GCB Bioenergy (2016), doi: 10.1111/gcbb.12339

Water for small-scale biogas digesters in sub-Saharan Africa

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Abstract

Biogas could provide a more sustainable energy source than wood fuels for rural households in sub-Saharan African. However, functioning of biogas digesters can be limited in areas of low water availability. The water required is approximately 50 dm^3 day^{-1} for each cow and 10 dm^3 day^{-1} for each pig providing manure to the digester, or 25 (±6) dm^3 day^{-1} for each person in the household, using a digester volume of 1.3 (±0.3) m^3 capita^{-1}. Here, we consider the potential of domestic water recycling, rainwater harvesting, and aquaculture to supply the water needed for digestion in different countries of sub-Saharan Africa. Domestic water recycling was found to be important in every country but was usually insufficient to meet the requirements of the digester, with households in 72% of countries need to collect additional water. Rooftop rainwater harvesting also has an important role, iron roofs being more effective than thatched roofs at collecting water. However, even with an iron roof, the size of roof commonly found in sub-Saharan Africa (15 to 40 m^2) is too small to collect sufficient water, requiring an extra area (in m^2) for each person of ($R/100$) (where R is the rainfall in mm). If there is a local market for fish, stocking a pond with tilapia, fed on plankton growing on bioslurry from the digester, could provide an important source of additional income and hold the water required by the digester. In areas where rainfall is low and seasonal, the fishpond might be stocked only in the rainy season, allowing the pond to be covered during the dry period to reduce evaporation. If evaporative losses (E in mm) exceed rainfall, an extra catchment area is needed to maintain the water level in the pond, equivalent to approximately ($1.5 \times ((E-R)/R)$) m^2 for each person in the household.

Keywords: aquaculture, biogas, rainwater harvesting, sub-Saharan Africa, water harvesting, water recycling

Received 21 October 2015; revised version received 23 December 2015 and accepted 29 December 2015

Introduction

Use of biogas digesters to provide household energy in sub-Saharan Africa

Wood, charcoal, and dung are traditional biomass fuels that currently supply over 70% of the household energy in sub-Saharan Africa (SSA) (Eleri & Eleri, 2009). Biomass fuels are often the preferred energy source in rural areas because they can usually be collected locally without incurring additional cost (Karekezi & Kithyoma, 2002). However, these sources of energy can create many problems for the environment and the people using them, especially for women and children (Bryceson & Howe, 1993; Biran *et al*., 2004). The collection of firewood has been linked to local deforestation (Subedi *et al*., 2014), which is currently occurring at a rate of 0.7% per annum in SSA (Eleri & Eleri, 2009). This, in turn, has a detrimental effect on soil quality and increases surface run-off (Leu *et al*., 2010; Hallett *et al*., 2012). Cooking on a wood fire releases carbon monoxide and particulates at levels detrimental to human health (Gordon *et al*., 2014); poor indoor air quality has been linked to over 3.5 million premature deaths annually (Lim *et al*., 2012) and contributes to a wide range of child and adult diseases (World Health Organization (WHO), 2014).

The UN Sustainable Energy for All Initiative (UN Department of Economics and Social Affairs, 2012) includes provision of modern cooking appliances and fuels as one of its 11 key action areas. A further international initiative, the Global Alliance for Clean Cookstoves (2014), is a public–private partnership that aims to create a global market for clean and efficient household cooking solutions. Improvement in cookstoves that use biomass fuels is critical to the reduction in demand for wood and improvement in indoor air quality (MacCarty *et al*., 2008). However, depending on thermal efficiency, improved biomass cookstoves may provide only part of the solution; Smith *et al*. (2015) estimated that if the thermal efficiency is improved from the typical value of 17% for a three-stone fire (Omer & Fadalla, 2003) to 38–50% for a pyrolysis cookstove (Roth, 2011),

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the rate of deforestation could be reduced by 41 (±25) to 50 (±30)%, with a further 21 (±12)% reduction if suitable crop residues are used as an additional fuel source, meaning that the total potential reduction in deforestation is only ~60% to 70%. Biogas presents an important opportunity to fill this energy gap, providing a clean, cheap, and renewable additional fuel source; assuming a thermal efficiency of 75% (Zielonka *et al.*, 2010), Smith *et al.* (2015) estimated that the rate of deforestation could be reduced by a further 23 (±14)%. Making use of the important opportunity presented by biogas has the potential to reduce deforestation due to wood fuel demand by a total of ~70% to 100% (Smith *et al.*, 2015).

Biogas is produced through the anaerobic digestion of organic compounds (Hamlin, 2012). Feedstock and water are added through an inlet pipe in equal ratios by volume (Amigun & Von Blottnitz, 2010). The feedstock is then broken down in an airtight chamber by anaerobic micro-organisms to produce methane and carbon dioxide. Biogas generally consists of around 60–70% methane and 20–30% carbon dioxide and can be used as energy for household cooking or lighting (Brown, 2006). The digester also produces a slurry, 'bioslurry', that is rich in available nitrogen, phosphorus, and potassium and can be used as a fertilizer to grow crops or feed fish for aquaculture (Orskov *et al.*, 2014). The composition of the bioslurry and biogas depends on the type of feedstock used, as different substrates contain different amounts of dry matter, nutrients, and volatile solids (Amigun & Von Blottnitz, 2010; Mao *et al.*, 2015).

Biogas technology is most suited to rural households with a readily available source of feedstock from livestock or crop residues. In Ghana, it is estimated that in 2006, at least 3.4 million households kept livestock, sufficient to generate 350 million m^3 of biogas in the year 2006 (Arthur *et al.*, 2011). Brown (2006) suggested that 1–2 cows or 5–8 pigs should provide enough manure to run a biogas digester for a household of four people (Brown, 2006). Orskov *et al.* (2014) agreed that sufficient biogas is produced by two cows, but suggested that the number of pigs required is at least eight. Human faeces can also be used to supply feedstock, but this would not provide sufficient feedstock for the digester. The more commonly used substrates for anaerobic digestion in SSA are cow and pig manure. Therefore, this study only considers use of cow and pig manure; crop residues and human faeces are omitted.

Over recent years, there have been increased efforts to disseminate biogas technology in SSA; in 2011, the total number of domestic biogas digesters installed in nine countries of SSA (Rwanda, Ethiopia, Tanzania, Kenya, Uganda, Burkino Faso, Cameroon, Benin and Senegal) was 24,990 (SNV, 2013); this is small compared to the numbers of domestic digesters in China, which reached 40 million by 2010 (Dong, 2012), but is increasing under the efforts of the African Biogas Partnership Programme, the Netherlands Development Organisation (SNV), and the Humanist Institute for Development Cooperation (HIVOS) (Africa Renewable Energy Access Program, 2011). Implementation of biogas digesters in SSA is often targeted at rural households (Amigun & Von Blottnitz, 2010). The digester size usually varies from 5 to 10 m^3, depending on the energy requirements of the household and the substrate retention time (Parawira, 2009). Most rural biogas plants have no moving parts to mix the feedstock and water, so this is usually done by hand; this can take up to 30 min each day, time that would otherwise be used for other household activities (Hamlin, 2012). Further time is taken in fetching water and collecting feedstock, especially if livestock are not housed, and this must be balanced against the potential time-saving due to reduced need to collect wood (Orskov *et al.*, 2014). The size of the digester depends on the amount of energy required by the household; typically 90–100% of the energy used by a rural off-grid household is for cooking (Karekezi & Kithyoma, 2002).

Biogas digesters are a promising option for providing household energy in rural SSA, but Mengistu *et al.* (2015) concluded that uptake is often limited by policies and institutional arrangements, financial constraints, lack of subsidies, availability of inputs, and consumers' awareness and attitudes to the technology. Financial constraints, particularly the inability to afford the high initial investment costs, are often considered to be the principal factor preventing uptake of digesters (Bensah & Brew-Hammond, 2010; Arthur *et al.*, 2011). Bedi *et al.* (2015) suggested biogas uptake in Rwanda is constrained by long payback periods and low rates of return. Mwirigi *et al.* (2014) recommended standardization and quality control, integrated farming using biogas and bioslurry, mobilization of local and external funds, such as from the clean development mechanism, to overcome initial construction costs, and the formation of user and disseminator associations for joint procurement and linkage to finance. However, even when subsidies and financial structures support investment in biogas, a high proportion of digesters stop working within a few years due to technical problems or lack of essential resources, such as water, feedstock, or labour (Parawira, 2009).

Water is often the key factor limiting implementation of biogas; a survey conducted in Ethiopia showed that of 700 biogas digesters, 60% were non-operational due to lack of water or manure (Eshete *et al.*, 2006). It is suggested that to run a biogas digester efficiently, the time taken to reach the water source should be no more than 30 min (Eshete *et al.*, 2006), and the household should be able to collect at least 25 dm^3 water per person per day (Orskov *et al*., 2014). In providing energy for household use and organic fertilizer for food production, but in using water, anaerobic digestion is at the centre of the 'water–energy–food nexus' in SSA (Conway *et al*., 2015; Smith *et al*., 2015). The aim of this study is to investigate how biogas digesters can be implemented in the often water limited conditions of rural SSA, and what methods can be used to improve water availability.

Water availability in sub-Saharan Africa

Most countries in SSA are classified as having economic water scarcity, suggesting that the available water sources are not used to their full potential due to poor governance, infrastructure, or management (Van Koppen, 2003). Water is accessed by the rural population mainly though hand pumps, boreholes, wells, water vendors, piped systems, and springs (Lockwood & Smits, 2011). Due to the poor infrastructure and management of these sources, many hand pumps are not operational. A study conducted by Water Aid in Tanzania found that 25% of hand pumps did not work 2 years after installation.

The WHO (2006) suggested that 20 dm^3 capita^{-1} day^{-1} is sufficient water to meet domestic needs in SSA. However, another study (Gleick, 1998) recommends up to 50 dm^3 day^{-1} for consumption and sanitation. The volume of water is related to the distance to the source and the household size. In most cases, water use per capita decreases with household size; this trend was observed in Malawi by Rosen & Vincent (1999) where a two-member household averaged 20 dm^3 capita^{-1} day^{-1}, but an eight-member household never exceeded 10 dm^3 capita^{-1} day^{-1}.

The time taken for water collection is the main factor controlling water available to the household. In an average year, women in SSA spend approximately 40 billion hours collecting water (Blackden & Wodon, 2006). As the distance to the water source increases, the quantity of water collected generally decreases. Sugita (2006) described this in a survey of households in Uganda, where average consumption varied from 15.6 dm^3 capita^{-1} day^{-1} for households using distant hand pumps to 155 dm^3 capita^{-1} day^{-1} for households who had piped systems.

A biogas digester requires extra water for anaerobic digestion, which may result in more trips to collect water. This could be problematic because water collection has been linked to numerous health and social problems in communities. Water collection is often done by women; the more water they have to collect, the less time is available for other activities such as education (Pickering, 2011). Carrying heavy buckets of water over long distances can cause skeletal injuries and exposes women to risk of assault and water-based diseases (Rosen & Vincent, 1999). To avoid the problems associated with an increased water demand and in the context of limited and seasonal water access and availability, additional water demand for anaerobic digestion requires alternative techniques for water collection. Therefore, three different ways to meet water demand that are appropriate to rural households are considered in this study: recycling domestic water, harvesting rainwater, and aquaculture.

Methods to meet water demand

Recycling domestic water. Recycling domestic water is the easiest way to increase the availability of water for households that get sufficient water for domestic use. Domestic water use includes drinking, laundry, bathing, cleaning, and cooking (Nyong & Kanaroglou, 1999). Gleick (1998) recommended that around 5 dm^3 capita^{-1} day^{-1} should be used for drinking, 10 dm^3 capita^{-1} day^{-1} for cooking, 15 dm^3 capita^{-1} day^{-1} for bathing, and 20 dm^3 capita^{-1} day^{-1} for cleaning; so for a four-person household, this would come to around 180 dm^3 day^{-1}. In addition, water is required for livestock, and this usually competes with domestic water use and increases the demand for water (Rosen & Vincent, 1999). Almost all of this water can be recycled in some way; water from drinking and livestock is recycled as urine and can be used for wet fermentation in the digester (Brown, 2006). The microbial content of the wastewater may be reduced by the anaerobic digestion process (Avery *et al*., 2014), and it is therefore considered safer for use in aquaculture or for application to crops (Ogunmokun *et al*., 2000).

The volume of water that can be recycled is largely dependent on how much is available and is allocated to different activities. The quantity of water consumed can vary greatly in different seasons; in north-eastern Nigeria, it was found that mean domestic water consumption in the rainy season was 215 dm^3 per household, whereas it was only 125 dm^3 per household in the dry season (Nyong & Kanaroglou, 1999). This was because activities, such as laundry and bathing, were done either fully or partially in streams to reduce the amount of water that must be carried to the household. However, the opposite pattern was seen in Malawi, where total household water consumption was higher in the dry seasons than the rainy seasons due to the drier climate driving higher water consumption and most households having a relatively good water source (Mloza-Banda *et al*., 2006).

 doi: 10.1111/gcbb.12339

One advantage of using wastewater for household anaerobic digestion is that it can result in better sanitation as wastewater is properly disposed of. Grey water includes all wastewater produced from domestic activities, excluding toilet waste, accounting for 50–80% of total wastewater generated (Madungwe & Sakuringwa, 2007). The biogas digester does not require clean water, so grey water can be used without pretreatment (Parawira, 2009), unless there is a high amount of detergent or disinfectant in the water which could cause the digester to stop working (Orskov *et al*., 2014). However, for this to become normal practice, perceptions of the use of grey water need to change, as much of the rural population do not use grey water, believing it to be dirty or unfit for use (Ogunmokun *et al*., 2000).

Urine from humans and livestock can also be a valuable resource for the digester. A pour flush toilet can be directly connected to the input chamber of the digester (Ogunmokun *et al*., 2000) where all flush water and waste goes directly into the digester, reducing the amount of additional water required. An average human produces 1 dm^3 of urine per day; if piped water is available, flush water would provide an additional 3–5 dm^{-3} (Sibisi & Green, 2005). Urine has also been shown to improve biogas production when added with cow manure and water; this is due to the nitrogen-rich urine reducing the carbon: nitrogen ratio of the slurry, which also improves the quality organic fertilizer output from the digester (Haque & Haque, 2006). Cattle urine was observed to increase gas production by 30% at a proportion by volume of 50 cattle dung: 35 urine: 15 water (Haque & Haque, 2006). When human urine was used in equal proportions to cattle manure, with no additional water, Haque & Haque (2006) observed gas production to have increased by 14%. However, as household members are often away from the household during the day, human urine is not included as a source of water in this study.

Rainwater harvesting. In 2015, Rockström & Falkenmark called for increased water harvesting in Africa, emphasizing the challenge faced by SSA in meeting water requirements for food production. Extra water demand for energy production will exacerbate this situation, and the need for water harvesting becomes even more acute. According to Siegert (1994), rainwater harvesting includes ‘all small-scale schemes for concentrating, storing, and collecting surface run-off water in different mediums, for domestic or agricultural use’. Lasage & Verburg (2015) classify rainwater harvesting techniques according to their size (household or community scale), and the way in which the water is stored (container, soil, or reservoir), which has implications for evaporation and the potential uses of the water. Rockström & Falkenmark (2015) suggest that harvesting of water stored in soils, ‘green water’, is needed for food and biomass production, whereas water stored in containers or reservoirs, ‘blue water’, is needed for energy development. Here, we consider small-scale rainwater harvesting techniques that can provide blue water to the household by collecting rainwater run-off from rooftops or ground catchments in containers or reservoirs. For effective domestic rainwater harvesting, three factors should be considered: the storage facility (above- or below-ground tanks), catchment area (rooftop or courtyard), and the target use (domestic use and/or biogas) (Mwenge Kahinda *et al*., 2010).

Rooftop rainwater harvesting is a popular choice for rainwater collection. The volume of water collected is determined by the surface area and run-off coefficient of the roof. The run-off coefficient is defined as the proportion of rain falling on a surface that will run off into a collection vessel (Conway *et al*., 2009). An iron roof has a run-off coefficient of 0.8–0.9 (Sturm *et al*., 2009), which provides an ideal surface for rooftop rainwater harvesting. In SSA, many rural households have thatched roofs (Mwenge Kahinda *et al*., 2007), which have a run-off coefficient of only 0.2 (DTU, 2002). In East Africa, Pachpute *et al.* (2009) reported that the roof area commonly varies from 15 to 40 m^2, but in Ghana, Issaka *et al.* (2012) reported roof areas up to 108 m^2. To improve the efficiency of rainwater collection from rooftops, splashguards and gutters can also be added, increasing the run-off coefficient (Sturm *et al.*, 2009). Mati *et al.* (2006) suggested that areas in SSA with an annual rainfall over 200 mm have potential for rainwater harvesting. If the roof area limits the amount of water collected, ground catchments can also be used.

Ground catchments allow a larger area to be used to collect the water required compared to rooftop rainwater harvesting, but may remove areas of the holding from alternative uses. Subsurface run-off can be captured from courtyards or compacted or treated surfaces with a sufficient run-off coefficient (Mwenge Kahinda *et al*., 2010). The run-off coefficient is higher in concrete lined catchments than in natural or treated surfaces (Sturm *et al*., 2009). Cement tanks are commonly used to capture rainwater from groundwater catchments as they prevent water loss; the size of these tanks typically ranges from 20 to 50 m^3 (Pachpute *et al*., 2009). Water collected from ground catchments is more likely to be contaminated than water collected from a rooftop (Mwenge Kahinda *et al*., 2007). Contaminated wastewater can be used to feed a digester, but higher levels of sand particles may mean that the digester must be cleaned out more frequently.

A problem with implementing rainwater harvesting in SSA is that rainfall is erratic and unevenly distributed (Vörösmarty *et al*., 2005; Mwenge Kahinda *et al*., 2007). Annual rainfall varies from 100 to 3000 mm with the highest potential for rainwater harvesting generally observed in central and western Africa (UNEP, 2010). Currently, rainwater harvesting is underutilised in SSA, and 95% of agriculture is directly fed by rainwater (Biazin *et al*., 2012; Rockström & Falkenmark, 2015), so in areas that are already dependent on rainfall for their livelihoods, rainwater harvesting is an important potential option to capture more of the water required.

Aquaculture. In many parts of Asia, aquaculture and biogas digesters are commonly linked to produce an integrated farming system (Chan, 1993). The effluent from the digester is used to fertilize the pond, which lowers the oxygen content allowing algae to reproduce; the algae can then be used as a feed for the fish or can be used as an additional feedstock for the digester to increase biogas production (Chan, 1993). Aquaculture has the potential to provide the water required for the digester at the same time as contributing to the food security of the household. Fish consumption is lower in Africa than in other continents, with an average of only 9.1 kg of fish consumed per capita per annum (FAO, 2012), but countries on the western coast have higher rates of fish consumption than other countries in Africa; in Ghana, Gambia, and Sierra Leone, fish contribute 50% of the total animal protein consumed (FAO, 2012). Globally, only 0.15% of total fish production from aquaculture is in SSA (Hishamunda & Ridler, 2006); aquaculture is still in its infancy in SSA (Brummett & Williams, 2000) as it was only introduced in the 1950s (Hishamunda & Ridler, 2006) and is still subject to many social and political constraints. In SSA, 31% of the region would be suitable to produce tilapia, making tilapia an ideal species for African aquaculture (Kapetsky, 1994).

There are 100 different species of tilapia, but the most common species found in SSA are the Nile tilapia (*Oreochromis niloticus*) and the Mozambique tilapia (*Oreochromis mossambicus*) (Murnyak, 2010). They have a fast reproductive rate, grow quickly into adults (Murnyak, 2010), and are well adapted to sub-Saharan climates as they reproduce best at temperatures between 28 °C and 32 °C. They are fairly resistant to disease and can adapt to poor water quality with low oxygen concentrations (Boyd, 2004). Their main benefit to a rural household with a biogas digester is that they thrive on the plankton that grows on slurry produced by the digester (Orskov *et al*., 2014). Tilapia are usually stocked in 1-m-deep earthen ponds (Murnyak, 2010); the ponds used are shallow because plankton require sunlight and carbon dioxide for photosynthesis (Chan, 1993).

Question being addressed

The aim of this study was to investigate the potential for domestic water recycling, rainwater harvesting, and aquaculture to meet the water demand of a small-scale biogas digester in rural households in different countries of SSA. The work will answer the questions:

- What proportion of the water demands of small-scale biogas digesters in rural households of sub-Saharan Africa can be met by domestic water recycling?
- Is it feasible to supply the remaining water requirement by rooftop rainwater harvesting? and
- Can aquaculture help to ensure a sufficient supply of water to run a biogas digester throughout the year?

Materials and methods

Summary of approach

The work described in this study uses a simple approach to estimate the amount of water that can be obtained for anaerobic digestion from domestic water recycling, rainwater harvesting, and aquaculture. The approach is detailed below, and a brief summary is provided here. The water required for anaerobic digestion in typical households in different countries was estimated from the national average household size. Water available for recycling to the biogas digester was estimated from the national statistics for domestic water use; the amount of extra water needed for digestion was then obtained from the difference between the water requirement and the amount that can be recycled. The time needed to collect this extra water by hand was estimated from the time required for each trip to collect water and the amount of water that can be carried in each trip; this provides an idea of the feasibility of collecting extra water without resorting to rainwater harvesting. The water that could be provided by rainwater harvesting was estimated for different roofing materials and areas of rooftop from national rainfall and potential evaporation data. The size of pond needed to stock the fish fed on nutrients from the bioslurry was estimated from the nitrogen contained in the bioslurry, and the nitrogen requirement and normal stocking density of the fish. The amount of water held by such a pond was then compared to the extra requirement of the digester to check the consistency of the water requirement and nutrient supply.

All symbol abbreviations used in this section are given in Table 1.

Water required for anaerobic digestion

Assuming that 200 dm^3 is required for anaerobic digestion of every 10 kg of manure dry matter (Orskov *et al*., 2014), the amount of water needed to provide the maximum potential production of biogas can be estimated from the fresh weight of manure produced by livestock, W_F (kg day^{-1}), and the percentage

Table 1 Meaning of symbols used in equations

Symbol	Definition	Units
A_c	Average area of catchment	m^2
A_p	Area of pond	m^2
A_{c_aq}	Additional catchment area needed for to harvest sufficient water for anaerobic digestion if water is stored in an open pond used for aquaculture	m^2
A_{roof}	Area of iron roof needed for each person in the household to harvest enough water to run a biogas digester with no domestic water recycling	m^2 capita^{-1}
D	Average depth of pond	m
D_{fish}	Stocking density of tilapia	fish dm^{-3}
E	Annual evaporation	mm y^{-1}
H_s	Household size	capita
K	Dimensionless run-off coefficient	
n_{fish}	Number of fish produced	
$N_{bioslurry}$	Nitrogen provided by bioslurry	g y^{-1}
N_{req}	Nitrogen requirement per fish	g dm^{-3} y^{-1}
P_{DM}	Percentage dry matter in manure	%
R	Average annual rainfall	mm y^{-1}
S	Annual rainwater supply	dm^3 y^{-1}
t	Average time required for each trip to fetch water	min
T_e	Extra time required	min day^{-1}
V_a	Volume of additional water required	dm^3 day^{-1}
V_c	Volume of water required for cooking	dm^3 capita^{-1} day^{-1}
V_d	Volume of water required for drinking	dm^3 capita^{-1} day^{-1}
V_E	Annual evaporation	mm y^{-1}
V_h	Volume of water consumed per household	dm^3 day^{-1}
V_p	Volume of pond	dm^3
V_r	Volume of water that can be recycled	dm^3 day^{-1}
V_{req}	Annual water requirement	dm^3 y^{-1}
V_t	Volume of water collected at source per trip	dm^3
V_u	Volume of water usage per capita	dm^3 capita^{-1} day^{-1}
V_w	Volume of water required for optimum anaerobic digestion conditions	dm^3 day^{-1}
W_f	Fresh weight of manure	kg day^{-1}

dry matter in the dung, P_{DM} (%).The volume of water required, V_w (dm^3 day^{-1}), was estimated as follows:

$$V_w = W_F \times \left(\frac{P_{DM}}{100}\right) \times \left(\frac{200}{10}\right) \quad (1)$$

The values for W_F and P_{DM} were taken from Omer & Fadalla (2003) and Taiganides (1978).

Orskov *et al.* (2014) suggested that the manure from two cows or eight pigs would provide sufficient biogas for a four-person household in rural SSA. Therefore, the volume of water needed to run digesters in households in different countries was calculated by multiplying the volume of water needed to run a digester using manure from two cows or eight pigs for a four-person household by the national average household size, H_s (capita)/4. This provides a comparative analysis of the potential of rural households in different countries to meet the water requirements to run a small-scale biogas digester.

Volume of domestic water that can be recycled

To calculate the potential volume of domestic water that can be recycled, the volume of water used each day by the household, V_h (dm^3 day^{-1}), was first determined. The national statistics for domestic water use, V_u (dm^3 capita^{-1} day^{-1}), were collected from Dorling (2007; data from 1987 and 2003), and the household size in each country, H_s (capita), was obtained from the World Bank (2001–2009), allowing the consumption per household to be estimated as follows:

$$V_h = V_u \times H_s \quad (2)$$

The amount of domestic water that can be recycled was estimated from water allocation to different activities. The water used for essential activities such as drinking, V_d (dm^3 capita^{-1} day^{-1}), and cooking, V_c (dm^3 capita^{-1} day^{-1}), was assumed to be unavailable for recycling. The volume of domestic water that can be recycled, V_r (dm^3 day^{-1}), was then calculated as follows:

$$V_r = V_h - ((V_d \times H_s) + (V_c \times H_s)) \quad (3)$$

In a survey of domestic groundwater consumption in Kisumu, Kenya, Okotto *et al.* (2015) found that 11.7–17.6% of household water was used for drinking, and 25.5–27.5% was used for cooking. These ranges were used to set minimum and maximum values for V_d and V_c. Any country where the average household size could not be determined was omitted from the calculations. This approach assumes that any water that is not used in drinking or cooking could be used for anaerobic digestion; this will not be the case if excessive amounts of detergents are used for cleaning, so this provides an estimate of the maximum amount of water available by recycling.

Additional water required to run digester

The additional water required to run the digester was calculated by subtracting the volume of domestic water recycled (V_r) from the water required to run the biogas digester (V_w). This gives an estimate of the amount of water that must be provided by rainwater harvesting or ponds to run the digester, V_a ($dm^3\ day^{-1}$),

$$V_a = V_w - V_r \tag{4}$$

Time required to collect extra water

The extra time required to collect the additional water needed for anaerobic digestion, T_e (min day^{-1}), was calculated from the time required for each trip to fetch water, t (min), and the average number of additional trips needed (calculated as V_a/V_t where V_a is the volume of additional water required ($dm^3\ day^{-1}$) and V_t is the volume of water collected per trip (dm^3)).

$$T_e = \left(\frac{V_a}{V_t}\right) \times t \tag{5}$$

If water is collected by hand, the volume of water collected per trip was assumed to be 20 dm^3 after Orskov *et al.* (2014), and the mean time required to collect water (t) was assumed to be between 19 min for a centrally located water source and 104 min for a distant source after Rosen & Vincent (1999). This was also expressed as water collected per capita by dividing by the national average household size, H_s (capita). If farmers have access to additional means of transporting water, such as by donkey or using a vehicle, clearly the amount transported each trip (V_t) and the time required for each trip (t) will be different, very much reducing the time required to collect water.

Water provided by rainwater harvesting

Two types of rainwater harvesting are commonly used: rooftop and ground catchment. It was assumed that all the rainfall collected could be used to feed the digester. Potential rainwater harvesting, S ($dm^3\ y^{-1}$), from a rooftop or ground catchment was calculated as follows:

$$S = R \times K \times A_c \tag{6}$$

where R is the rainfall (mm y^{-1}), K is the run-off coefficient, and A_c is the area of the catchment (m^2).

Annual precipitation data were taken from the FAO AQUASTAT database (http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en). A variety of different roof materials were considered, with run-off coefficients that ranged from 0.2 to 0.9 (DTU, 2002). The roof catchment area was assumed to range from 15 to 40 m^2 after the range of roof sizes reported for East Africa by Pachpute *et al.* (2009). The annual rainwater supply was divided by 365.25 to give the average volume of water collected each day.

Sufficient water is collected for anaerobic digestion if the water supply, S ($dm^3\ y^{-1}$), is at least equal to the annual water requirement, V_{req} ($dm^3\ y^{-1}$), and the water lost each year by evaporation, V_E ($dm^3\ y^{-1}$), from the holding tank.

$$S = V_{req} + V_E \tag{7}$$

The annual water requirement, V_{req} ($dm^3\ y^{-1}$), is calculated from the daily water requirement, V_a ($dm^3\ day^{-1}$) as follows:

$$V_{req} = 365.25 \times V_a \tag{8}$$

For an open tank, the volume of water lost by evaporation (V_E) is given by the annual evaporation, E (mm y^{-1}), and the area of the water holding tank, A_t (m^2), as follows:

$$V_E = E \times A_t \tag{9}$$

Substituting V_{req} and V_E into equations 6 and 7 for S gives:

$$S = (365 \times V_a) + (E \times A_t) = R \times K \times A_c \tag{10}$$

Rearranging equation 10 gives an equation for the area of catchment required:

$$A_c = \frac{(365 \times V_a) + (E \times A_t)}{(K \times R)} \tag{11}$$

For a covered holding tank, the evaporation can be assumed to be low, so Equation 11 simplifies to:

$$A_c = \frac{(365 \times V_a)}{(K \times R)} \tag{12}$$

For open holding tanks, the evaporation rates were obtained from FAO AQUASTAT (2005). The countries without evaporation values were omitted from the calculations.

Aquaculture

The amount of water required by aquaculture is dependent on the stocking density of the fish and the number of fish that can be supported by the nutrients contained in the bioslurry. Assuming that nitrogen is limiting the growth of the fish, the number of fish that can be produced by the bioslurry, n_{fish}, can be calculated from the available nitrogen provided by the bioslurry, $N_{bioslurry}$ (kg y^{-1}), and the nitrogen requirement of each fish, N_{req} (kg $fish^{-1}\ y^{-1}$), as follows:

$$n_{fish} = \frac{N_{bioslurry}}{N_{req}} \tag{13}$$

The nitrogen requirement (N_{req}) was estimated from the minimum (0.001 kg) and the maximum weight (0.01 kg) of a fingerling and using the FAO values for the proportion of protein required with respect to the gain in body weight of fish (35–40%) (FAO, 2013b). The available nitrogen in the bioslurry ($N_{bioslurry}$) was calculated from the total nitrogen content of the feedstock, N_{feed} (kg y^{-1}), the percentage of total nitrogen lost during anaerobic digestion, P_{Nloss} (%), and the proportion of nitrogen that is available as ammonium, $p_{NH4:totalN}$, as described by Smith *et al.* (2013).

$$N_{bioslurry} = N_{feed} \times \left(1 - \frac{P_{Nloss}}{100}\right) \times p_{NH4:totalN} \quad (14)$$

The value of P_{Nloss} was set to 5 and $p_{NH4:totalN}$ to 0.5 after Schievano *et al.* (2011). The total nitrogen content of the feedstock (N_{feed}) was calculated as follows:

$$N_{feed} = 365.25 \times \frac{P_{used}}{100} \times \frac{P_{waste}}{100} \times n_{animal} \times M_{animal} \times p_{N:TS} \quad (15)$$

where P_{used} is the percentage of the available waste of each type that is used in the digester (assumed to be 100%), 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) $^{-1}$), n_{animal} is the number of each of the different types of animals on the farm, M_{animal} is the typical live weight for the type of animal specified (kg), and $p_{N:TS}$ is the proportion of nitrogen to total solids. The values used to calculate N_{feed} are given in Table 2. The value of N_{feed} was then calculated for each country by multiplying by H_s (capita)/4.

The area of the pond required to stock this number of fish, A_P (m^2), was then obtained by dividing the number of fish by the stocking density.

$$A_P = \frac{n_{fish}}{D_{fish}} \quad (16)$$

The stocking density (D_{fish}) was taken from Yi *et al.* (2008) and ranged from 0.0005 to 0.003 fish dm^{-3} (note that stocking density is typically quoted as fish per area of pond surface; this was converted using an assumed 1 m depth of the pond).

The volume of water required to fill this size of pond, V_P (dm^3), was obtained from the area (A_p) and depth, d (m), assumed to be 1 m (Murnyak, 2010).

$$V_P = A_p \times d \times 1000 \quad (17)$$

If annual rainfall exceeds evaporation ($R > E$), the pond will increase the amount of water available for digestion and aquaculture by $A_p(R-E)$. However, if evaporation exceeds rainfall, the additional catchment area needed to harvest sufficient water, A_{c_aq} (m^2), is given by:

$$A_{c\_aq} = \frac{A_p \times (E - R)}{(R \times K)} \quad (18)$$

Note that in practice, the fish must be harvested at a time to allow the water in the pond to be utilized for the digester. This will require careful planning to synchronize rainfall, growth of fish, and the requirement of water for the digester .

Results

Water required for anaerobic digestion

For a household in SSA, using manure from two cows or eight pigs, assuming all the manure produced can be used in the digester, the volume of water required for anaerobic digestion is between 78 and 124 dm^3 day^{-1}, with a mean volume of 101 dm^3 day^{-1}. Assuming an ideal feedstock retention time of 40 days (Price & Cheremisinoff, 1981) and a digestate to gas ratio of 6 : 1 (Smith *et al.*, 2013), this would require a digester tank of 5 (±1) m^3. This is equivalent to a water requirement for digestion for each person in the household of 25 (±6) dm^3 capita^{-1} day^{-1}, using a digester volume of 1.3 (±0.3) m^3 capita^{-1}. The typical values for water needed to run a digester in different countries of SSA obtained from the national average household size are shown in Fig. 1, ranging from a water requirement of 73 (±17) dm^3 day^{-1} with the national average household size of 2.9 capita in Cameroon, to 247 (±56) dm^3 day^{-1} with the national average household size of 9.8 capita in Senegal (Table 3).

Domestic water recycling

The potential volume of domestic water that can be recycled ranges from 21 to 411 dm^3 household^{-1} day^{-1} (Fig. 2a) and is highly dependent on country. The amount of domestic water that could potentially be recycled in 28% of countries considered (Guinea-Bissau, Zambia, Cote d-Ivoire, Cape Verde, Mauritania, Congo, Morocco South Africa and Gabon) exceeds the water requirement for the digester (Fig. 2b). However, in the

Table 2 Data used to calculate the nitrogen content of the feedstock available from two cows or eight pigs

Type of animal	Wet waste produced per animal as a percentage of its live weight, P_{waste} (kg fresh waste day^{-1} [100 kg live weight] $^{-1}$)	Number of animals, n_{animal}	Typical live weight per head, M_{animal} (kg)	Proportion of nitrogen to total solids, $p_{N:TS}$	Nitrogen content of the feedstock, N_{feed} (kg y^{-1})
Cows					
Minimum	4.6[a]	2	170[a]	0.0095[b]	54
Maximum			270[a]		86
Pigs					
Minimum	5.1[a]	8	45[b]	0.04[b]	268
Maximum					

[a]Omer & Fadalla (2003); [b]Polprasert (2007).

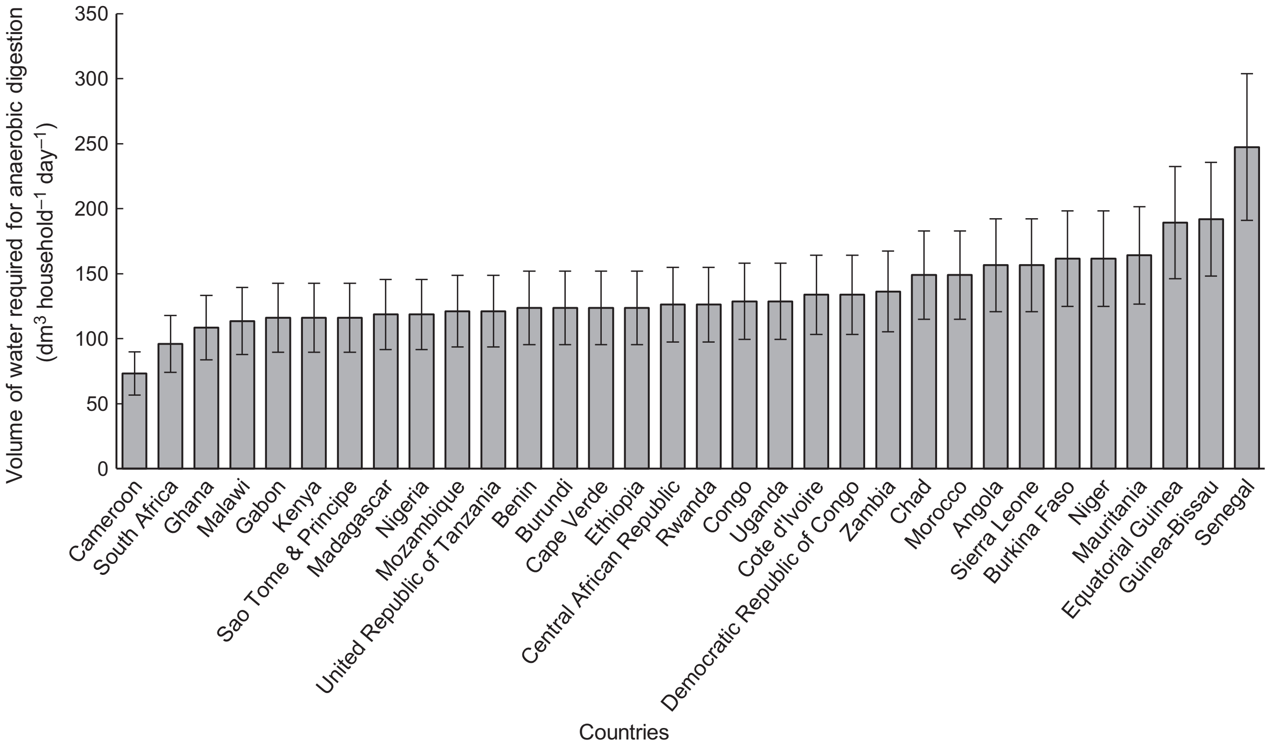

Fig. 1 Volume of water required to run the size of biogas digester needed to meet the energy demand of an average household, as per national average household statistics obtained from World Bank (2001–2009).

Table 3 Water required for anaerobic digestion of manure from two cows or eight pigs

Type of animal	[a]Wet weight of organic waste produced (% total live weight) day^{-1}	[b]Average weight of animal (kg)	Fresh weight of manure produced livestock per head, W_F (kg day^{-1})	Percentage dry matter in manure, P_{DM} (%)	Number of animals, n_{animal}	Volume of water required, V_W (dm^3 day^{-1})
Cows						
Minimum	4.6	170	7.8	25	2	78
Maximum	4.6	270	12.4	25	2	124
Pigs						
Minimum	5.1	45	2.3	25	8	92
Maximum	5.1	45	2.3	25	8	92

[a]Taiganides (1978); [b]Omer & Fadalla (2003).

remaining 72% of countries considered, recycling domestic water could only meet a proportion of the additional water required (average 44%), so installation of a biogas digester requires consideration of how the additional water needed will be accessed, either by collection from a local source or by rainwater harvesting.

Additional water requirement

The additional water required for anaerobic digestion after accounting for recycling domestic water is shown in Fig. 3. Of the countries needing extra water to run the digester, the average additional water required is 70 (±23) dm^3 $household^{-1}$ day^{-1}, but Senegal, with its large national average household size (9.8 $capita^{-1}$) and below average per capita water consumption (49% of the average of countries considered), requires over 136 (±49) dm^3 $household^{-1}$ day^{-1}.

Time to collect additional water

The time taken to collect the additional water required for anaerobic digestion by hand from a distant water source averages 7 h $household^{-1}$ day^{-1}, ranging from

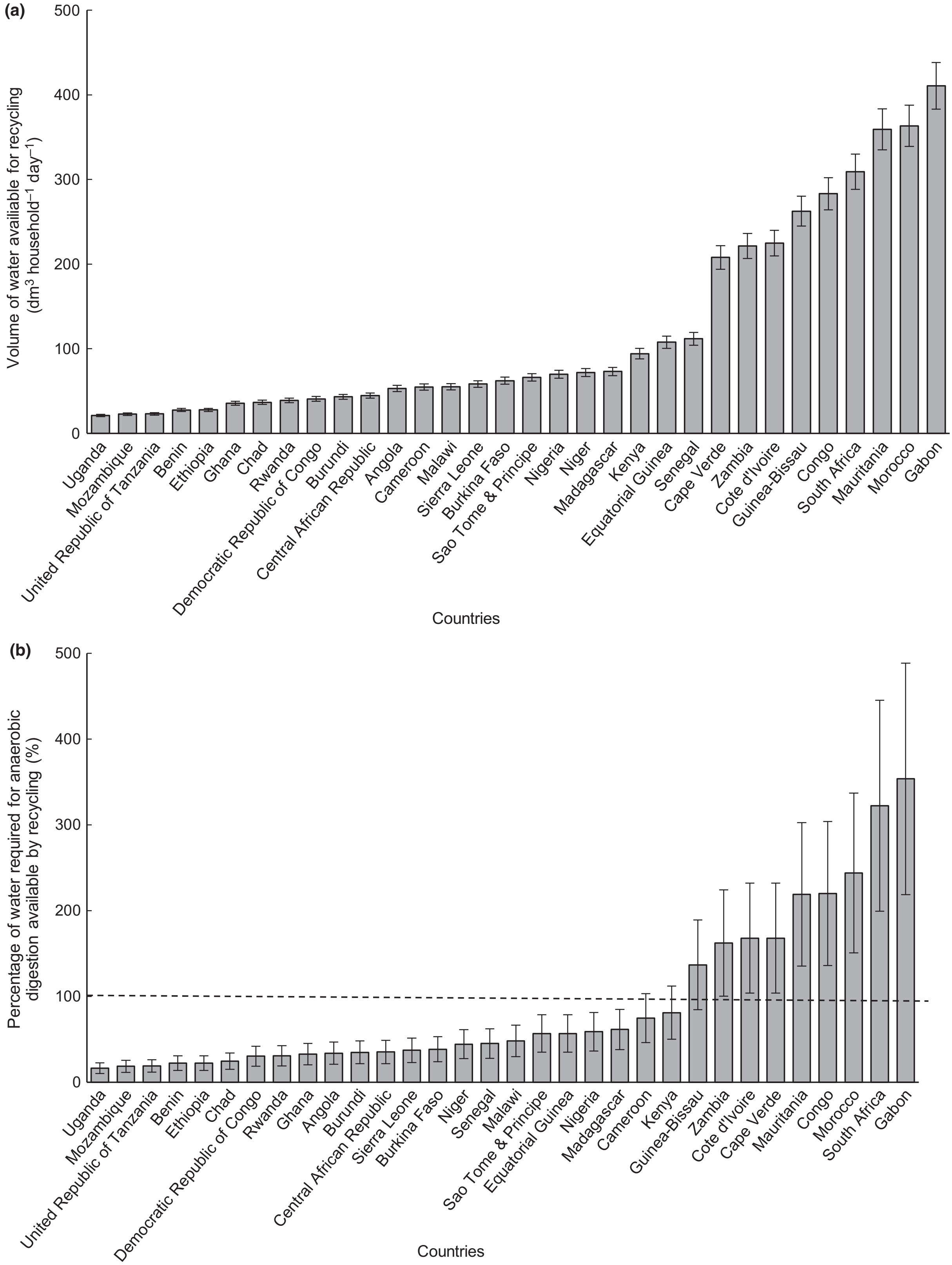

Fig. 2 Household water that could be recycled for anaerobic digestion in countries of Africa assuming domestic water use provided by Dorling (2007), household size specified by the World Bank (2001–2009), and the percentage of household water used for drinking and cooking as given by Okotto *et al.* (2015) (a) Volume of water; (b) percentage of water required for anaerobic digestion.

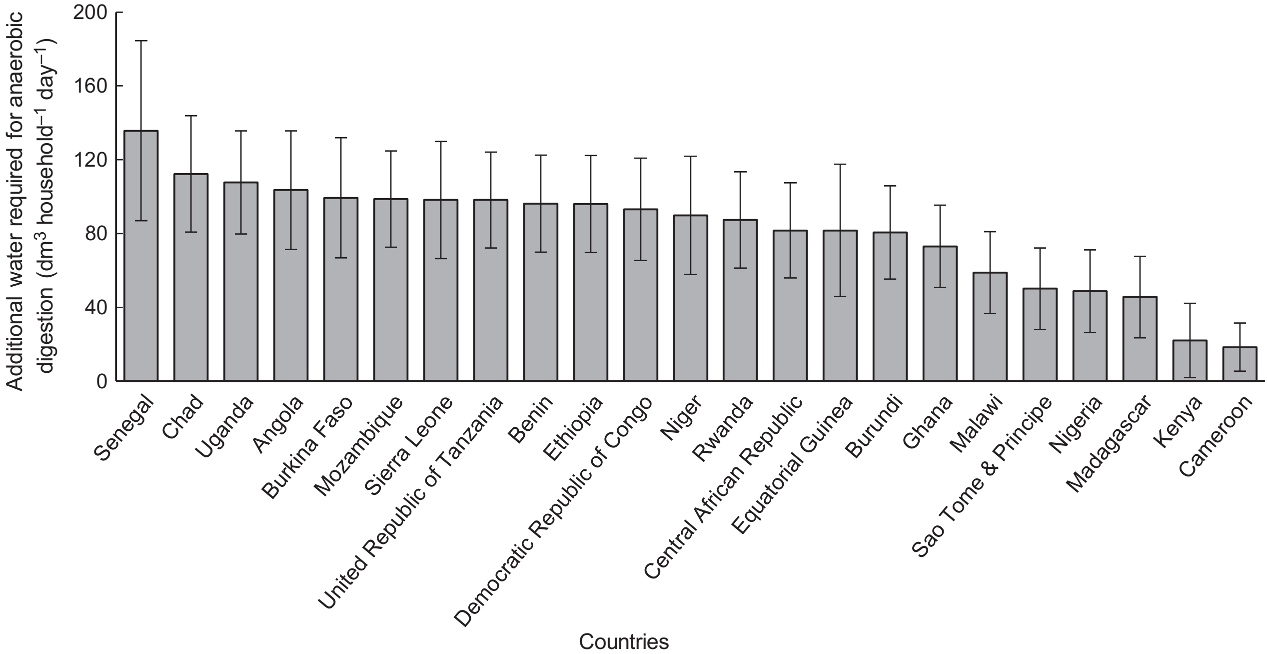

Fig. 3 Volume of additional water required to feed a biogas digester by country after accounting for recycled household water.

1.6 (±0.4) h household^{-1} day^{-1} in Cameroon to 12 (±2) h household^{-1} day^{-1} in Senegal (Fig. 4a). This assumes that the time for each trip to collect water from the distant water source is 104 min (Rosen & Vincent, 1999); if the time taken is less, then the time required to collect the water will be proportionally less. From a more central water source, where the time for each trip is assumed to be 19 min (Rosen & Vincent, 1999), the time required to collect the additional water by hand averages 1.3 h household^{-1} day^{-1}, ranging from 0.3 (±0. 2) h household^{-1} day^{-1} in Cameroon to 2 (±0.8) h household^{-1} day^{-1} in Senegal. If this is re-expressed as time required for each person, this ranges from 5 (±4) min capita^{-1} day^{-1} for a central source in Kenya to 110 (±10) min capita^{-1} day^{-1} for a distant source in Uganda (Fig. 4b). Collection of additional water takes less than 30 min capita^{-1} day^{-1} in all countries for a central source, but in only 33% of countries if the source is distant. If no water is available from domestic water recycling, time taken to collect the additional water is even higher, between 24 (±5) min capita^{-1} for a central source and 131 (±30) min capita^{-1} for a distant source. Therefore, rainwater harvesting would appear to be an important adjunct to a biogas digester in most countries of SSA.

Rainwater harvesting

The rainfall collected varies greatly across different countries and different roofing materials (Fig. 5). Thatched roofs, with a run-off coefficient of 0.2, have the lowest potential for rainwater collection, while galvanized iron roofs, with a run-off coefficient of 0.9, have much higher potential. Tiled and asbestos roofs, with run-off coefficients of 0.6 and 0.8, respectively, have potential for rainwater collection in between these extremes. Figure 5 shows the potential for rainwater collection, assuming a 28 m^2 roof, the average of 15 and 40 m^2, which is the range of roof sizes reported in the literature for East Africa by Pachpute *et al.* (2009). The highest potential for rainwater harvesting is seen in Sierra Leone and Liberia, collecting over 150 (±35) dm^3 day^{-1} with a 28 m^2 galvanized iron roof, and the lowest potential of under 25 (±6) dm^3 day^{-1} being observed in Niger, Cape Verde, Mali, Somalia, and Chad.

Figure 6 shows the size of roof that would be required to meet the additional water requirement of the biogas digester, assuming no evaporative losses from the storage tank and all water that is not used for cooking or drinking is recycled. In all countries except Cameroon and Malawi, the area of a thatched roof required to harvest the extra water for anaerobic digestion would be outside the range of values reported in the literature (15–40 m^2 – Pachpute *et al.*, 2009). For an iron roof, the area of roof is significantly lower, and 50% of countries considered are able to harvest sufficient water with an iron roof of 40 m^2 of less. This is consistent with observations in the field; householders use iron roofs for rainwater harvesting rather than thatched roofs. A larger roof will be required if significant evaporation occurs of if less water can be recycled.

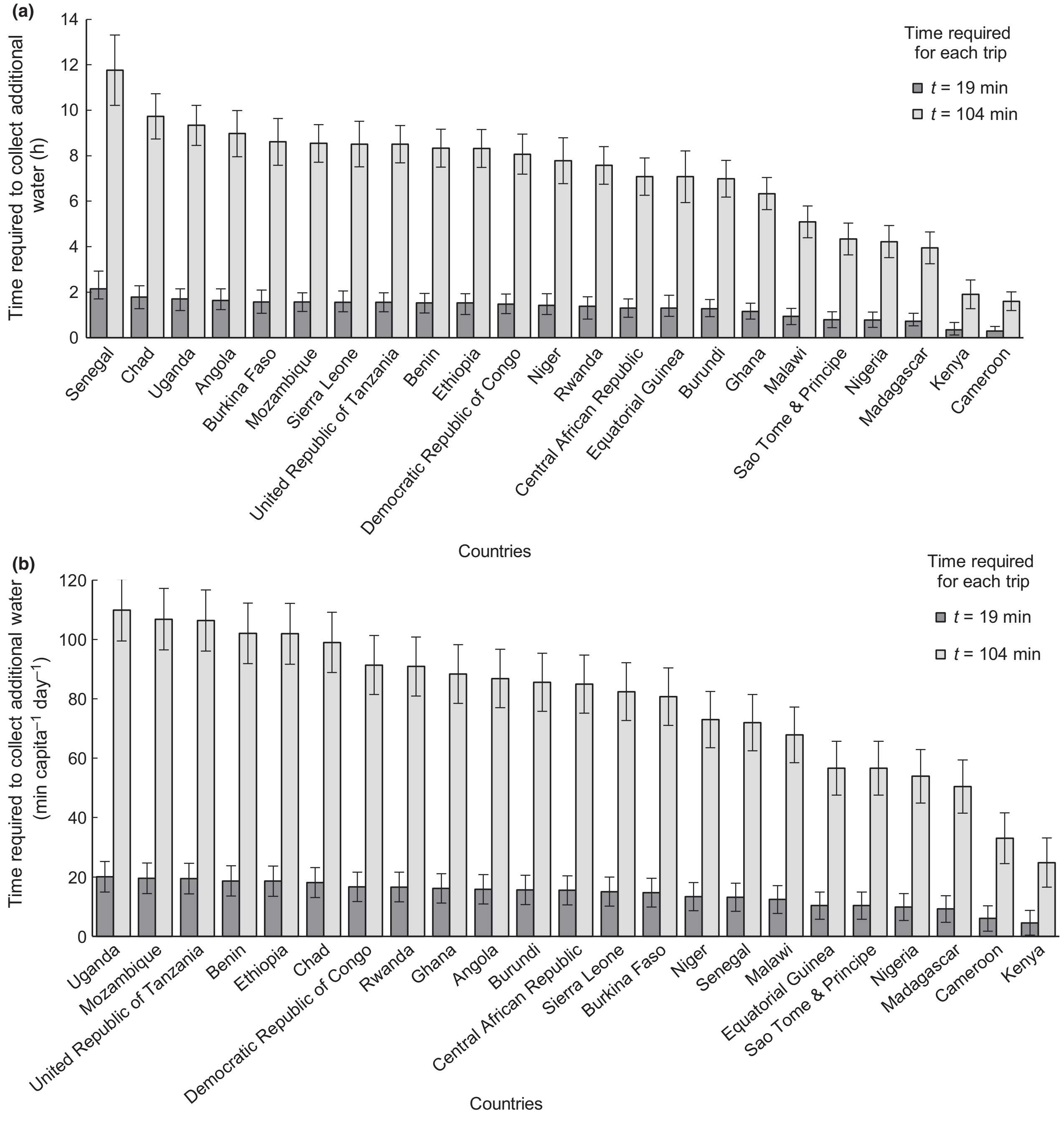

Fig. 4 Time required to collect additional water needed for anaerobic digestion. The volume of water collected per trip was assumed to be 20 dm^3 after Orskov *et al*. (2014), and the mean time required to collect water was assumed to be between 19 min for a centrally located water source and 104 min for a distant source after Rosen & Vincent (1999) (a) time taken per household; (b) time taken per capita.

For the remaining countries, even using an iron roof and including domestic water recycling, an additional area is required for rainwater harvesting. If no domestic water can be recycled, the area of iron roof needed to harvest the additional water for the biogas digester with an annual rainfall of 1000 mm y^{-1} is 10 ($\pm$2) m^2 $capita^{-1}$. This translates into a general equation for the area of iron roof needed for rainwater harvesting if no domestic water is recycled.

$$A_{roof} = \frac{R}{100} \quad (19)$$

where A_{roof} is the area of roof needed for each person in the household (m^2 $capita^{-1}$) and R is the annual rainfall (mm y^{-1}).

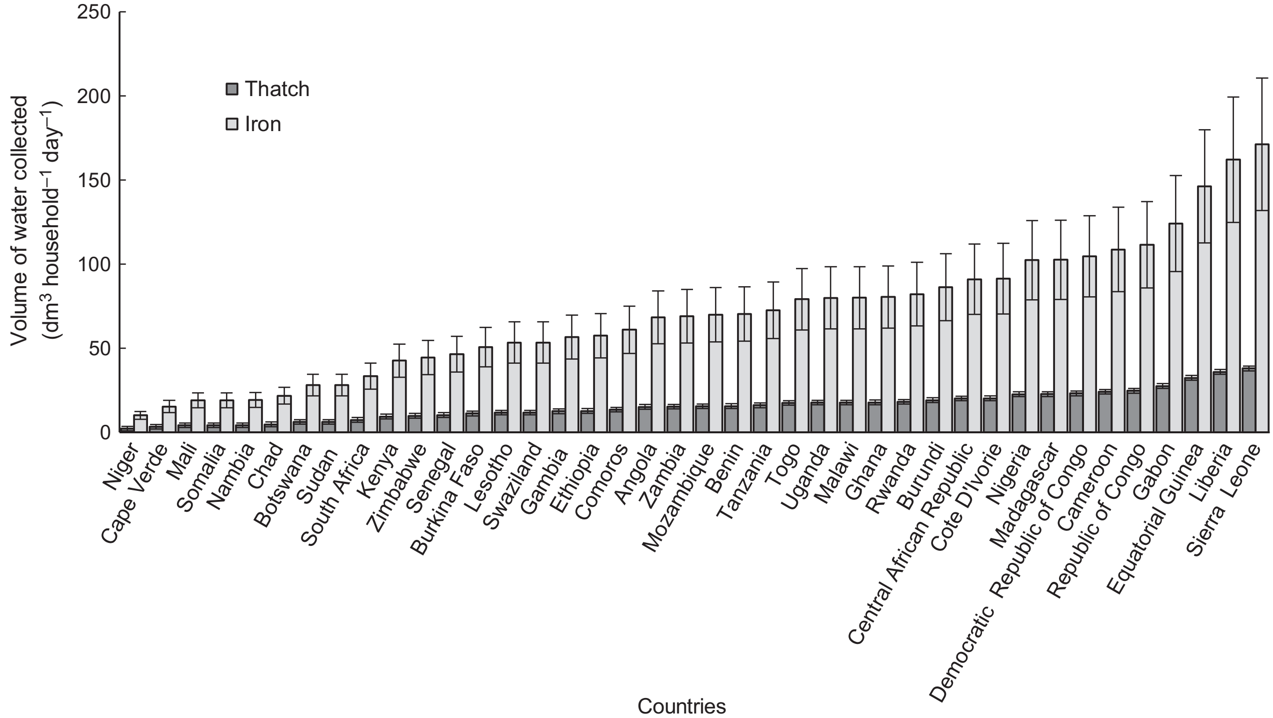

Fig. 5 Volume of water collected by rooftop rainwater harvesting. Water collection shown for a 28 m^2 roof, and the average of values reported in the literature of 15–40 m^2 (Pachpute *et al.*, 2009). Error bars show the rainwater collected at these two extremes.

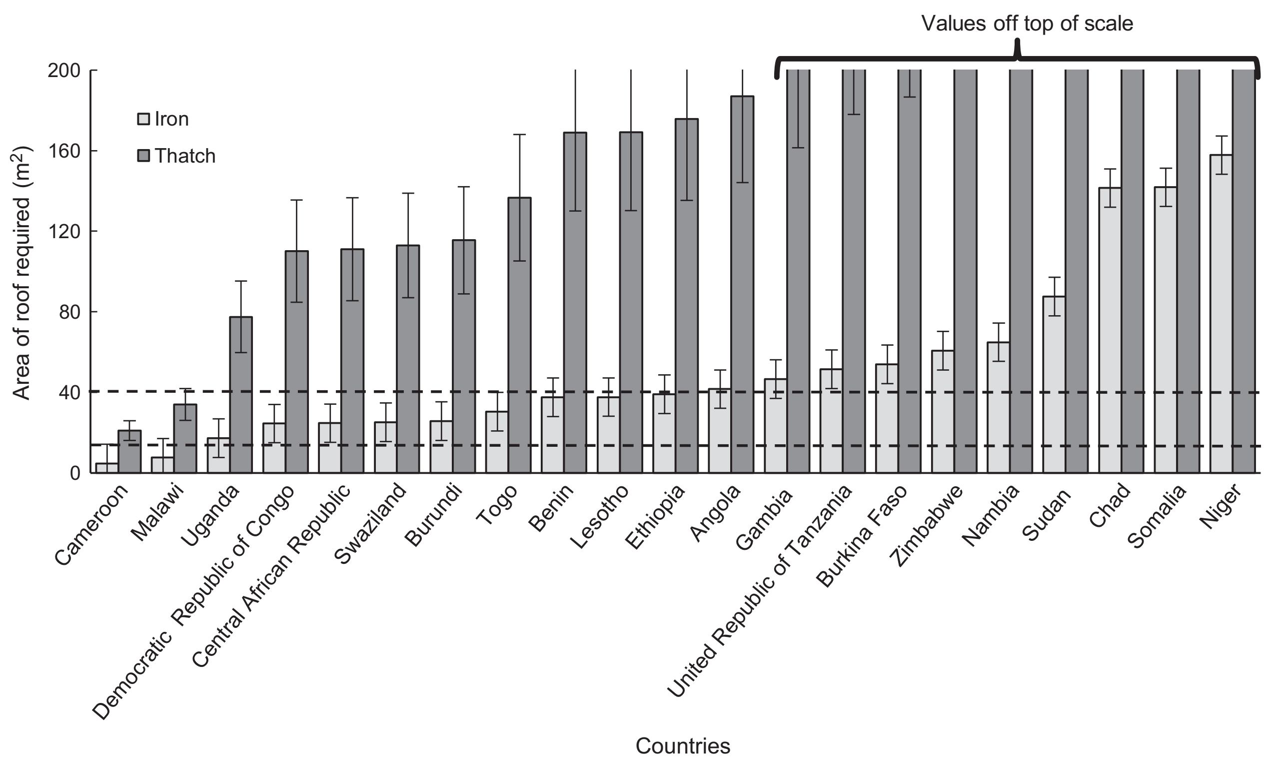

Fig. 6 Area of roof required to collect the volume of additional water needed to feed a biogas digester. Dotted lines show the normal range of roof areas reported in the literature; 15 and 40 m^2 (Pachpute *et al.*, 2009).

Aquaculture

Between 18 and 32 tilapia could be raised from the nitrogen in the bioslurry produced by a household with two cows. If, however, the household produces its biogas from nitrogen-rich pig manure (eight pigs), a much higher number of tilapia, between 87 and 100, can be produced (Table 4). Scaling this by $H_s/4$ gives an average over the countries considered of 117–135 tilapia. Assuming a fingerling stocking density of 0.5 to 3 fish m^{-2} (Yi *et al.*, 2008), the size of pond needed for the fish fed on the bioslurry from the pigs would be 29 to 200 m^2, equivalent to a square pond with sides 5.4 to 14.1 m. A 1-m-deep pond of this size would hold (2.9×10^4) to (2.0×10^5) dm^3 of water, providing 79–548 dm^3 day^{-1}. The distribution of pond sizes needed across countries for both pig and cow manure is given in Fig. 7.

The maximum amount of additional water required for anaerobic digestion is 136 dm^3 day^{-1} (Fig. 3). This is equivalent to an annual requirement of 5.0×10^4 dm^3. A 1-m-deep fish pond of area 50 m^2 could supply this amount of water (equivalent to a square pond with 7 m sides). This would allow a stocking density of 1.8 to 2.0 fish m^{-2} with the nitrogen available in the bioslurry produced by eight pigs, which is within the range of stocking densities given by Yi *et al.* (2008). Therefore, the size of pond needed to hold the additional water for anaerobic digestion, the stocking density of fish, and the nitrogen provided by anaerobic digestion for pig slurry are all compatible. By contrast, for the bioslurry produced by cow manure, the stocking density of 0.4 fish m^{-2} is less than the normal range, suggesting that an aquaculture/biogas digester system less viable using cow than pig manure.

As discussed above, the water required to fill the pond can be collected from rainwater harvesting from an iron roof or from an impermeable surfaced groundwater catchment surrounding the pond. However, because the pond must be uncovered to allow growth of the algae used to feed the fish, the evaporative losses from the pond may further increase the amount of water that must be collected. If annual rainfall exceeds evaporation ($R > E$), the pond will increase the amount of water available for digestion and aquaculture by $A_p(R-E)$. Assuming the average stocking density, the size of pond that can be stocked by the bioslurry produced for each household member is 23 ($\pm$2) m^2 capita^{-1}, meaning that extra water of 3.7 ($\pm$0.25) dm^3 day^{-1} will be provided to the digester for each 100 mm y^{-1} of hydrologically effective rainfall ($R-E$). However, if evaporation exceeds rainfall, additional catchment area is needed for rainwater harvesting. If ($R-E$) = 100 mm y^{-1} and R = 1000 mm y^{-1}, this comes to 1.5 ($\pm$0.1) m^2 capita^{-1}. This can be generalized to give the extra catchment area needed, A_{c_aq} (m^2), from the household size, H_s (capita), the rainfall and evaporation as follows:

$$A_{c\_aq} = 1.5 \times H_s \times \left(\frac{(E-R)}{R}\right) \quad (20)$$

The evaporation data available from FAO (2013a) suggest that in many cases, the potential evaporation exceeds rainfall, so water for aquaculture would need to be harvested from rooftops and a surrounding catchment.

Discussion

Water required for anaerobic digestion

The water required for anaerobic digestion was estimated from the manure provided by two cows or eight pigs (Orskov *et al.*, 2014), proportioned according to the size of household. If a different amount of biogas is needed per capita, the volume of water required would also be different; the volume required is approximately 50 dm^3 day^{-1} for each cow and 10 dm^3 day^{-1} for each pig providing manure to the digester. The uncertainty in this estimate is associated with the variation in the amount of manure produced by each animal and the

Table 4 Number of fish produced by nitrogen in bioslurry from two cows or eight pigs

Type of animal	Nitrogen content of the feedstock, N_{feed} (kg y^{-1})	Available nitrogen in the bioslurry, $N_{bioslurry}$ (kg y^{-1})	Number of fish (minimum) (N_{req} = 1.46 kg fish^{-1} y^{-1})[a]	Number of fish (maximum) (N_{req} = 1.28 kg fish^{-1})[a]
Cows				
Minimum	54	26	18	20
Maximum	86	41	28	32
Pigs				
Minimum	268	127	87	100
Maximum				

[a]FAO (2013b).

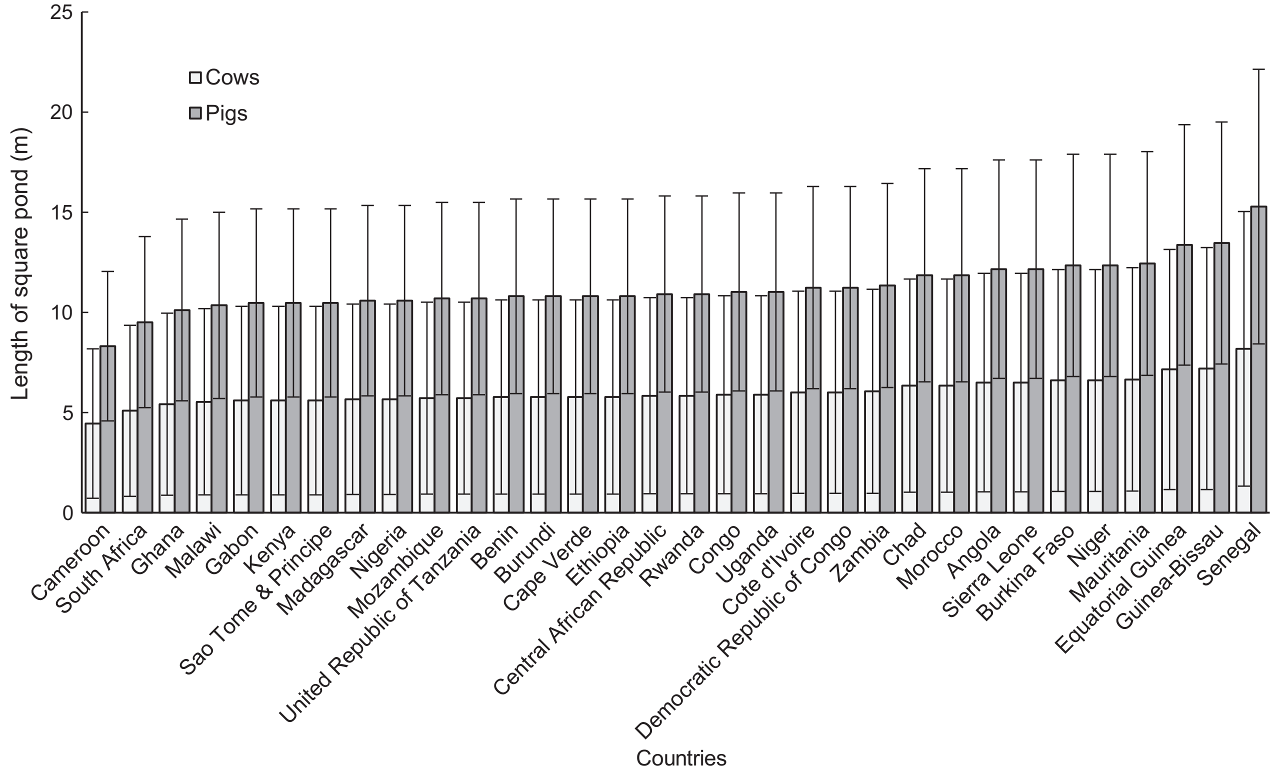

Fig. 7 The size of a square pond needed to stock the tilapia that could be raised on the household production of bioslurry. Stocking densities assumed to be 0.5 to 3 fish m^{-2} after Yi *et al.* (2008).

percentage dry matter in the manure, and is dependent on the species, breed, and diet of the livestock. For cows in Sudan, the uncertainty calculated using data provided by Omer & Fadalla (2003) was 23%; a similar level of uncertainty might be expected for pigs.

In these calculations, we estimated water requirement using the potential household requirement for biogas, rather than the potential for biogas production. In practice, the availability of feedstock to the household usually limits the biogas produced. The national potential for biogas production could be estimated using national livestock statistics, as done by Subedi *et al.* (2014). However, this potential for biogas production is unevenly distributed between households; wealthier households are likely to have more livestock and so a surfeit potential to produce biogas, while biogas production in poorer households tends to be more limited. The estimates of water required for anaerobic digestion given here represent the water requirement of households with access to sufficient feedstock to meet all of their energy needs.

Domestic water recycling

The amount of domestic water that can be recycled was calculated from national statistics, partitioned into different activities using data from a survey in Kisumu, Kenya. Within country and within year variation is likely to occur, depending on the accessibility of water to households in different regions and at different times of year. Furthermore, cultural differences may change the distribution of water use for different activities. For a more detailed analysis of the potential for domestic water recycling in a particular location, local surveys of water use should be done.

Domestic water use is dependent on the distance and quality of the water source, with per capita water consumption increasing if the water source is close to the household (Sugita, 2006). More economically developed countries are more likely to have water piped into households or to centrally located sources. Household in these countries are likely to be able to more easily meet the water requirements of the digester by collecting water by hand. In less economically developed countries, with less opportunity for piped water or centrally located water sources, rainwater harvesting becomes more important to the success of the digester.

Despite domestic water being available for recycling, it is often not used in the digester due to cultural perceptions that using wastewater could spread diseases (Ogunmokun *et al.*, 2000). Therefore, a successful biogas programme should include an education programme to encourage safe reuse of household wastewater. The use of urine from humans was not considered here. Humans can produce up to 1 dm^3 in urine every day (Sibisi & Green, 2005), which provides additional water to the digester. This was not included because it is not likely that everyone is in the house all day.

Collection of additional water required to run digester

In the majority of the countries in SSA, recycling domestic water is insufficient for anaerobic digestion and additional water collection is needed. Therefore, before a biogas digester is installed, potential sources of additional water should be surveyed, and the feasibility of different methods of water collection considered. For many households, without access to transport for collecting water, collecting the extra water by hand is not an attractive option as it is likely to be too time-consuming. The calculations using national data suggest that, with a distant water source, only 33% of the countries considered would require less than 30 min capita^{-1} day^{-1} to collect the additional water needed. While there will be local and seasonal variation around this national norm, this result suggests that it is important to consider rainwater harvesting as an adjunct to installation of a biogas digester in most conditions in SSA. Without associated rainwater harvesting, in many areas of SSA, biogas digesters are unlikely to be successful in providing a long-term, sustainable, and widely applicable source of household energy; only households with a very local and reliable water source will be able to use biogas.

Rainwater harvesting

Thatched roofs are commonly used in SSA, but are not well suited to rainwater harvesting. Thatched roofs can be improved to collect water more efficiently by using polythene sheeting or by folding the roof to increase the surface area and so collect more water. However, erecting a roof with these features would require more labour (DTU, 2002). Alternatively, asbestos roofing could be used as it has a high run-off coefficient, but this is not recommended as the particles released from asbestos can be related to breathing problems (Worm & van Hattum, 2006). Corrugated iron and tile roofs are a more viable option, with a high run-off coefficient and producing good quality water that can also be used for human consumption. Gutters, splash guards, and pipes can also be installed on the roof edges to increase capture of water, leading water straight into the inlet pipe of the digester to avoid evaporative losses (Sturm *et al*., 2009).

The size of roof is critical when looking at the potential for rooftop rainwater harvesting. In east Africa, it is common to find roof sizes from 15 to 40 m^2 (Pachpute *et al*., 2009), but even using an iron roof, in 50% of countries a roof size larger than 40 m^2 would be needed to provide the water required. This could be provided by a ground catchment or open pond. The results presented here are based on national data for annual rainfall; clearly within country rainfall distribution will dictate the amount of water that can actually be harvested in a particular household. Seasonality also impacts the amount of water that can be harvested; if a rainfall event is particularly heavy, it may be difficult to capture all of the run-off occurring in a very short period of time.

Aquaculture

Aquaculture has great potential to ensure a sufficient supply of water to run a biogas digester throughout the year. In practice, some bioslurry could be used in aquaculture, and the remainder used to fertilize crops, so the size of pond can be chosen to meet the preferences of the household. Aquaculture ponds require regular drainage to prevent accumulation of solids on the bottom of the pond (Boyd, 2004). This could be done by draining and refilling of the pond throughout the year. The fishpond could be partially drained and resupplied with rainfall run-off to ensure good water quality as well as providing additional water and organic wastes to the digester (Boyd, 2004). The tilapia could be partially harvested every few months (Murnyak, 2010), so allowing a smaller pond to be used to produce the same number of fish each year. In areas where rainfall is low and seasonal, the fishpond could be stocked with fish only in the rainy season, allowing the pond to be covered during the dry period to prevent evaporative losses (Murnyak, 2010). Seasonal use of the biogas digester might also provide a more feasible solution to household energy needs, with biogas being used in the rainy season when biomass sources are wet and water is more plentiful, and biomass fuels being used in the dry season when biomass is dry and easy to burn and water is scarce. The financial viability of seasonal use of biogas digesters needs further consideration; if the digester is only use for 50% of the year, then the payback period for the digester will be doubled.

Constructing the pond requires an initial input of labour, but could also provide significant advantages to the household. As well as storing water for use in the digester, aquaculture can provide an important source of income. The average market value of Nile tilapia in

SSA in 2001 was \$1.27 kg^{-1} (Josupeit, 2005). The FAO Aquaculture Feed and Fertiliser Resources Information System (2013) suggests that tilapia yields of 3000 kg ha^{-1} can be sustained in a well fertilized pond. Therefore, from the 29 to 200 m^2 pond that could be fertilized using the N available in bioslurry from pigs (Table 4), the yield of tilapia would be 9–60 kg y^{-1}, with a 2001 market value of \$11–\$76. The annual value of the tilapia produced using the bioslurry from cows is estimated to be only \$1 to \$3, meaning aquaculture using the bioslurry from cows is not likely to be viable, unless the cows are fed on an unusually nitrogen-rich diet.

Recommendations

- Use of household wastewater is important to the success of the biogas digester, but is sometimes not done because it is culturally unacceptable. Therefore, an education programme should be included alongside installation of the biogas digester to encourage efficient reuse of household wastewater.
- In the majority of the countries, recycling domestic water could only meet a proportion of the additional water required for anaerobic digestion. Therefore, before the installation of the digester, methods that will be used to collect the additional water needed for the digester should be considered.
- Collection of the water needed can take a significant amount of time. Therefore, before installation of the digester, the time spent doing different activities should be budgeted to ensure that the total time spent on household activities does not significantly increase with the installation of the digester.
- In most countries, rainwater harvesting on a thatched roof cannot provide sufficient water for the digester. Therefore, if possible roofs with a higher rainwater coefficient should be used to harvest rainwater, such as iron or tile roofs.
- In 50% of countries of SSA, even an iron roof cannot harvest sufficient water for the digester. Therefore, an open pond or ground catchment should be used to collect additional water.
- If there is a local market for fish, bioslurry from pigs could be used to grow plankton to feed fish in the pond, designing the management of the pond to match local rainfall conditions.
- In countries with very low and highly seasonal rainfall, consideration should be given to the potential for limiting the use of biogas to the rainy season when water is more plentiful and the alternative biomass sources of household energy are wet and difficult to burn.

Acknowledgements

This work was part-funded by the UK Natural Environment Research Council funded ESPA project, NE/K010441/1 'ALTER – Alternative Carbon Investments in Ecosystems for Poverty Alleviation'. We are also grateful to the AUC for funding part of this work under the Afri-Flame project on 'Adaptation of small-scale biogas digesters for use in rural households in sub-Saharan Africa'.

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