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Review

Small-Scale Biogas digester for Sustainable Energy production in Sub-Saharan Africa

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Abstract: Interest in the use of small scale biogas digesters for household energy generation and treatment and utilization of organic wastes in rural areas of Sub-Saharan Africa (SSA) has been increasing with numerous organisations promoting their adoption for both socioeconomic and environmental benefits. In this paper, we review energy production using small scale biogas digesters in SSA, a technology that is already improving the lives of poor people in many parts of the developing world, but has to-date had only limited uptake in Africa. Small-scale biogas digesters have great potential to contribute to sustainable development by providing a wide variety of socioeconomic benefits, including diversification of energy (cooking fuel) supply, enhanced regional and rural development opportunities, and creation of a domestic industry and employment opportunities. Potential environmental benefits include reduction of local pollutants, reduced deforestation due to logging for fuel, and increased sequestration of carbon in soils amended with the digested organic waste. Ecosystem services that are potentially delivered through implementation of biogas digesters include carbon sequestration, improved water quality and increased food production. Carbon can be directly sequestered in the soil through application of soil organic matter originating from the digested material. Indirect carbon sequestration can also be achieved through reduced carbon losses due to logging as household fuel is replaced by methane produced by the digester. Replacement of household fuel by biogas has added benefits to household air quality. Water quality can be improved through reduced runoff of waste material and reduced erosion of sandy soils due to stabilisation of the soil through increased input of organic matter. Food production can be improved by application to the soil of digested material containing readily available nutrients. The productivity of the soil can also be improved through improved soil structure and water holding capacity achieved by the organic amendments of digested material to the soil.

Keywords: Biogas, Sustainable energy production, Sub-Saharan Africa.

1. Introduction

Globally, 55% of the wood extracted from forests is for fuel, and fuel wood is responsible for 5% of global deforestation (UNFCC, 2010). Over 80% of Sub-Sahara Africa relies mainly on solid biomass, that is to say firewood, charcoal, agricultural byproducts and animal waste in order to meet basic needs

for cooking and lighting (Davidson et al, 2007; Brown, 2006). Firewood and charcoal account for 74% of the total energy consumption in Africa as compared to 37% in Asia and 25% in Latin America (Davidson, 1992). Although the developed world has replaced these highly polluting fuel sources with cleaner sources, such as liquefied petroleum gas and electricity, it is estimated that 50% of all households worldwide and 90% of all rural households continue to use biomass fuel as their main domestic source of energy (Bruce et al, 2000).

Sub-Saharan Africa is confronted with both commercial (petroleum products, natural gas, coal, and electricity) and biomass (firewood, charcoal, and agricultural by-products) energy crisis. Energy has been supplied in deficient amount, at a fee, form and quality that has restricted its consumption by the majority of the people in the SSA region, (World Energy Outlook, 2009; Parawira, 2009). The continent's energy utilization and demand is expected to continue to grow as development progresses at rates faster than those of developed countries, (Parawira, 2009). This gap will keep on widening, and the livelihood of people in the region will continue to be significantly impaired by energy poverty, therefore slowing down the socioeconomic development. The desire for improved quality of life and rises in population together with energy demands from the transport, industrial and domestic sectors will continue to drive this growth, (Parawira, 2009).

In most developing countries, for example, Bangladesh, Burundi, Bolivia, Ivory Coast, Tanzania and Thailand, biogas is produced through anaerobic digestion of human and animal excreta using the Chinese fixed-dome digester and the Indian floating cover biogas digester, (Omer and Fadalla, 2003). These plants were built for schools and small-scale farmers, in most cases by non-governmental organisations. Most of the plants have only operated for a short period due to poor technical quality. There is thus a need to introduce more efficient reactors to improve both the biogas yields and the reputation of the technology.

Lack of access to clean and efficient energy can impact household health in many ways. The most important direct health effects result from the air pollution caused by burning solid fuels, often indoors on open fires and simple stoves (WHO, 2006; Singh and Sooch, 2004). Globally, three billion people are exposed to biomass smoke in poorly ventilated rooms, making biomass smoke one of the most important sources of indoor air pollution globally (Barnes et al, 1994). Poor household air quality is linked to pneumonia, lung cancer and chronic lung disease. It is estimated that it leads to approximately 1.6 million premature deaths annually (Ezzati et al., 2004). It is linked to poverty, with poor people more likely than richer people to use fuels that result in poor household air quality (animal dung, crops, wood and charcoal). The challenges are overwhelming; a joint effort by all stakeholders is required to achieve considerable progress, (World Energy Outlook, 2009).

Biogas technology is an integrated waste management system (Verstraete et al., 2005) that is a clean, renewable, naturally produced and under-utilized source of energy. Biogas is produced in an air tight tank from a variety of substrates, such as animal manure, food waste, energy crops and industrial wastes. This is a multi-biological process where the organic waste is mainly converted to a gaseous product composed of 50-70% methane and 25-40% carbon dioxide and trace of hydrogen sulfide, water vapor and ammonia (Igoni, 2007; Angelidaki et al., 2003). The benefits to the household include diversification of energy supply, indoor air quality and health improvement, provision of an organic fertilizer with rich crop nutrients, enhanced regional and rural development opportunities, and creation of a domestic industry and employment opportunities (Rio and Burguillo, 2008; Vasudeo, 2005).

A range of socioeconomic factors influence uptake (Walekhwa et al, 2009). Possible negative impacts are the potential for pathogens harboured in the digester slurry to infect humans who handle it or eat crops fertilised by it (Yongabi et al, 2009; Brown, 2006), the use of scarce economic and material resources in installation of digesters (Amigun and von Blottnitz, 2009), the potential for water pollution through losses from faulty digesters or from runoff of undigested material that has been

applied to soils, and possible leakage of methane before complete combustion to CO₂, so increasing the global warming potential of the emitted gases (Rabezandrina, 1990).

Practical problems include prohibitive initial investment costs (Karekezi, 2002) and availability of materials for construction of digesters that will not leak materials or gases (Rabezandrina, 1990). Digesters must be designed to function efficiently in low rainfall conditions (Rabezandrina, 1990). The amount of biogas produced must be sufficient to meet the needs of the households, and this depends on the availability of feedstocks from human, animal and plant sourced organic wastes (Rabezandrina, 1990). The use of the fuel produced and the digested product should be socially acceptable to the rural community if digesters are to be adopted (Fox, 1993). Policy measures may be needed to encourage adoption, including training and capacity building programmes, flexible financing mechanisms and dissemination strategies (Karekezi, 2002; Greben and Oelofse, 2009).

The market oriented household scale biogas support programmes in China, India, Nepal and Vietnam have demonstrated the success of anaerobic digestion in Asia (Sanne, 2009). Biogas was introduced at different times in the various SSA countries that include Kenya (1950), Tanzania (1975), South Sudan (2001) and to date, biogas digesters have been installed in several sub-Saharan countries including Burundi, Botswana, Burkina Faso, Cote d'Ivoire, Ethiopia, Ghana, Guinea, Lesotho, Namibia, Nigeria, Rwanda, Zimbabwe, South Africa and Uganda (Renwick et al, 2007). Africa has not seen such propagation of domestic biogas.

The number of biogas installations across Africa is increasing, largely in the domestic energy sector, due to national domestic biogas programmes in Rwanda, Tanzania, Kenya, Uganda, Ethiopia, Cameroon, Benin and Burkina Faso, each with national targets of over 10,000 domestic systems to be installed from 2009 till 2013. In Africa compared to Asia, biogas technology dissemination has been relatively unsuccessful. Njoroge (2002) attributes the non-progressiveness of most biogas programmes to failure of African governments to support biogas technology through a focused energy policy, poor design and construction of digesters, wrong operation and lack of maintenance by users, poor dissemination strategies, lack of project monitoring and follow-ups by promoters, and poor ownership responsibility by users. Despite the relative stagnation of biogas programmes in Africa, the future prospects are encouraging. Aside energy (cooking and lighting, fuel replacement, shaft power), several biogas plants in recent years have been constructed as environmental pollution abatement system in several countries including Ghana, Kenya, Tanzania, Rwanda, Burundi, and South Africa (Amigun et al, 2007). Between 4000 –5000 digesters is estimated to have been built in Tanzania (Marree et al, 2007).

In this paper, we review the potential impact of biogas digesters in Sub-Saharan Africa on household energy, improved food production, improved indoor air quality, reduced deforestation, carbon sequestration in soil, erosion and soil degradation, sanitation, water reuse and recycling, reduction in odours and local job creation.

2. Potential of small scale biogas systems to improve livelihood in SSA

2.1. Biogas on poverty

Conventional approaches define poverty as “low income or low consumption”. Over recent decades poverty concepts have changed to include multiple dimensions of deprivation and wellbeing. “Attacking poverty” sets out a comprehensive assessment on understanding poverty and its causes. Poverty encompasses not only low income and consumption, but also low achievement in education, health, nutrition, and other areas of human development. Four major dimensions of poverty are included: 1. lack of opportunity (material deprivation); 2. lack of capability (low achievement in

education and health, malnutrition); 3. vulnerability (low level of security); 4. being voiceless and powerless.

While lack of opportunity and capability are well measured, vulnerability is not appropriately measured and being voiceless and powerless is not measured at all. Income or consumption poverty is measured by the World Bank using the “international poverty line”, based on consumption or income data from 96 countries. An income of \$1 / day is defined as low income, while \$2/day is defined as low to middle income. These levels are only useful as indicators of global progress as there are huge inter and intra country variations. The cost of basic needs approach, (Foster et al, 1985) aggregates a food and non-food poverty components, to provide indices for absolute poverty, poverty gaps, and the severity of poverty. A weighted poverty index based on multiple indicators of poverty, (Zeller et al, 2006) aggregates a range of quantitative and qualitative poverty indicators into a single poverty index. Examples of this are the Human Development Index (HDI) based on longevity, knowledge and a standard of living, (UNDP, 2010); and the HPI based on a short life, lack of basic education and lack of access to public and private resources, (UNDP, 2010). Another approach uses community ranking of households according to their wealth; this is a useful approach for identifying vulnerable groups within a community.

The benefits of biogas digesters can be expressed in terms of poverty indicators. If households spend less time in collecting wood and more time generating valuable income this increases the poverty indicator income. Switching to cleaner fuels can reduce health risks, so increasing the poverty indicator health and life expectancy. Spending less time collecting wood can allow more time for children’s education, so increasing the poverty indicator knowledge/education. Finally, the potential environmental improvements increase the poverty indicators productivity increase and income.

Two issues impact access to biogas technology: 1. technical potential and 2. economic potential. Heegde and Sonder (2007) suggest availability of dung and water to run a biogas installation are two basic requirements. For a biogas plant to be attractive to a household, it should be able to provide at least 0.8 to 1 m³ biogas daily. To generate this amount of biogas, the household should have 20 to 30 kg of fresh dung available on a daily basis. An African household would need at least 3 or 4 night-stabled cattle to achieve this. This requirement is met by a large percentage of households, especially in East Africa.

2.2. Household energy

Households in Sub-Saharan Africa rely mainly on biomass; firewood, charcoal and agricultural by-products to meet their energy needs (cooking and lighting) (IEA, 2003; Ekouevi, 2001). The consumption of firewood is the predominant source of biomass energy and represents the largest single source of energy for most families in SSA. Incomplete combustion of biomass fuels and poor ventilation, result in high indoor concentrations of health-damaging pollutants including particulate organic matter and carbon monoxide, (Jetter and Kariher, 2009; Rehfuss, 2006).

Biogas technology is a vital component of the alternative rural energy program in Africa. Biogas generation is a renewable energy technology that utilizes organic waste sources to produce a flammable methane gas suitable for cooking and lighting purposes (Lansing, et al., 2008). This technology has the potential to provide an alternative to the current unsustainable biomass sources and provide environmental, social, and economic benefits. Biogas technology has not yet been successfully adopted as either an energy or economic strategies, potentially serving as a means to overcome energy poverty, poses a constant barrier to economic development in Africa, (Biogas for better life an African initiative, 2008).

Biogas is a high-grade fuel; it can be used in gas mantle for lighting purposes or internal combustion engines like dual fuel engines (adopted diesel engine) for electricity generation. Although biogas lighting, using mantle lamps similar to kerosene pressure lamps, cannot compete with the comfort of electric lighting, it may offer the best option for lighting in areas that are not connected to the grid.

2.3. Improved food production

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, water availability and climate. The widespread introduction of biogas digesters is likely to have an impact on all of these environmental constraints.

Biogas digesters can improve the nutrition of households through the application of the effluent (slurry) as an organic fertilizer to improve agricultural yield (LEISA, 2005; Kangmin and Ho, 2006). As manure is used and traded as an energy source in many countries, biogas digesters have the added value of providing both energy and plant nutrients. Therefore, biogas programs should not neglect the economic value of improved yields. The effluent/slurry contains 1-12% solids and consists of refractory organics, new cells formed during digestion, and ash. The liquid or solid fraction of the slurry can be used either in dried form or as a wet slurry.

The slurry from biogas digesters is odorless and dark-colored with a higher protein content compared to the raw manure (Le Ha Chau, 1998). According to Marchaim and Criden (1981) and Marchaim (1983), there are no clear differences between compost and effluent manure but application of the effluent does not increase the salinity of the soil. Crops treated with fresh organic wastes often show signs of nutrient deficiency due to immobilization of nutrients during decomposition of the C rich organic materials in the waste. Marchaim (1983) observed that application of digested effluent over a period of years leads to increased crop production. Crops treated with composts and bioslurries from anaerobic digestion do not usually show nutrient deficiency because carbon rich materials have already been decomposed during the treatment, immobilizing the nutrients in the organic waste, rather than the plant available nutrients in the soil. This tends to provide a store of rapidly available nutrients that will be released to the crop over the course of the growing season, so providing nutrients when the crop can make use of them and minimizing losses. Long-term experiments demonstrated the physical and chemical properties of the soil improved markedly after a few years of applying digester effluent, while total crop yields were 11-20% higher than in controls (Marchaim, 1992). The use of slurry without anaerobic digestion is still very common in many countries, and its value cannot be ignored (Vetter et al. 1988).

2.4. Improved sanitation, water and indoor air quality

Health problems associated with leakage of human wastes into the wider environment can occur due to pit toilets becoming overfull due to inadequate pit depths and toilets being cited too close to water sources. Human wastes can also leach into ground water from a functioning pit toilet if cited on a highly permeable soil type. Contamination of groundwater and reservoirs by running storm water and flash floods can result in significant sporadic pollution events (such as reported in Malawi in 2009 by Pritchard et al, 2009). The type of contamination includes enterobacteria, enteroviruses and a range of fungal spores. Some key human/animal pathogens that may be spread in this way include *Salmonella typhi*, *Staphylococcus spp*, *E. coli*, *Campylobacter coli*, *Listeria monocytogenes*, *Yersinia enterocolitica*, *Hepatitis B* and *C* viruses, *Rotavirus*, *Aspergillus spp*, *Candida spp*, *Trichophyton spp.*, *Cryptosporidium*, mycobacteria, *Toxoplasma* and *Clostridium botulinum*. Many of these can be passed between animal and human populations. Cattle slurry introduces a range of pathogens including *Clostridium chavoie* (black leg disease); *Ascaris ova*, *E. coli* and *Salmonella spp*. as reported in cow dung slurries in Bauchi state, Nigeria (Yongabi et al., 2003); *Salmonella spp*, *E. coli*, yeasts and

aerobic mesophilic bacteria in poultry wastes in Cameroon (Yongabi et al., 2009). Pathogen prevalence in the environment is affected by local climate, soil type, animal host prevalence, topography, land cover and management, organic waste applications and hydrology (e.g. Gagliardi and Karns, 2000; Jamieson et al, 2002; Hutchison et al, 2004; Tyrrel and Quinton, 2003; Tate et al, 2006).

Access to an improved water source is not prevalent in Africa and contaminated or polluted water sources present a major health risk. Access to water is a precondition for sedentary agriculture and livestock husbandry, improved sanitation and the proper operation of a biogas plant. Occurrence of diarrhoea is closely related to polluted water sources and poor sanitation practices. For African children, diarrhea is a very serious health threat. All countries in the central east-west band of Africa suffer major health and sanitation problems. Many of these countries have the potential to improve their sanitation through use of domestic biogas digesters, and improvements in the technology may further increase the potential for use of biogas digesters.

Biogas digesters have the potential to reduce the risks of encountering these pathogens if properly operated. However, risks could be increased due to the person handling the materials undergoing increased direct contact with these pathogens, the digester amplifying the growth of certain pathogens, or the processed material from the digester being used as a fertiliser for agricultural crops where it would not otherwise have been used. The risks from these pathogens can be mitigated by developing a toolkit that includes safe operating instructions. Microbiological data should be generated for the pathogens or indicator organisms to determine the extent to which the levels change during the anaerobic digestion process. Advice on the use of the processed materials in agricultural production should also be provided.

While there is very little literature on the impact of installing biogas digesters on household air quality there is considerable evidence that homes burning traditional biomass fuels such as wood, charcoal, coal and dried crop/animal residues have very high concentrations of fine particulate matter and carbon monoxide (Fullerton et al., 2009). Evidence from studies of charcoal and LPG burning homes in Nepal suggests that fine particulate concentrations in LPG using homes were about one-tenth of the concentration of those in homes burning solid-fuels (Kurmi et al., 2008). It seems likely that similar order of magnitude reductions in indoor air pollutants will be experienced in homes switching from traditional biomass fuel to biogas systems. Significant improvements in respiratory and cardiovascular health of householders who experience such reductions in indoor air pollution concentrations can be anticipated, given results obtained from stove-based interventions in Guatemala (McCracken et al., 2011; Northcross et al., 2011).

3. Potential of small scale biogas in improving soil quality and reducing deforestation

3.1 Carbon sequestration in soils, soil erosion and degradation

Carbon sequestration in the soil not only removes carbon dioxide from the atmosphere, but also increases crop productivity by increasing the water holding capacity of the soil (Batjes et al, 1996), improving the aggregate structure (which favours root exploration and makes the soil less susceptible to erosion and loss of nutrients - Renshaw et al, 2006), and increases the supply of nutrients from the decomposing organic matter (Smith et al., 2010).

When organic matter is added to soil, it decomposes under aerobic conditions to release carbon dioxide. The amount of carbon sequestered is a balance between the inputs of organic matter and the rate of decomposition. The organic inputs to the soil depend on plant inputs (which are affected by crop nutrition, water availability and crop management) and organic amendments (either as aerobically composted organic wastes, as slurry from a biogas digester, or as charcoal produced by pyrolysis). The rate of decomposition depends on soil temperature, moisture, pH, salinity and clay content (Smith et

al., 2010). The rate of decomposition increases exponentially with temperature up to a maximum rate at about 30°C (Jenkinson et al, 1987). Increases in the soil moisture content result in an approximately linear increase in the rate of decomposition until just below field capacity (Stanford and Epstein, 1974). Above field capacity, the rate of decomposition tends to decline as the soil becomes more anaerobic. The rate of decomposition declines with decreases in soil pH below ~pH 5 (Leifeld et al, 2008). As salinity increases, the rate of decomposition decreases exponentially (Setia, et al, 2011). The clay materials in the soil provide physical protection to the organic matter, and so impact the proportion of the decomposing material that is lost to the atmosphere, so affecting the rate of sequestration (Coleman and Jenkinson, 1996).

The organic carbon content of soils in Sub-Saharan Africa tends to be low due to the high temperatures, low clay contents (or cation exchange capacity) and low organic inputs due to poor crop nutrition. However, increasing the organic inputs, increases the steady state carbon content, and so sequesters soil carbon. If organic inputs were increased, for instance by adding material from a biogas digester to the soil, the carbon content of the soil would increase until it reached a new steady state level; after that no more carbon would be sequestered unless the organic inputs were further increased. The sequestered carbon is not a permanent store; it will only remain in the soil while the balance between the organic inputs and the rate of decomposition remains the same. If the organic inputs were reduced to their original level, for instance because the material from the biogas digester was no longer available, the amount of carbon held in the soil would return to its original level. Furthermore, if the rate of decomposition increased, for instance due to increased temperatures associated with climate change, the amount of carbon held in the soil would also decrease. The rate of decomposition of material added to the soil also depends on the quality of the organic matter. If sufficient nutrients are available to allow decomposition, fresh material tends to decompose more quickly than material that has been composted or digested. Composted and digested material decomposes more quickly than material that has been converted to charcoal, which is highly recalcitrant.

Further work is needed to determine the amount and decomposability of material produced by aerobic composting, anaerobic digestion and pyrolysis, so allowing the carbon sequestered following the different treatments of a unit of fresh organic matter to be estimated. The nutrient content and the rate of nutrient release from organic waste depend on the source and treatment of the material. Further laboratory analyses and field trials are needed to determine differences in nutrient availability from material that has undergone the different treatments. This information is of crucial importance if the value to the farmer of compost, digest or charcoal is to be quantified and compared.

3.2 Reduced Deforestation

FAO (2000) statistics suggest that some 1.86 billion m³ of wood is extracted from forests for fuel wood and conversion to charcoal. Of this total, roughly one-half comes from Asia, 28% from Africa, 10% from South America, 8% from North and Central America and 4% from Europe. Reductions in access to fuel wood supplies can negatively affect poor subsistence users as well as adversely affecting those generating income from fuel wood to bridge their income between seasons. In the 1970s, population pressures and increases in oil prices were already considered to be major drivers of deforestation (Arnold et al, 2003). It was estimated that tree planting in Africa would need to increase by a factor of 15 to meet the predicted 2000 demand for fuel wood (Anderson and Fishwick, 1984). There was a resultant increase in woodlots on communal land, but these initiatives largely failed because they were often commercialised, and the very poor could not afford what previously had been free. Improved cook stoves were provided, but were not reliable. Therefore, other forms of energy were subsidised. However, Arnold (2003) suggested that although fuel wood shortages did exist, much of the fuel wood collected was obtained from land cleared anyway for agriculture, dead and fallen wood, and supplies from trees outside forests (e.g. agro-forests). Other supplies, such as dung and crop residues are also used. Therefore, deforestation was not occurring at the rate initially predicted.

Problems appear to relate to access rather than supply of fuel wood. Since the 1990s, concerns have centred on urban demand and the consequent reliance on charcoal.

Globally, projections based on modelled values suggest that fuel wood consumption has now peaked, and may even be in decline in some countries (Broadhead et al, 2001). However, in Africa, the consumption of firewood and charcoal continues to increase, with fuel wood consumption predicted to increase by 2030 to over 137% of the 1970 base rate, while charcoal consumption is expected to increase to over 5 times the 1970 base rate. This is especially worrying, as the process of charcoal production means that more wood is used in providing energy from charcoal than would be needed for firewood. Furthermore, by 2030 the number of people in Africa relying on biomass for cooking and heating is expected to increase to over 140% of the 2000 rate.

Switching to biogas is often assumed to automatically result in reduced deforestation. However, fuel wood collection does not always result in deforestation: much firewood is obtained from land already being cleared for agriculture; dead and fallen wood may be collected rather than wood being obtained by felling of live trees (this practice can actually stimulate forestry growth); supplies may be obtained from trees outside forests (such as in agroforestry); or other fuel supplies may be used (such as dung or crop residues). The problems of fuelwood supply are often related to access rather than to supply. Work is needed to review the factors driving deforestation and its link to biogas. Further consideration of the role of Reducing Emissions from Deforestation and Forest Degradation (REDD) in promoting biogas digesters should also be considered.

4. Conclusion

Developing alternative energy source to replace non-renewable sources has recently become more and more attractive due to the high energy demand, the limited resource of fossil fuel, and environmental concerns around the globe. Biogas has become more attractive as an alternative to non-renewable fuels because it is an integrated system with multi-benefits such as diversification of energy (cooking fuel) supply, reduction of local pollutants, reduced deforestation due to logging for fuel; air quality, sanitation and crop yield improvement through sequestration of carbon in soils amended with the digested organic waste.

The challenge does not lie in the development of the small-scale biogas digesters; the processes of digestion are already well understood and different designs for low-cost digesters are operational. What is needed is the translational research to make it possible for these digesters to become available to people in SSA who have little or no disposable income and access to only limited material resources. Development is needed of effective, safe and affordable methods for using small scale biogas digesters to provide household energy and improve sanitation in the range of special conditions found in SSA, while obtaining the maximum economic and environmental benefits from the digested products, which are an important source of scarce nutrients.

Issues that must be considered further to increase accessibility of biogas technology to the rural poor are:

- a) Can the poor afford the initial investment and maintenance costs?
- b) Do the poor have access to finance/credit?
- c) Is there commitment from national governments in disseminating the technology?
- d) Are the non-government organisation initiated biogas schemes sustainable?
- e) What is the economic efficiency?
- f) Is there potential for reducing costs by working at a larger scale?
- g) What potential is there for improving cost-effectiveness?

There is a need for further research into behavioural studies (choices and preferences) including experimental economics, quantification issues (capturing various costs & benefits components), socio-economic design mechanisms, barriers to uptake, knowledge transfer (awareness, training, and participation).

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Conflict of Interest

The authors declare no conflict of interest.

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