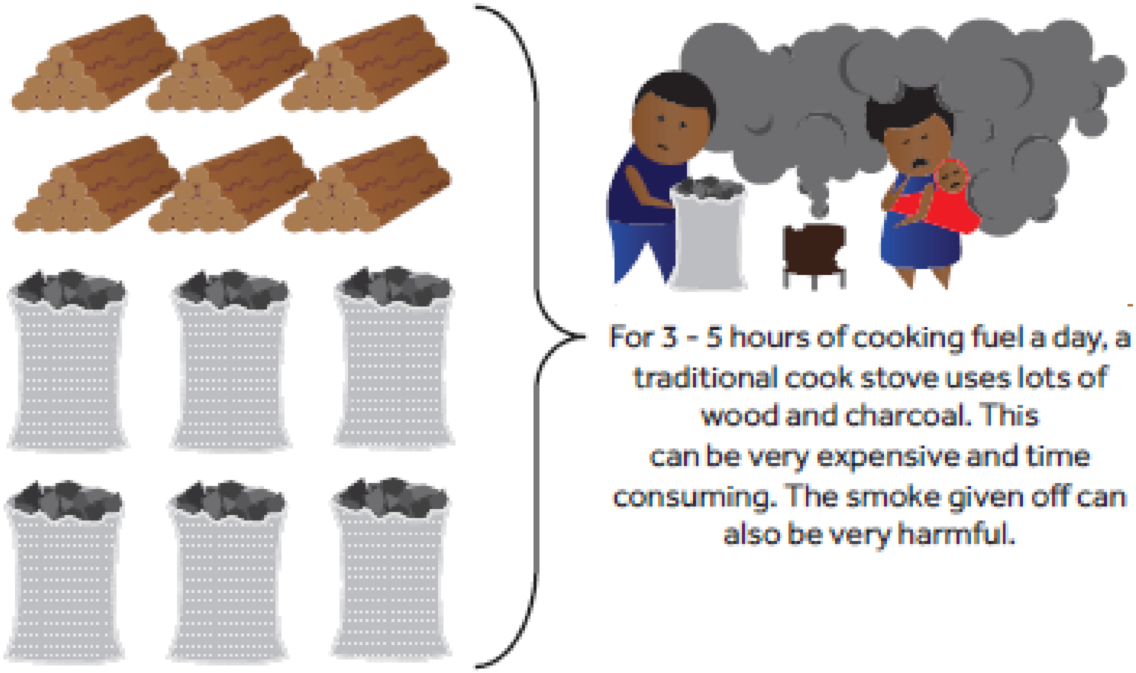


How To Look After It

Biogas works at its best when it is looked after properly.
For it to be at its most efficient follow these guidelines.



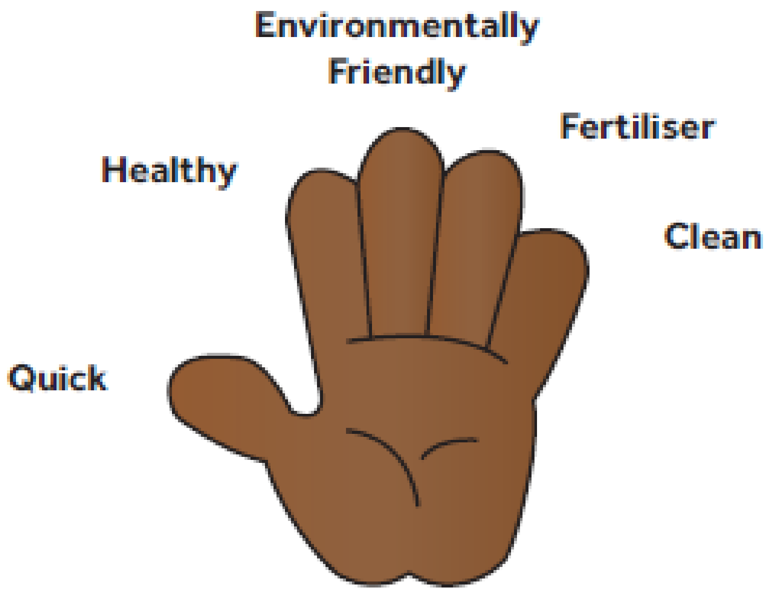
For 3 - 5 hours of cooking fuel a day, a biogas digester requires the animal waste from either 2 cows or 4 - 8 pigs, dead plants, leftover food waste and 75 litres of water.



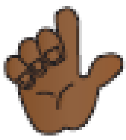
For 3 - 5 hours of cooking fuel a day, a traditional cook stove uses lots of wood and charcoal. This can be very expensive and time consuming. The smoke given off can also be very harmful.

Benefits of Biogas

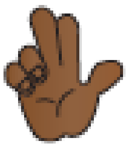
There are 5 main benefits to using biogas over traditional cooking methods.



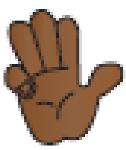
Quick
Biogas can be turned on instantly. You do not need to spend time collecting firewood and making a fire.



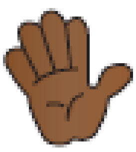
Healthy
Smoke from charcoal and wood stoves is harmful. Biogas produces very little smoke.



Environmentally Friendly
With biogas there is no need to cut down trees for firewood.



Fertiliser
You do not need to buy charcoal or firewood to cook with biogas. All you need is human/animal waste, dead plants and water.



Clean
Helps to clean up animal and human waste to prevent spread of diseases.

Benefits - Quick

When fed regularly biogas produces instant cooking fuel.
This means less time is spent collecting fuel.

Cooking with a charcoal/wood stove

Cooking with a biogas stove

Benefits - Healthy

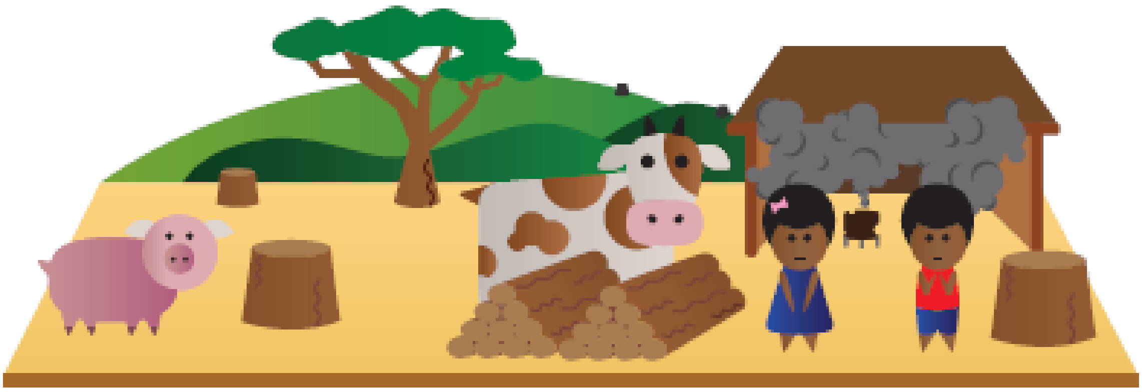
Cooking with biogas produces a lot less air pollution inside your home. This dramatically reduces the risk of many health problems such as coughs, eye problems, pneumonia, heart problems and even death.

Cooking with a charcoal/wood stove

Cooking with a biogas stove

Benefits - Environmentally Friendly

Cooking with biogas means that less fuel needs to be collected. This means that trees do not need to be cut down. which helps to promote a natural and sustainable environment.

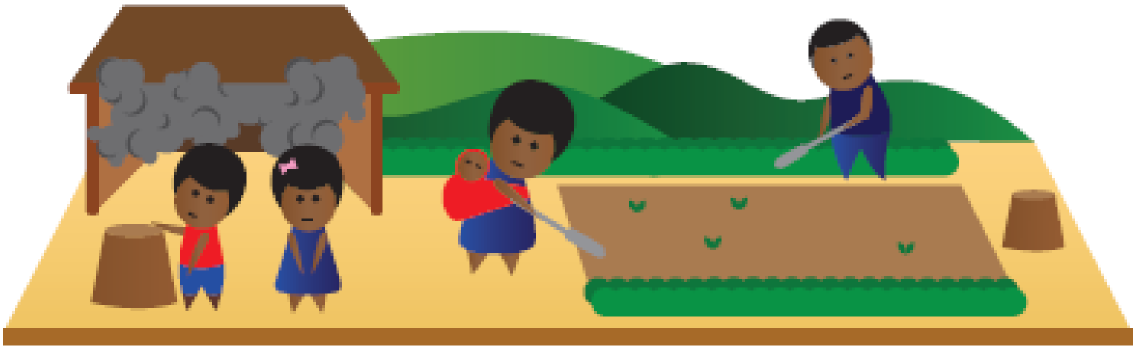


Cooking with a charcoal/wood stove

Cooking with a biogas stove

Benefits - Fertiliser

The slurry left over from the biogas digester can be used as a good fertiliser for crops and plants. This will help to improve agricultural productivity.

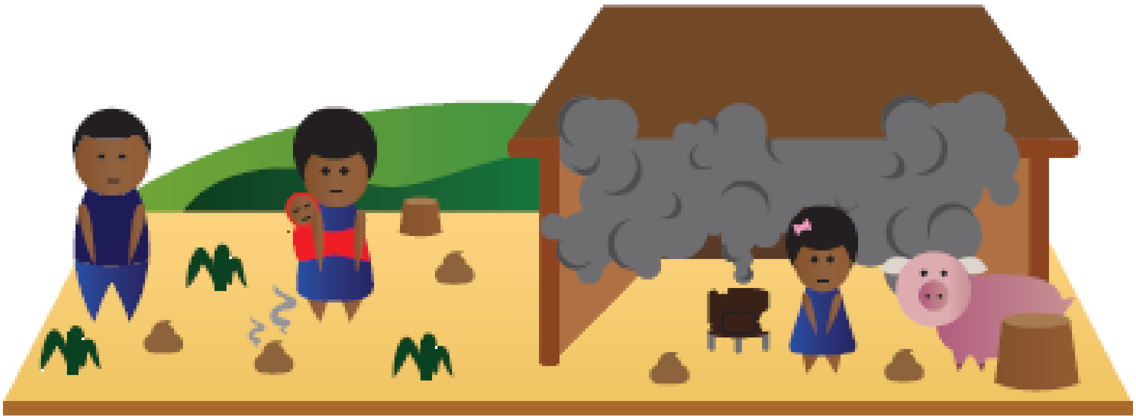


Cooking with a charcoal/wood stove

Cooking with a biogas stove

Benefits - Clean

Cooking with biogas improves sanitation because human and animal waste can be placed into the digester to produce cooking gas. This helps to create a cleaner environment and reduce the risk of spreading germs and diseases.



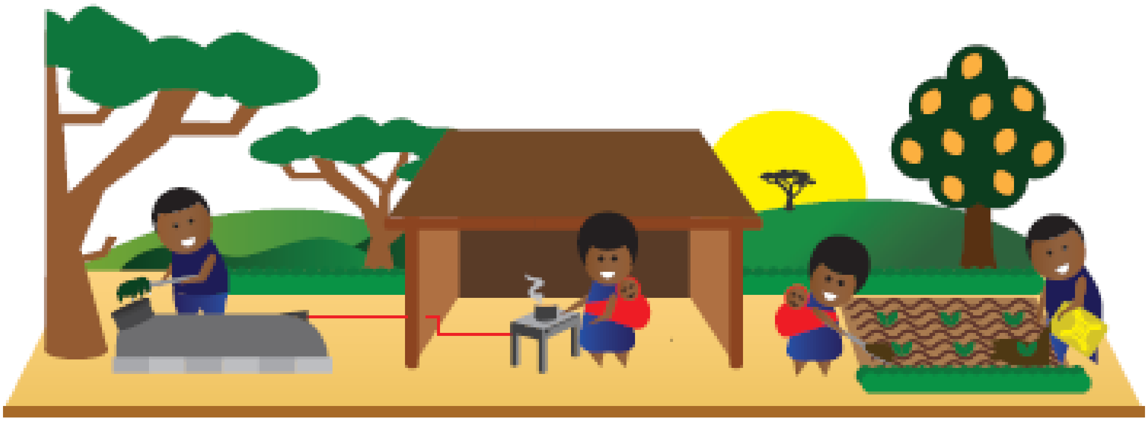
Cooking with a charcoal/wood stove

Cooking with a biogas stove

Appendix F – Information sheets translated into the local Bantu language, Luganda

Engeri Bayogaasi Gye Gukola

Bayogaasi; guno guba mukka ogufumbisibwa nga gukolebwa okuva mu nnakavundira w'ebisasiro ebya buli ngeri, okugeza ng'obusa n'empitambi y'abantu n'ensolo wamu n'ebimmera ebyononeese; waliwo emigaso mingi nnyo egiri mu kufumbisa bayogaasi ekigufuula okuba ogw'enkizo okweyambisibwa okusinga okukozesa ammanda n'enku ku ssigiri n'ebyoto ebya bulijjo binansangwa.



Wano mu kifaananyi olaba nga ebisasiro ebibisi, empitambi n'obusa bitekebwa mu ttogero mwe byettukkutira okutuuka lwebyefumbamu omukka.

Wano olaba nga omukka guno guyita mu muddumu ogugutuusa ku kyooto gyegufumbisibwa mu ngeri ennyonjo ate mu bwangu awatali bulabe bwonna.

Wano ate olaba nga, ebisigalira mu ttogero bijjibwamu nga bifuuse ebijimusa eby'obutonde ebitaliimu nkeka yonna ebisobola okweyambisibwa okujimusa ebirime n'ebibala awamu ne ku nnima eyomunda.

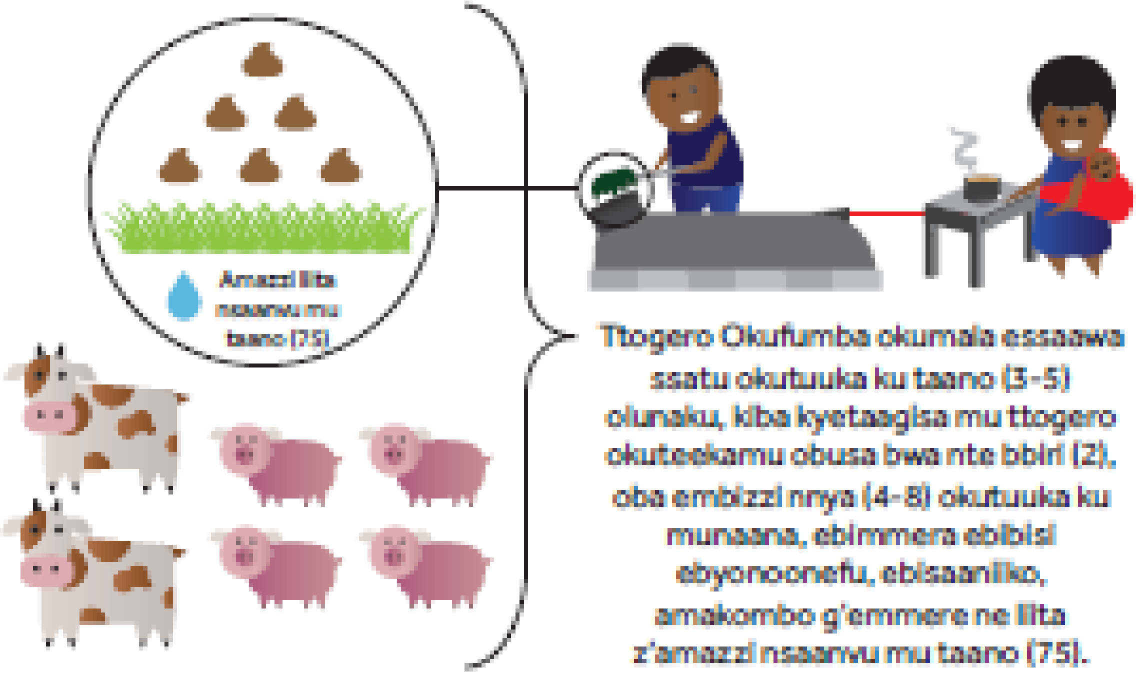
Ebitateekeddwa Kuteekebwa Mu Togero

Bayogaasi okusobola okukola obulungi, kiba kikulu nnyo okukozesa ebintu ebituufu, ebisasiro n'amazzi bisaana okuteekebwa mu ttogero buli lunaku; Mu ttogero temutekwa kuteekebwamu bintu nga ebya pulastiika, ebiveera wamu ne birawuli.

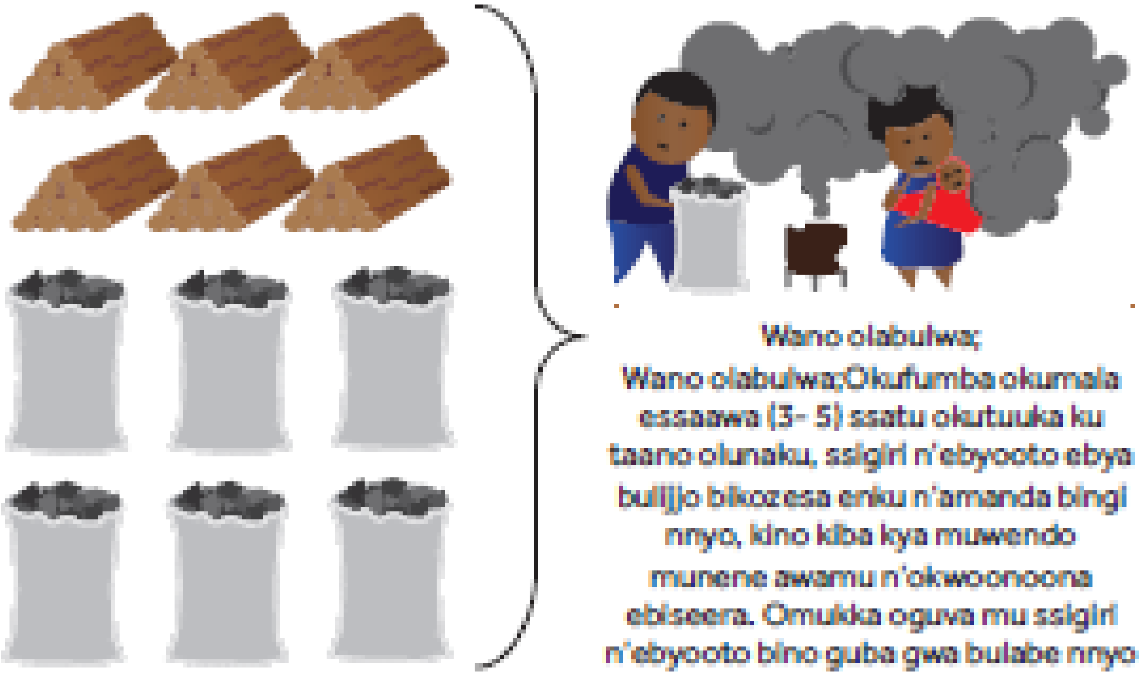
Wano mu kifaananyi olaba byolina okuteeka mu ttogero

Engeri Y'okugulabiriramu

Bayogaasi gukola okwemalayo singa guba gulabiriddwa bulungi.



Ttogero Okufumba okumala essaawa ssatu okutuuka ku taano (3-5) olunaku, kiba kyetaagisa mu ttogero okuteekamu obusa bwa nte bbiri (2), oba embizzi nnya (4-8) okutuuka ku munaana, ebimmera ebibisi ebyonoonefu, ebisaaniiko, amakombo g'emmere ne lita z'amazzi nsaanvu mu taano (75).

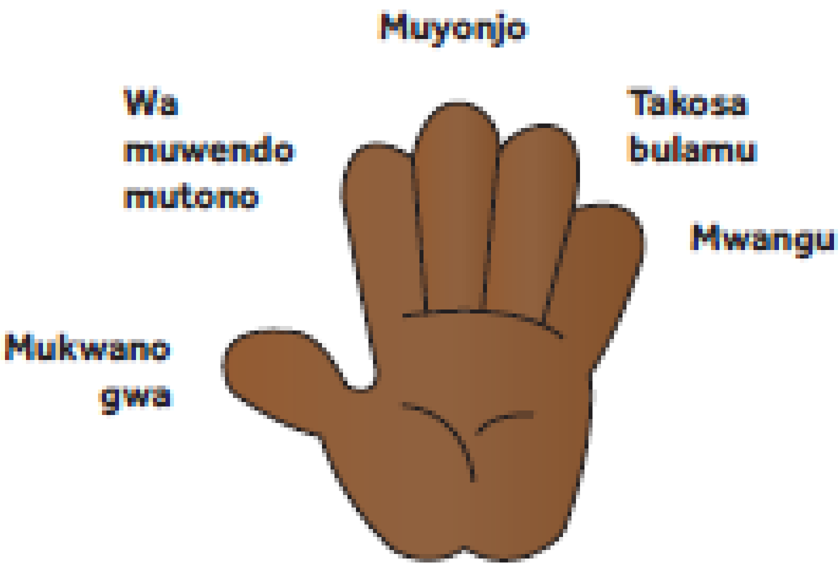


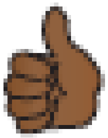
Wano olabulwa;

Wano olabulwa;Okufumba okumala essaawa (3- 5) ssatu okutuuka ku taano olunaku, ssigiri n'ebyooto ebya bulijjo bikozesa enku n'amanda bingi nnyo, kino kiba kya muwendo munene awamu n'okwoonoona ebiseera. Omukka oguva mu ssigiri n'ebyooto bino guba gwa bulabe nnyo ku bulamu.

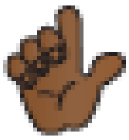
Emiganyulo Gya Bayogaasi

Waliwo emiganyulo emikulu etaano egiri mu kweyambisa bayogaasi okusinga engeri endala zonna mu kufumba.

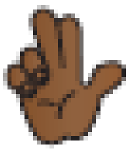




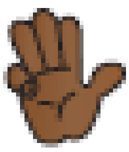
Mukwano gwa butonde bwa nsi
Awali bayogaasi tewaba kyetaagisa kutema miti kufuna nku.



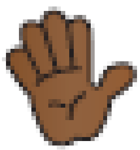
Wa muwendo mutono
Tekikwetaagisa kugula manda oba nku okufumbisa bayogaasi, byeweetaaga bwe bubi bw'abantu, obusa bw'ensolo, ebisasiro n'amazzi.



Obuyonjo
Kituyamba okuyonja netuggyawo obusa bw'ensolo n'obubi bw'abantu ne kiziyiza okusaasaanya endwadde.



Si gwa bulabe eri obulamu
Omukka ogw'enziro oguva mu manda n'enku gwa bulabe ku bulamu, wabula ye bayogaasi afulumya omukka ogw'enziro mutono ddala.

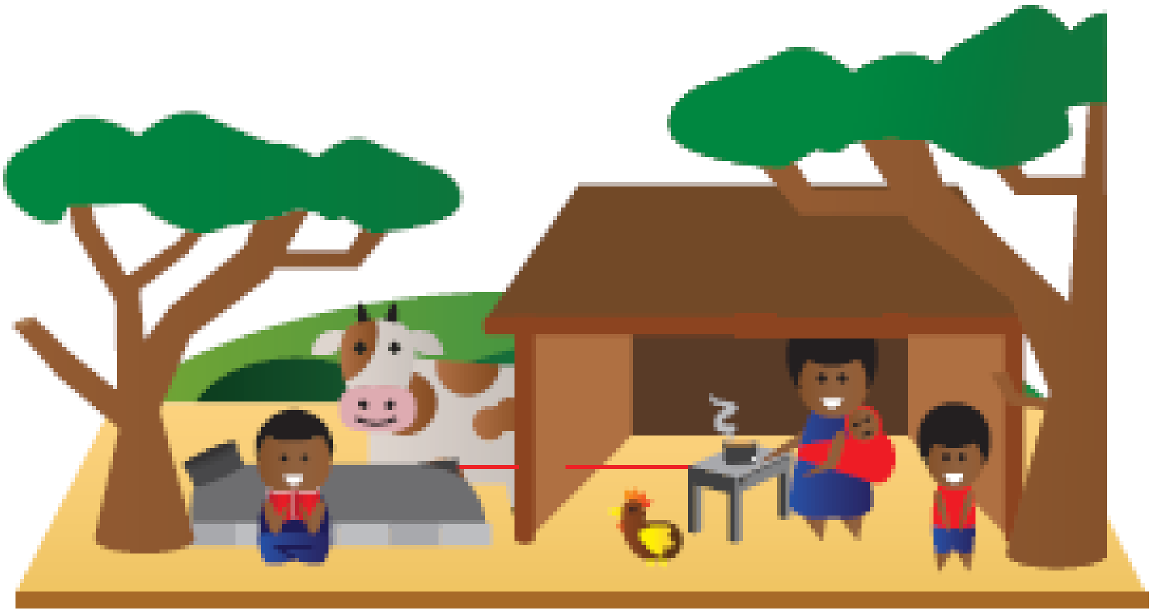


Mwangu
Bayogaasi guteekebwako mu bwangu, teweetaaga kwonoona biseera ng'onoonya enku n'okukuma omuliro.

Emiganyulo – Ku Bulamu

Okufumbisa bayogaasi tekuleeta nnyo mukka mubi gwonoona mpewo mu makaago, kino kikendeereza ddala obulabe obwandituuse ku bulamu gamba ng'okukolola, ebizibu by'amaaso, lubyaamira, endwadde z'omutima oluusi n'okufiira ddala.

Mu kifaananyi olaba okwononeka kw'obutonde olw'okufumbira ku kyooto eky'amanda oba enku



Mu kifaananyi olaba embeera ennungi eva mu kufumbisa bayogaasi

Emiganyulo – Ebigimusa

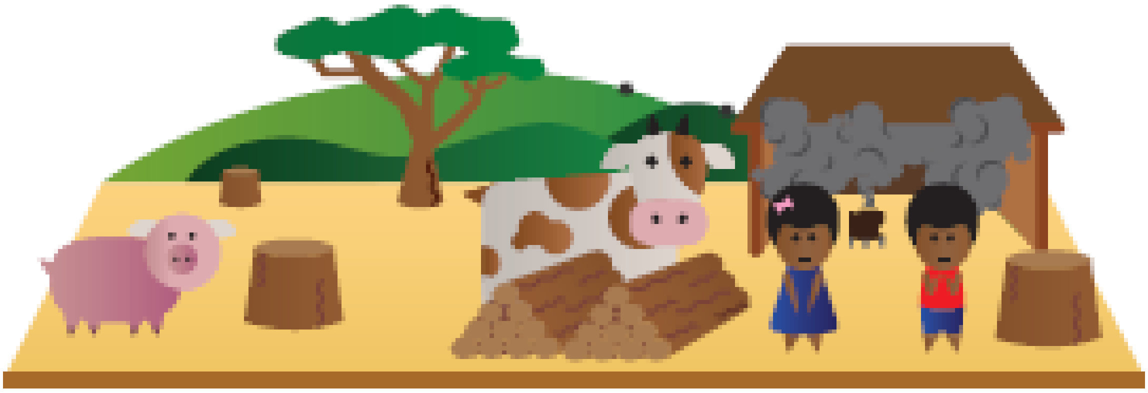
Ebikudumu ebisigala mu ttogero omukenenulirwa bayogaasi bisobola okukozesebwa ng'ebigimusa ebirungi ddala mu kulima ebibala n'ebimera, kino kiba kiyamba ku kwongera ku bungi bwe bikungulibwa mu kulima.

Enziro mu bbanga n'obukalu bw'ennimiro ebiva mu kufumbira ku kyooto eky'amanda oba enku

Mu kifaananyi olaba obulungi bw'embeera y'awaka obuva mu kufumbisa bayogaasi

Emiganyulo – Obuyonjo

Okufumbisa bayogaasi kitumbula obuyonjo bw'awaka kubanga empitambi y'abantu n'ebisolo eba ekunganyizibwa n'etekebwa mu ttogero ne mukolebwamu omukka ogufumba, kino kiyamba okulongoosa obutonde bw'ensi n'okukendeeza obuzibu obuva mu kusaasaanya obuwuka obubi n'endwadde.



Wano olaba embeera embi eyeetooloodde okufumbira ku kyooto eky'amanda oba enku

Mu kifaananyi olaba abantu nga beetooloddwa embeera ennungi olw'okufumbisa bayogaasi

Emiganyulo – Mukwano Gwa Butonde Bwa Nsi

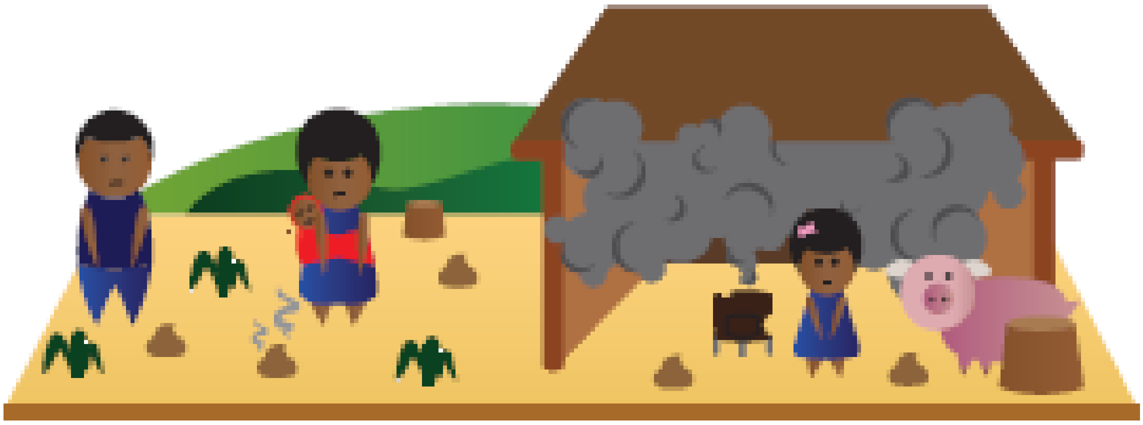
Okufumbisa bayogaasi kitegeeza kukendeera kwa byetaagisa okufumba, kino kitegeeza nti emiti tegyetaaga kutemebwa n'akamu, ekiyamba okutumbula n'okukuuma embeera y'obutonde bw'ensi.

Wano olaba enziro n'okutemebwa kw'emiti nga kiva ku kufumbira ku kyooto eky'amanda oba enku

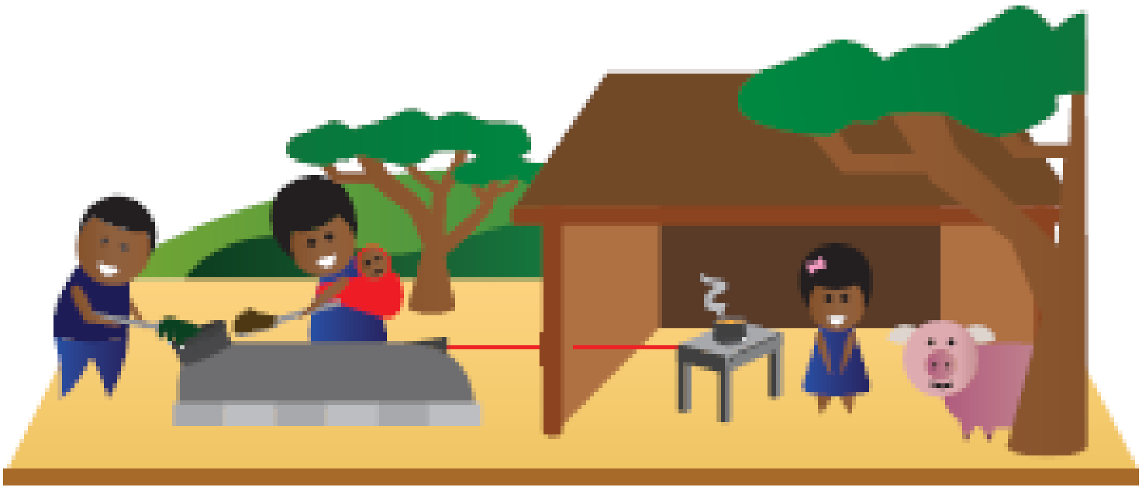
Wano mu kifaananyi olaba obutonde obweyagaza obuva mu kufumbisa bayogaasi

Emiganyulo – Obwangu

Ettogero bwe liba liteekebwamu ebyetaagisa buli kiseera, bayogaasi avaamu akwanguyiza okufumba mu bwangu ddala, kino kitegeeza nti kitwala obudde butono ddala okunoonya ebifumbisibwa.



Wano mu kifaananyi olaba abo bwe bakabasana nga batema emiti n'okusomba enku basobole okufumbira ku kyooto eky'amanda oba enku.



Mu kifaananyi olaba abo ab'awaka bo tebatawaana okujjako okuteekaako obuteesi bayogaasi ne bafumba bye baagala.

Appendix G – Information sheets translated into Swahili

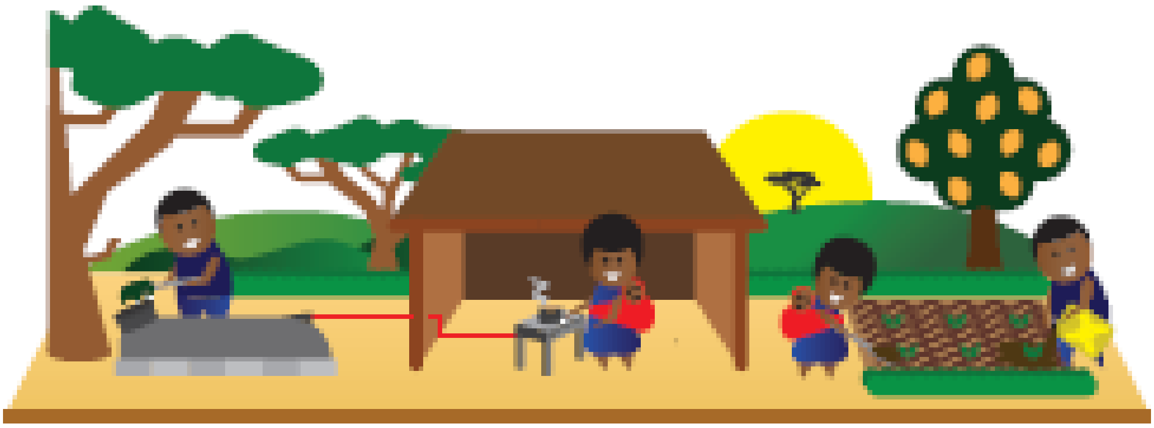
DIGESTERS

Developing Innovative Green Energy
Systems to Enhance Rural Sustainability

UKaid
from the British people

Jinsi Gesi Asilia Inavyofanya Kazi

Gesi asilia huzalishwa kutoka katika uwozo wa matamahuluku kama vile kinyesi cha wanyama, kinyesi cha binadamu na mimea iliyokufa. kuna faida nyingi za kutumia gesi asilia, ambayo hulfanya iwe zaidi ya matumizi ya mkaa na kuni na majiko ya kupikia. Gesi asilia pia inawezakutumika kwa kuzalisha na kuwasha umeme.



Mimea yenye unyevu iliyokufa, kinyesicha wanyama na binadamu vinawekwakwenye kimeng'enyo cha gesi asilia, ambapo vinavunjwa na kuwa gesi.

Gesi hii inapitishwa kwenyemrija uliounganishwa na jikoambapo hutumika kama mafutasafi ya kupikia, salama na haraka.

Mabaki kutoka katikakimeng'enyo yanaweza tumikakama mbolea bora na asiliakwa mazao na mimea au ufugaji wa samaki na mimea ya majini.

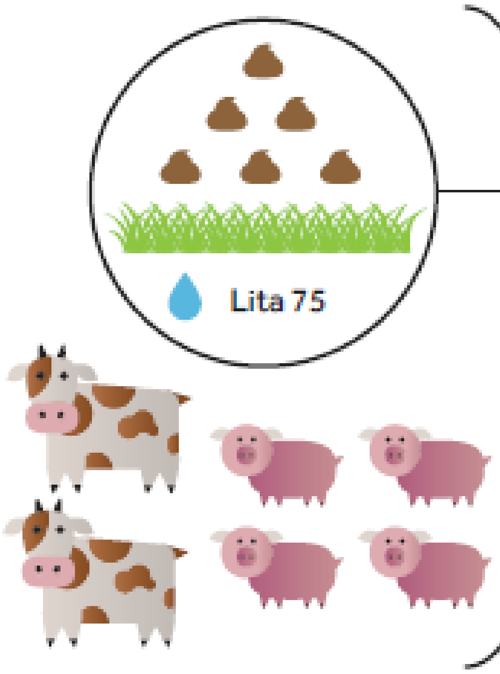
Vitu Visivyopaswa Kuwekwa Ndani Ya Kimeng'enyo

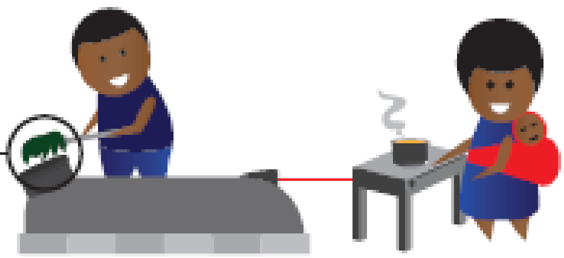
Ili gesi asilia iweza fanya kazi vyema, ni muhimu kuiweka kwa usahihi) Matamahaluku na maji hupaswa kuwekwa katika kimeng'enyo kila sikusiweke taka kama plastiki na glasi katika kimengenyo.

Vitu vinavyoweza kuwekwa ndani ya kimengenyo

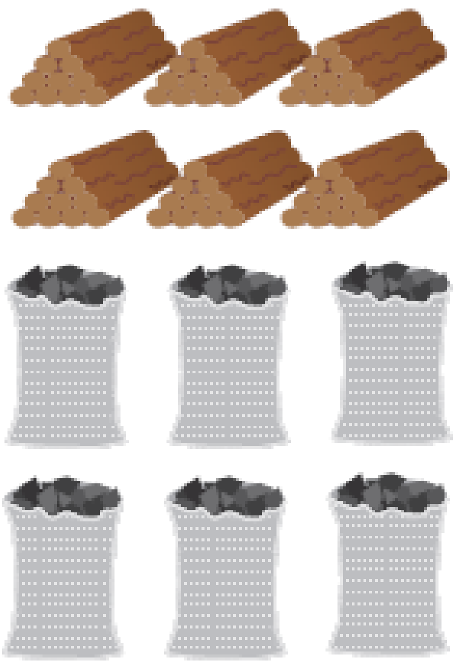
Jinsi Yakut Unza Kimeng'enyo

Gesi asilia hufanya kazi kwa ufasaha ikitunzwa vyema.
Okusobola okuguganyulwamu ennyo; goberera bino wammanga.
Ili iweze kuwa bora zaidi maelezo yafuatayo yafuatwe.





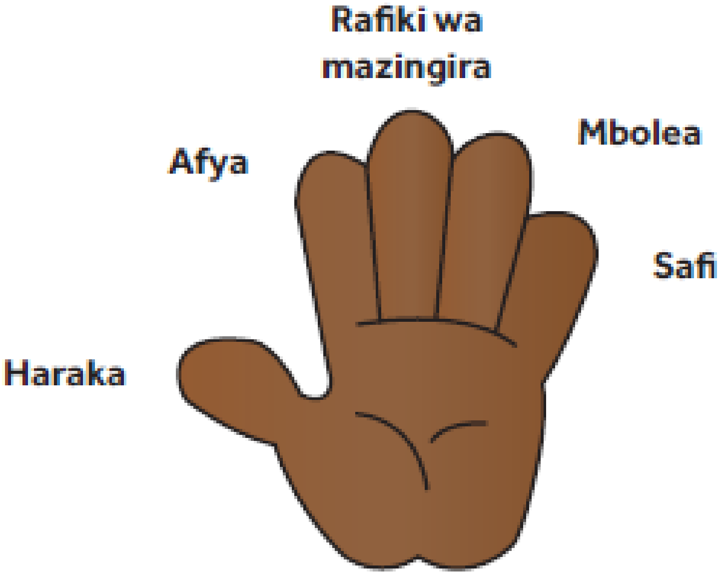
Mafuta ya kupikia kwa masaa 3-5 kwa siku, kimeng'enyo kinahitaji kinyesi cha wanyama cha ng'ombe wawili aunguruwe wanne mpaka nane, mimea iliyokufa, mabakiya chakula na lita 75 za maji.



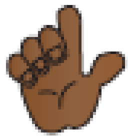
Mafuta ya kupikia kwa masaa 3-5 kwa siku, jiko asiliahutumia mkaa mwingi na kuni nyingi. Ni gharama sanana huchukua muda mwingi. Moshi utokanao na matumiziya kuni ni hatari sana kwa afya na mazingira.

Faida za Gesi Asilia

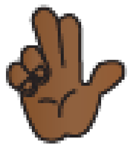
Kuna faida kuu 5 za kutumia gesi asilia kuliko njia nyingine za kupikia za kitamaduni



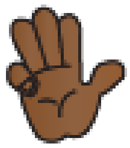
Haraka
Gesi asilia inaweza kuwashwa kwa mara moja.na haupotezi muda kuokota kuni na kuwasha moto.



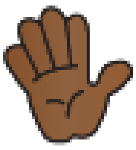
Hulinda Afya
Moshi utokanao na mkaa na jiko la kuni una madhara. Gesi asilia hutoa moshi kidogo sana.



Rafiki wa mazingira
Gesi asilia haihitaji ukataji wa miti ili kupata kuni.



Mbolea
Huitaji kununua mkaa au kuni unapopikia gesi asilia. kile unachohitaji ni samadi na kinyesi cha binadamu, mimea iliyokufa na maji.



Ni safi
Husaidia kusafisha kinyesi cha wanyama na binadamuna hivyo kuzuia maambukizo ya magonjwa.

Faida - Haraka

Napowekwa mara kwa mara, gesi asilia huzalisha mafuta ya kupikia kwa mara moja. Hii humaanisha muda mfupi hutumika ku kusanya mafuta.

Kupika kwa kutumia mkaa/jiko la kuni

Kupika kwa kutumia jiko la gesi asilia

Faida - Afya

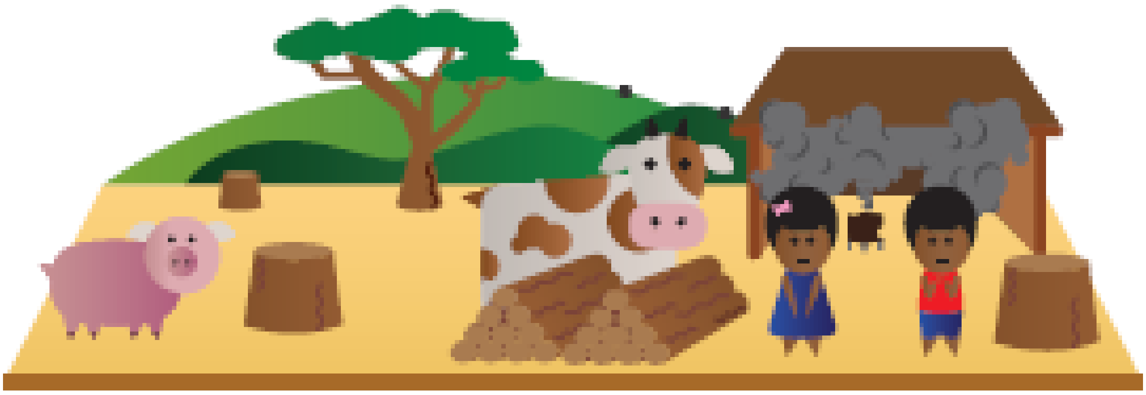
Kupika kwa kutumia gesi asilia huzalisha hewa chafu kidogo ndani ya nyumba. Hii hupunguza hatari ya magonjwa mengi kama kikohozi, macho, magonjwa ya moyo, pumu na hata kifo

Kupika kwa kutumia mkaa/jiko la kuni

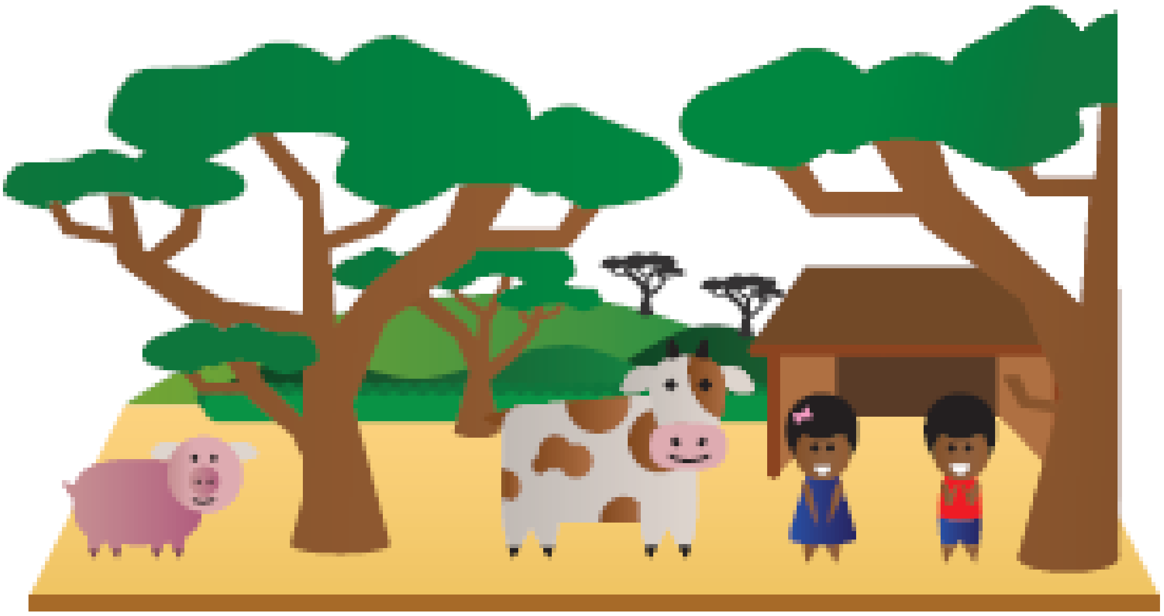
Kupika kwa kutumia jiko la gesi asilia

Faida - Rafiki Wa Mzingira

Kupika kwa kutumia gesi asilia hutumia mafuta kidogo. Hii inamaana kwamba miti haikatwi kwa matumiziya kuni. Hii husaidia kuweka mzingira asilia na endelevu.



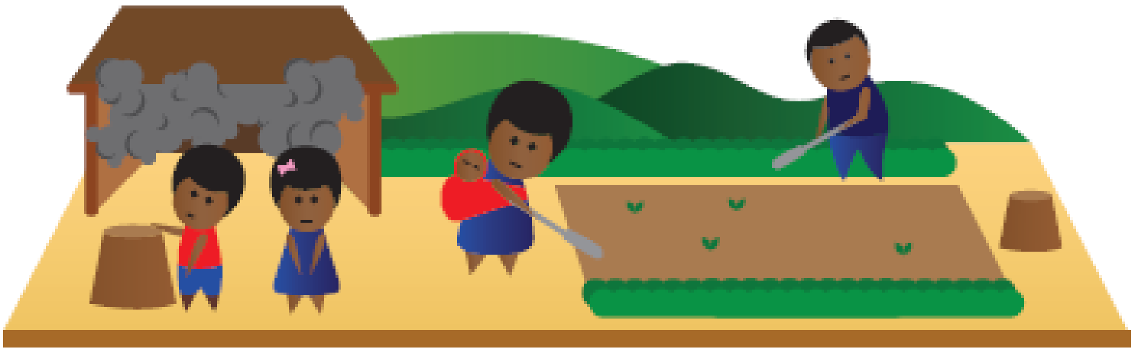
Kupika kwa kutumia mkaa/jiko la kuni



Kupika kwa kutumia jiko la gesi asilia

Faida - Mbolea

Mabaki ya gesi asilia katika kimeng'enyo yanaweza kutumika kama mbolea nzuri kwa mazao na mimea.Hii itasaaidia kuongeza uzalishaji katika kilimo

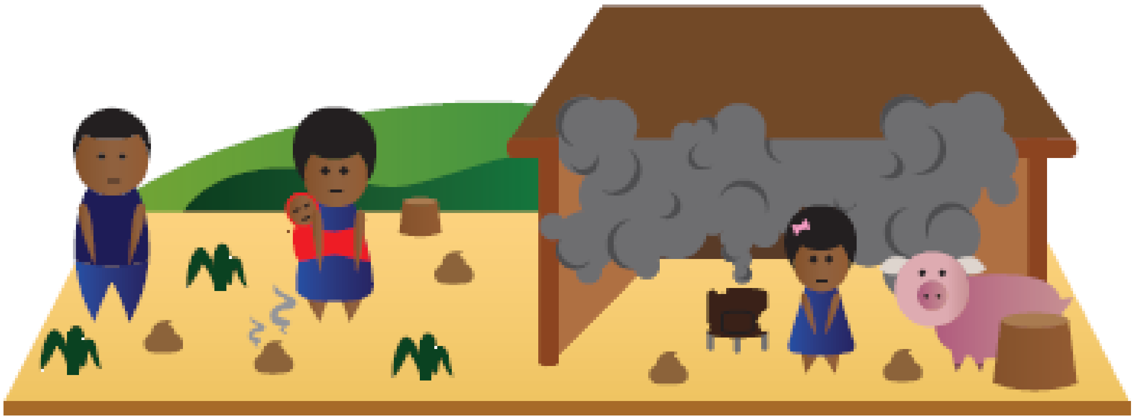


Kupika kwa kutumia mkaa/jiko la kuni

Kupika kwa kutumia jiko la gesi asilia

Faida - Usafi

Kupika kwa kutumia gesi asilia huboresha usafi kwa sababu samadi na kinyesi cha binadamuhuweza kuwekwa katika kimeng'enyo ili kuzalisha gesi. Hii husaidia kuweka mazingira safi nakupunguza hatari ya magonjwa na vijidudu ambukizi



Kupika kwa kutumia mkaa/jiko la kuni

Kupika kwa kutumia jiko la gesi

Appendix H – Media coverage

http://www.abdn.ac.uk/sustainable-international-development/research/networks/digesters-p/the-digesters-project/

The potential of small-scale biogas digesters to improve livelihoods and long term sustainability of ecosystem services in sub-Saharan Africa

The project is working with households in Tiribogo village in Mpigi District, about 40km north-west of Kampala, to study the use of flexible-balloon biogas digesters. This is a simple technology that enables the use of human, animal and food waste material to produce both a reliable supply of methane gas for cooking and a valuable bio-slurry that can be applied to crops to increase yields.

Biogas digesters have proven to be successful in other areas of the world including China and India, where more than 40 million have been installed. The uptake of the technology in Africa has been considerably slower.

The DIGESTERS team hope to examine potential barriers that may exist and look for ways to overcome these. Dr. Jo Smith, Professor Liz Baggs, Dr. Nick Morley, along with colleagues from the Makerere University, Green Heat Uganda and the James Hutton Institute will explore the impact of these systems on soil nutrients within and around Tiribogo village and how this may help improve the productivity of the land and increase food production.

Work by Dr. Norval Strachan of the College of Physical Sciences and Dr. Lisa Avery from the James Hutton Institute will focus on the changes on microbial exposures due to the need to transfer animal manures to the digester. This work will also look at how the digester removes potential pathogenic organisms from the village environment and may produce health benefits in terms of reductions in incidence of diarrhoeal disease.

Cooking with biogas is likely to produce much lower levels of smoke within the home and Dr. Sean Semple and Dr. Andrew Apsley of the Respiratory Group will measure concentrations of fine particulate matter and CO both before and after the homes install the digesters. This element of the study will also estimate the potential reductions in health problems including pneumonia and obstructive lung disease that are common in Africa as a direct result of exposure to smoke and cooking fuels in homes.

Socio-economic factors affecting uptake of biogas digesters in Africa will be examined by a team led by Dr. Jonny Mugisha and Dr. Peter Walekhwa from Makerere University, along with Dr. Bedru Balana from the James Hutton Institute and Dr. Klaus Glenk from the Scottish Agricultural College. This research will provide socio-economic analyses, explore costs/benefits and willingness to pay. Measurements of resource flows will provide a basis for the full economic value of flexible-balloon biogas digesters to households to be quantified.

Press release

UNIVERSITY OF ABERDEEN

November 15, 2012

Where there's muck there's gas

Aberdeen scientists are investigating the potential of a renewable energy source that uses organic waste to generate a fuel called biogas to see if it can help communities in sub-Saharan Africa.

The University of Aberdeen and The James Hutton Institute are collaborating on a project using the technology, which has also featured in a storyline in Radio 4's long running serial The Archers.

The Department for International Development is funding the work which involves looking at ways biogas digesters could help livelihoods and the environment in Uganda.

Digesters work very like the digestive process of a cow – they generate biogas as they decompose organic material such as human and animal waste and dead plants.

The captured biogas can then be used for 'cleaner and greener' cooking and lighting - cooking in Sub-Saharan Africa is often done in an enclosed space without good ventilation, resulting in a smoky atmosphere which is very harmful to human health.

Leftover slurry produced by the digester can also be used to fertilise land and in aquaculture.

Nine digesters are being installed in a village in Tiribogo near Kampala, Uganda, which is very close to a forest undergoing rapid deforestation.

Dr Jo Smith, Reader in Soil Organic Matter and Nutrient Modelling at the University of Aberdeen, is leading the work. She said: "The aim of this project is to determine the potential of the cheapest design of biogas digester.

"We want to see what changes are needed in farmers' attitudes and in the design of farming systems in order for these devices to be used.

"We also want to assess the value of biogas digesters in terms of energy, organic fertiliser, reduction in deforestation, improved sanitation, improved household air quality and reduced labour."

Grant Davidson, International Development Co-ordinator at the Hutton Institute, added: "Greater use of biogas at the household level can have wider environmental benefits too, as it means there is no need to cut down trees or spend time collecting firewood for cooking.

Dr Smith added: "Biogas digesters have really taken off in Asia but that is not the case in many Africa countries. This project will provide evidence that hopefully starts to reverse this trend, leading to greater use of this cheap, sustainable and clean energy across Africa. "

*Biogas was the talk of Ambridge and beyond when David and Ruth hoped to build a digester on their land to make biogas from farm waste.

ENDS

Notes to Editors/ Picture Editors:
Dr Jo Smith is available for interview. Pictures are also available of the biogas digestors being used in Tiribogo. To arrange, contact Jennifer Phillips on 01224 273174.

Issued by the Communications Team, Office of External Affairs, University of Aberdeen, King's College, Regent Walk. Tel: 01224 273174.

Interviews given and articles in press

Date	Organisation	Comments
15/11/2012	106 Original	Broadcast 16/11/12
16/11/2012	North Sound	Broadcast 19/11/12
16/11/2012	Scotnews	will@swns.com
16/11/2012	Daily Record	
16/11/2012	Press & Journal	
16/11/2012	The Scottish Sun	
17/11/2012	The Evening Express	
19/11/2012	The Telegraph	
17/01/2013	UBC TV – Uganda (E.Sabiiti & S.Semiyaga)	
06/03/2013	Daily Monitor Newspaper – Uganda (Magazine: "Seeds of Gold")	

NOTE – REPORTS REPRODUCED BELOW ARE NOT ENTIRELY FACTUALLY CORRECT AND ARE NOT THE OPINION OF THE PROJECT TEAM

Daily Record

Section: News
Edition: 01
Date: 16 November 2012
Page: 24
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Source: ABC Jul 2012

GAS PUMPS

Our mechanical cows are a real blast

▲ **MOO** A real cow

SCOTS scientists are to test mechanical cows designed to "break wind" to power stoves in Africa.

Researchers at Aberdeen University say the "digesters" work like a cow's intestine – generating biogas from plants and animal waste.

The nine machines are being installed in a village in

By Tim Bugler
reporters@dailyrecord.co.uk

Uganda, where local women will use the captured gas for "cleaner and greener" cooking and lighting.

Project leader Dr Jo Smith said: "Cooking in sub-Saharan Africa is often done in an enclosed space without good ventilation, resulting in a smoky atmosphere harmful to human health. This project will hopefully lead to greater use of cheap, sustainable and clean energy across Africa."

Grant Davidson, of research foundation the James Hutton Institute, added: "Greater use of biogas at household level has wider environmental benefits as it means there is no need to cut down trees or spend time collecting firewood for cooking."

Press and Journal
The Voice of the North

Section: News
Edition: Highlands & Islands **Circulation:** 67781
Date: 16 November 2012 **Source:** ABC Jan 2012
Page: 17

'Cows' heat things up in Africa

SCIENCE

BY JESSICA MURPHY

Scottish academics are to test nine mechanical cows which have been designed to "break wind".

The researchers at Aberdeen University hope the resulting gases could be used to power stoves in sub-Saharan Africa.

The machines, called digesters, mimic the internal workings of a cow – generating biogas as they decompose organic material such as dead plants and animal waste.

Leftover slurry can also be used to fertilise land and in aquaculture.

The nine machines – which do not physically resemble the animals – are being installed in a village near Kampala, Uganda, where women will use the biogas in their homes.

At present they follow the example of many people in sub-Saharan Africa – cooking in enclosed spaces without good ventilation, resulting in a smoky atmosphere which is very harmful to human health.

Project leader Dr Jo Smith, reader in Soil Organic Matter at Aberdeen University, said: "The aim of this project is to determine the potential of the cheapest design of biogas digester. Biogas digesters have taken off in Asia but that is not the case in many African countries. This project will provide evidence that hopefully starts to reverse this trend, leading to greater use of this cheap, sustainable and clean energy across Africa."

Grant Davidson, international development co-ordinator at the Hutton Institute, which is collaborating with the university, said: "Greater use of biogas at the household level can have wider environmental benefits too, as it means there is no need to cut down trees or spend time collecting firewood for cooking."

THE SCOTTISH Sun

Section: News
Edition: 01 **Circulation:** 1528561
Date: 16 November 2012 **Source:** ABC Jun 2012
Page: 23

Cook on 'cow gas'

SCIENTISTS are testing mechanical cows made to produce gas to power stoves in African homes – by breaking wind.

Experts at Aberdeen University reckon the machines work like the animals' digestive systems by breaking down waste to produce biogas.

They will provide energy for villagers near Kampala, Uganda.

Project leader Dr Jo Smith said: "We want to see what changes are needed for these devices to be used."

Evening Express (City Final), 17 Nov 2012

Cow project could cut biogas costs

FLATULENT robot cows could help provide cheaper power to homes in an African village.

Researchers at the University of Aberdeen are to test nine mechanical cows which have been designed to imitate the animal's digestive cycle.

The units generate biogas as they decompose organic material, such as dead plants and animal waste.

Project leader Dr Jo Smith said: "The aim is to determine the potential of the cheapest design of biogas digester."

If successful the machines will be installed in a village in Uganda.

The Telegraph

Monday 19 November 2012

Prince Charles takes on energy giants with biogas plant
By Richard Gray, Science Correspondent

"…Researchers at the University of Aberdeen are among a number who are now attempting to find ways of reducing the cost of building biogas plants that use anaerobic digestion…."

Where there's muck, there's gas for scientists in the north-east

By Neil Drysdale 17 November 2012 06:30 GMT

Wholly cow: Aberdeen scientists are helping turn cow waste into a green fuel source. Aberdeen University

North-east scientists are investigating the potential of a renewable energy source, which uses organic waste to generate a fuel called biogas.

Aberdeen University and the James Hutton Institute are collaborating on the project, using the technology, which has also featured in the long-running radio serial The Archers.

The Department for International Development is funding the work, which is designed to create biogas digesters and help communities living in parts of Africa, including Uganda.

The new fuel works on similar lines to the digestive process of a cow - they generate biogas as they decompose organic material, such as human and animal waste and dead plants.

The captured fuel can then be used for cleaner and greener cooking and lighting, which should improve living conditions for many people in the sub-Saharan parts of Africa.

And nothing is put to waste - any leftover slurry which is produced by the digester can subsequently be used to fertilise land and in aquaculture.

Dr Jo Smith, a Reader in Soil Organic Matter at Aberdeen University, is leading the work.

She said: "The aim of this project is to determine the potential of the cheapest design of biogas digester. We want see see what changes are needed in farmers' attitudes.

"We also want to assess the value of biogas digesters in terms of energy, organic fertiliser, reduction in deforestation, improved sanitation and improved household air quality."

Nine digesters are being installed in a village in Tiribogo, near Kampala, Uganda, which is very close to a forest which is undergoing rapid deforestation.

Cow flatulence has previously been blamed for helping destroy the ozone layer. Now, they might be the inspiration for turning the brown stuff into green gold.

Daily Monitor

SEEDS OF GOLD

Smarter farming for bumper harvest.

LAND PROJECT TO BENEFIT FARMERS> Pg

Biogas digester: A source of energy and fertiliser

The technology makes use of farm waste to make energy and the residue to nourish the crops

BY ESTHER OLUKA

On many farm, there is an abundant source of energy from farming and domestic activities like animal droppings, dead plant material and human waste that can be used to generate biogas, which is released from the decomposition of such organic matter in the absence of oxygen.

Biogas can be produced from cow dung, goat and chicken droppings or harvest leftovers from the gardens or postharvest activities such as coffee or rice husks or maize stover. Besides methane being the main component, there are some amounts of carbon dioxide and smaller quantities of other gases—hydrogen, hydrogen sulphide and nitrogen—and other substances.

Simple process

Since methane, hydrogen and carbon monoxide can be combusted, biogas can be used as a fuel for heating or cooking and it can be used to power machines. But the process of making biogas has to happen within what is known as a digester.

Swaib Semiyaga, a teaching assistant at the Department of Civil and Environmental Engineering, Makerere University, states that the process of making the gas is a simple process. "For instance, if cow dung is used, mix it with water, which acts as the catalyst, and then feed the mixture into a digester," he says.

A digester is a specially constructed container for storing the matter to rot and release the gas or softened, often for further processing.

The common types used include the floating dome digester also known as Gobar Gas Digester, which is mainly made of bricks and mortars, and the Puxin Digester, which is made up of a gas storage bag as well as a gas pump. There are various types of digesters based on different principles depending on the use for which they are designed. The similarity between different types is that they have an inlet where the matter is fed in and an outlet for the gas.

Helpful

Semiyaga points out that digesters are usually filled up halfway because the gas emitted occupies the remaining space.

Lauren Harvell, a researcher at the Centre for Research in Energy and Energy Conservation (CREEC), says biogas can serve a number of purposes on the farm. For instance, it can be used as a fuel to operate machinery such as generators for electricity or mills to process produce.

This is helpful in cutting costs on the side of the farmer. "It is cheaper when used as electricity since the particular farmer gets it directly from his farm," she says.

Other benefits

The farmer can extract other benefits from the slurry (organic residue that remains after the emission of biogas). "It is a very good source of manure," says Peter Walakira, lecturer at College of Agricultural and Environmental Sciences, Makerere University.

The slurry contains significant quantities of nutrients such as sodium, potassium and phosphate which help in soil fertility. Compared to raw manure, slurry has more nutrients. It is more environmentally friendly and less costly than chemical fertilisers.

Also, the nitrogen present in cattle dung is conserved when processed through a biogas digester, yet in open-pit composting, some of the nitrogen may be lost due to evaporation.

With biogas, farmers will incur fewer expenses and yield more through the use of biogas and its residue on their farms.

COST OF DIGESTER

[illegible]

[illegible]

Swaib Semiyaga
Makerere University

...Winston Churchill described Kampala ... visible" for being concealed by the "... innumerable banana plantations". Today ... moved beyond Kampala's concrete jung... only bananas you see will be ones tra... from western Uganda.

So, where did the banana plantations ... During a recent farmers' networking eve... I bumped into a veteran banana farmer ... explained where the bananas Churchill s... went, and why western Uganda will soo... as bananas. According to him, since the... troduction many centuries ago, bananas ... been migrating from one area to another...

Moving on

By the time Churchill visited, Kyadondo, one of the counties of Buganda Kingdom ... the main banana producer. The rich soils ... the heavy rainfall were perfect. With tim... however, the soils were exhausted and th... bananas migrated to Buganda, which wa... virgin.

The legend goes that the people of Bug... were obliged to send bananas to the Kab... court. But although they produced the be... they sent the smallest bunches, which we... easier to carry.

Like it happened in Kyadondo, the soils ... were exhausted and the banana moved ... Buddu, better known as Masaka, from wh... moved further west to Mbarara and Bush...

Besides being delicious, the banana is packed with lots of nutrients – it is natur... power bar.

Replace nutrients

As long as the soils where it is grown sti... have all the necessary nutrients, the bana... will thrive. But once the nutrients run out,...

Bananas thrive where there are nutrients and fe...

TRUTH EVERYDAY

Daily Monitor

Jan, 2013

http://www.monitor.co.ug/Magazines/Farming/Biogas-Digester--A-source-of-energy-and-fertiliser/-/689860/1713328/-/gwmdnaz/-/index.html

Biogas Digester: A source of energy and fertiliser

A biogas digester: Because the gas is produced where there is no oxygen, it has to be airtight. Internet Photo.

IN SUMMARY

The technology makes use of farm waste to make energy and the residue to nourish the crops.

On any farm, there is an abundant source of energy from farming and domestic activities like animal droppings, dead plant material and human waste that can be used to generate biogas, which is released from the decomposition of such organic matter in the absence of oxygen.

Biogas can be produced from cow dung, goat and chicken droppings or harvest leftovers from the gardens or postharvest activities such as coffee or rice husks or maize stover. Besides methane being the main component, there are some amounts of carbon dioxide and smaller quantities of other gases—hydrogen, hydrogen sulphide and nitrogen—and other substances.

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Since methane, hydrogen, and carbon monoxide can be combusted, biogas can be used as a fuel for heating or cooking and it can be used to power machines. But the process of making biogas has to happen within what is known as a digester.

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A digester is a specially constructed container for storing the matter to rot and release the gas or softened, often for further processing.

The common types used include the floating dome digester also known as Gobar Gas Digester, which is mainly made of bricks and mortars, and the Puxin Digester, which is made up of a gas storage bag as well as a gas pump. There are various types of digesters based on different principles depending on the use for which they are designed. The similarity between different types is that they have an inlet where the matter is fed in and an outlet for the gas.

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Other benefits

The farmer can extract other benefits from the slurry (organic residue that remains after the emission of biogas). “It is a very good source of manure,” says Peter Walekhwa, lecturer at College of Agricultural and Environmental Sciences, Makerere University.

The slurry contains significant quantities of nutrients such as sodium, potassium and phosphate which help in soil fertility. Compared to raw manure, slurry has more nutrients. It is more environmentally friendly and less costly than chemical fertilisers.

Also, the nitrogen present in cattle dung is conserved when processed through a biogas digester, yet in open-pit composing, some of the nitrogen may be lost due to evaporation.

With biogas, farmers will incur fewer expenses and yield more through the use of biogas and its residue on their farms.

editorial@ug.nationmedia.com

TRUTH EVERYDAY

Daily Monitor

Wednesday May 1, 2013

http://www.monitor.co.ug/Magazines/Farming/Three-farmers--experiences-with-putting-farm-waste-to-good-use/-/689860/1801724/-/item/0/-/davlmoz/-/index.html

Three farmers' experiences with putting farm waste to good use

Karoli Kamuli uses the waste from his cattle to make biogas for cooking

IN SUMMARY

Cow dung is a common sight at farms and is treated as waste. But as Esther Oluka found from these two farmers, it can be a lot more useful to produce fuel for domestic activities such as cooking and to make fertiliser for crops

My name is Kalori Kimuli, a farmer in Kiziiko, Tirobigo, in Mpigi District, who rears several domestic animals such as cattle, goats, sheep, chicken and pigs. I have been doing this for the past ten years. Right now, I have five sheep, eight pigs, 10 goats, 15 cows and 30 chicken.

Besides rearing animals, I grow bananas on a two-acre piece of land. But much as I earn profits from these

different activities, the money made is not enough to look after my family. I have a wife and three young children aged 16, 11 and nine.
For instance, out of all the domestic animals, the cows, goats and chicken are the most rewarding since they are a constant source of milk and eggs. I sell both cows' and goats' milk on a daily basis at a price of Shs600 per litre to my village mates.

Helpful

For the eggs, I do sell them weekly at a price of Shs200 each. I also sell each layer between Shs15,000 and Shs20,000. The broilers are from Shs16,000 to Shs18,000.However, the pigs are not as rewarding as the other animals since these do not give me milk or eggs.
I just have to sell the whole animal in order to get money. The piglets cost more than Shs 20,000 depending on the size one wants. I sell them on an annual basis. That is the only time I make money from them.

There are harvests from my banana plantations occasionally. When they get mature, the price for each bunch ranges between Shs 20,000 and Shs 30,000. I used to rely on fertilisers from shops to use in the banana plantations. However, this changed in January last year when I was approached by some people from the Department for International Development.

They sold me the idea of purchasing a PVC bio-digester. When I asked them what purpose it would serve, they replied that it would help me generate biogas, which is helpful as fuel for cooking as well as slurry for manure. Then, I asked them where I could find this PVC bio-digester. They said they were going to give it to me free of charge.

A few weeks later, they came back, dug a wide hole, about two feet onto the ground and placed it there. Before leaving, they instructed me how to operate it. Every morning, I gather dung from the cows. Though I do not use wastes from the chicken, pigs, goats and sheep since theirs are produced in smaller quantities.

I also collect dung from some of the cows in the neighbourhood as well. I do the dung collection for about a week. Then I put everything in a big water drum. Each day tafter the collection, I add a bit of water so that the content remains soluble.

During the first day of the second week, I mix up everything until the solution becomes "porridge-like". After this, I feed the manure onto the digester five times. I do the measurements using a 20-litre jerry can. Afterwards, I leave the mixture settle for 21 days.
After this period, the gas will have been formed in the digester. It travels through a pipe up to an outlet that is found in the kitchen. This outlet is connected to a stove that I use for cooking in the kitchen. I was using firewood for cooking before but not anymore.

The gas lasts for more than two weeks, generally depending on how one uses it. When the gas gets finished, the slurry is what remains behind inside the digester. It is what I use to fertilise the soil in my banana plantation. I noticed a huge difference with this kind of manure compared to the fertilisers I used to buy.

Saving costs

For instance, I noticed that the manure makes the banana plant grow at a somewhat faster rate hence making it mature faster. The banana fingers are also quite bigger in size and the plant is not easily affected by various diseases. On the other hand, it is also cheaper since one can easily obtain it from the backyard of their homes.

This is unlikely with the other fertilisers, which are expensive and I could only buy them when I had the money. Otherwise, I am so happy that the bio digester idea was sold to me. It has really helped me save a lot of money since I no longer spend on firewood and fertilisers.

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I sell manure to supplement my income

I am called Jane Nakawuki, 36 years, a peasant farmer in Kiziiko, Tirobigo, Mpigi and I earn a living by selling milk on a daily basis from my 30 cows. The price of a cup is Shs500. On average, I can get about Shs30,000 in profits in a day. However, this money has not always been enough to provide for me and my six children.

I was always looking for a way to supplement this income with another income-generating enterprise. I eventually settled on one in 2011. I received a bio digester (which is known as a flexible balloon bio-digester) from some generous people, who said that they were from the Department for International Development, in the UK.

Besides me, they were other people in the village who were given bio digesters as well. I do not remember how many they were though. But it was part of a project in this area.
They told me that it could emit biogas, which is very helpful for cooking. Therefore, I did not have to rely on using firewood or charcoal for cooking anymore. Also, they went ahead to tell me that the residue known as the sludge or slurry that remains after the gas is finished from the digester can be used as a fertiliser in a garden.

When I told them that I did not have plantation where to apply the sludge, they proposed that instead I sell it instead in order to make extra money. That is what I decided to do then.
I sell the sludge, measuring it in a five-litre jerry can. Each is at Shs1,000. I make the sales every fortnight. On average, I can make about Shs 20,000. This is the money I supplement onto that earned from milk sales.

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Expert take: Formation of slurry and its benefits

Swaib Semiyaga, an environmental public health engineer and a teaching assistant, Department of Civil and Environmental Engineering, Makerere University explains that slurry is produced from the biogas units during anaerobic digestion of organic matter.

It is a valuable organic fertiliser that can be applied directly to the fields or mixed with other organic material to improve crop yields. Semiyaga points out the following outstanding benefits of using slurry as a fertiliser:

• If applied for over a long period of time, it increases activities of micro-organism in the soil, improves the soil aeration, makes the soil softer hence reducing its hardness, slurry enhances water holding ability, therefore reducing erosion caused by wind and water.

• It gives a higher chance for crops to yield faster compared to other ordinary fertilisers. This because the liquid form substance contains water (more than 90 per cent), which may not be contained in other fertilisers. So, applying it even in periods of low or no rainfall can supply additional water to crops, which is also needed for plant growth.

• Applying slurry can reduce 30 per cent to 100 per cent development of insects and diseases. If 10 per cent of pesticide in volume was mixed into slurry,, efficiency of the pesticide would increase.

-Esther Oluka