Overview of Holistic Application of Biogas for Small Scale Farmers in Sub-Saharan Africa

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ABSTRACT

Holistic farming systems provide designs for the whole farm that make long term sustainable use of nutrients, water, labour, finances and energy. In using organic residues to produce energy, and safely recycling the digested residues back into the farming system, a biogas digester could be a central component of many holistic systems. This paper discusses the influence of environmental, socioeconomic and cultural constraints on the use of biogas digesters in holistic farming systems in Sub-Saharan Africa. In higher altitude areas where maintenance of optimal temperature can constrain anaerobic digestion, floating drum or fixed dome digesters are a better option than flexible balloon digesters because they are less susceptible to temperature changes. If water is a key constraint, rainwater harvesting could be used to reduce the additional labour needed to collect water. If energy is the most limiting resource in the farming system, the optimum use of organic residues might be as a fuel for anaerobic digestion, whereas, if water is limiting, energy production by burning or pyrolysis might be a better option. The bioslurry from anaerobic digestion can be used in fish ponds to produce plankton to feed fish, and can be applied to fertile fields and fields of intermediate fertility, while biochar from pyrolysis is better used to improve the soil in infertile fields. If labour is limiting, it is particularly important that the system design minimises any additional labour needed to process the organic residues on a daily basis, considering trade-offs between labour and other resources.

Keywords

Biogas
Holistic farming
Resource use
Sub-Saharan Africa
Anaerobic digestion

Abbreviations

1. Introduction

All farming systems, whether holistic or not, are structured around the availability of the resources; water, energy, nutrients, carbon, labour and finance. Holistic farming systems attempt to maximize re-use of resources so as to maximize efficiency and long term sustainability, incorporating financial, land and grazing planning, as well as biological monitoring [1]. Biogas digesters can form a central component of a holistic farming system, allowing the efficiency of many aspects of the system to be optimized by providing energy for household use, cleaning and recycling of waste water and producing an organic fertilizer that can be used in aquaculture or can be used to return carbon and nutrients to the soil to improve crop productivity [2]. There is a significant move within many countries in Sub-Saharan Africa (SSA) to increase the implementation of zero grazing systems. This provides a timely incentive for biogas development in order to fully utilise the increased animal excreta captured at the household level. The number of biogas installations across Africa is increasing, largely in the domestic energy sector, due to national domestic biogas programmes, such as supported by the African Biogas Partnership Programme, aiming at constructing 70,000 biogas plants in Rwanda, Tanzania, Kenya, Uganda, Ethiopia, Cameroon, Benin and Burkina Faso by the year 2013 [3]. Success of these systems depends on them being fully integrated into the farming system so that the multiple potential benefits of biogas digesters can be realized.

As for many issues related to rural development with small scale farmers in Africa, there is never only one solution [4]. Rural areas, in most cases, are characterized by heterogeneity in physiographic, climatic and socio-economic conditions [5]. A range of different approaches is required to cater for the technological demands of different areas. The same applies to production of biogas. In principle, anaerobic digestion is a conversion of organic materials into methane, carbon dioxide and biogas slurry [6]. While the principles are the same, there are many different methods that can be used, depending on the climate, soils, organic residues and water availability at different times of the year. Methods of anaerobic digestion are classified by critical operating parameters including continuity (batch or continuous), operating temperature (psychrophilic, mesophilic or thermophilic), reactor design (plug-flow, complete-mix or covered lagoons), and solid content (wet or dry) [7]. Designs most commonly used by small scale farmers in Africa and Asia are continuous, mesophilic (30-38 °C [8]), plug-flow, wet processes and include flexible balloon [9], fixed dome [10,11] and floating drum digesters [10]. The design of the digester has implications for the conditions that must be supplied by the farming system to achieve optimum biogas production (amount and quality of feedstock, water, temperature etc), and so profoundly influences the nature of other operations that can be included on the farm. Choice of method is also dependent on the culture and tradition of the people. For instance, for some cultures human excreta can be incorporated; for other cultures not so [12]. This impacts the nature of the feedstock available for digestion.

Different authors have attempted to formalise methods used in farming system design. De Jager et al. [15,16] presented the NUTMON concept (Nutrient Modelling for Tropical Farming Systems - now rebranded at farm scale as MONQI - Monitoring for Quality Improvement), which integrates agronomic, economic and social objectives to arrive at specific nutrient management practices, using a questionnaire to produce a farm inventory of nutrient and economic flows to and from all farm units. The NUANCES approach (Nutrient Use in Animal and Cropping Systems: Efficiencies and Scales [4]) uses dynamic simulation models to maximise the use efficiency of all inputs at farm level; this allows modelling techniques, such as inverse modelling [15], to be used to suggest farming strategies that would result in the best possible trade-offs between different farming objectives. These approaches have not yet included biogas digesters; here we review the information that is needed to use such methods to design a farming system around a biogas digester.

By carefully planning the holistic farming system around the recycling of resources provided by a biogas digester, improved returns for the input of labour and the investment needed for the installation and operation could be achieved. This article discusses how the elements of such a holistic farming system can be brought together and designed to suit the particular environmental, socioeconomic and cultural constraints of operation. By bringing together, in one paper, a review of the impact of different constraints on the design of a farming system centred on a biogas unit, the potential impacts on resource flows and feedbacks are considered. This provides a new emphasis on the design of biogas digester based farming systems in SSA that has not yet been considered in previous work.

2. Environmental constraints

2.1. Temperature

The optimal temperature for anaerobic digestion is between 35 and 40 °C [16]. In an investigation of the impact of temperature on methane production capacity and energy output, Wei et al [17] observed the optimum temperature for anaerobic digestion was 35 °C, producing the largest amount of methane, in only 31 days. At lower temperatures, total methane production was reduced and required a longer period for complete fermentation. However, methane production continued at temperatures as low as 20 °C. Bohn et al [18] investigated methane production in a laboratory-scale reactor, inoculated with mesophilic bacteria and operated at temperatures as low as 12 °C. Hydrolysis was observed to decrease below 25 °C, and below 16 °C, acidogenesis and methanogenesis became rate limiting steps; this was accompanied by adaptation of the microbial population in the digester.

If the temperature is much lower than the optimum, other means may be required to raise the temperature in the digester. Kumar and Bai [19] used a greenhouse canopy to raise the temperature in a plastic digester, allowing gas production to continue during the winter period when temperatures ranged from a maximum of 16-21 °C to a minimum of 2 °C. Hong [20] reported the use of compost to insulate and heat an anaerobic digester. The biogas produced can also be used to generate the heat required to raise the slurry temperature to the optimum for anaerobic digestion [21].

The heat lost during anaerobic digestion is a function of the surface area and the insulation of the digestion vessel. Therefore, small scale anaerobic digesters lose a higher proportion of their heat than larger digesters. This is one reason why small scale biogas units are found in Asia and Africa but are not common in more temperate climates. Even in Asia and Africa, biogas technology is not popular in high altitude areas due to low temperatures. Biogas units in temperate zones are generally very large and not used by small scale farmers, and even in sub-tropical zones, part of the year maybe too cold to maintain efficient small scale biogas production. This suggests that small scale biogas units are more suitable for tropical and sub-tropical than for temperate regions.

Digester design affects the temperature profile that can be maintained in the digester; in cold, hilly conditions, a fixed dome digester was observed to maintain a lower temperature than a floating drum digester for most of the year due to its shallow structure and exposure of slurry to ambient temperatures [22]; a flexible balloon digester was even more affected by ambient temperatures than the fixed dome digester, reducing biogas production by 34% compared to the fixed dome digester [9]. Therefore, if maintenance of optimal temperature is a problem at a site, a fixed dome or floating drum digester may be preferable to a flexible balloon digester.

The average annual air temperature in SSA ranges from 33.9 °C in Dallol, Ethiopia, to 20 °C along the coast of Angola [23]. The highest recorded temperature extreme across Africa is 57.8 °C in El Azizia, Libya, and the lowest extreme is -11 °C at high elevation in Ifrane, Morocco [24]. While the annual average air temperatures at many sites in SSA are suitable for mesophilic anaerobic digestion, the digesters must also be designed to function with a wide extreme of temperatures, so insulation of the digester will improve methane production in many regions.

2.2. Water

For optimal anaerobic fermentation, the amount of dry matter in each 100 kg of water must be between 2 and 5 kg [25]. Because 1 kg of water occupies a volume of approximately 1 dm^3, this is equivalent to 0.02 – 0.05 kg dm^{-3} water. This means that for each 10 kg of dry matter there is a need for a minimum of 200 dm^3 of water. Pandey et al. [26] expressed this as approximately equal volumes of water and dung being fed into the digester daily. Table 1 provides estimates of the daily production of dry matter in organic manure for different types of livestock in SSA, so allowing the water requirement for anaerobic digestion to be calculated. Using the estimated feedstock requirement given in section 3.3, a 4 person household would require between 88 and 100 dm^3 water per day to run a biogas digester. Whilst this may not be a problem in the wet seasons, it may cause difficulties in dry seasons, and the distance to water supply may become a limiting factor for parts of the year.

TABLE 1 HERE

If water is limiting, the design of the holistic farming system can incorporate recycling of water from household uses. Because the digestion operates in a closed tank, in contrast to composting, losses of water during the treatment are likely to be very low [27]. Therefore, diverting water to the digester before using it for irrigation retains water in the farming system and results in only a small reduction in the waste-water available to irrigate the crops. Because household digesters are not usually used to treat toxic materials, the bioslurry produced is suitable for direct application to crops. Furthermore, the digestion process can adjust the chemical composition and reduce the number of pathogens in the household waste-water, so making it more suitable for use in irrigation. However, waste-water with an excessive detergent or disinfectant content should be avoided as it could interfere with the digestion process [28].

Water is used in SSA households for drinking, cooking, hygiene (bathing, laundry, washing hands, food and dishes) and irrigation [29]. The amount of water used by a household depends on the availability of the water source; whereas WaterAid [30] suggested that the average person in the "developing world" uses 10 dm^3 d^{-1} for drinking, washing and cooking, Cairncross and Cliff [31] reported that households in Mozambique with a centrally-located water source used an average of 11.1 dm^3 $caput^{-1}$ d^{-1}, and those relying on a distant source averaged only 4.1 dm^3 $caput^{-1}$ d^{-1}. The minimum water intake required for survival in tropical areas is estimated at 1.8-3.0 dm^3 $caput^{-1}$ d^{-1} [32], so in households relying on a distant source, this would amount to waste and irrigation water of less than 2 dm^3 $caput^{-1}$ d^{-1}, whereas in households with a centrally-located water source, waste and irrigation water would increase to nearly 10 dm^3 $caput^{-1}$ d^{-1}. Assuming an average water use of 10 dm^3 $caput^{-1}$ d^{-1} [30] and consumption of 2 dm^3 $caput^{-1}$ d^{-1} [32], a 4-person household would output approximately 30 dm^3 $caput^{-1}$ d^{-1}. This amounts to only 30-35% of the water required to run the biogas digester discussed above, and an extra 60-70 dm^3 water per day would need to be collected. As discussed in section 3.2, this could amount to an average across SSA of 3 to 4 hours extra labour per household per day.

Household rainwater harvesting may help to alleviate the labour needed to collect additional water [33,34,35]. Harvested rainwater is mainly used for irrigating crops, but may be used for many additional purposes, including watering of livestock and domestic use [36]. This puts additional demands on the amount and quality of water available for crop irrigation. One advantage of using domestic waste water in a biogas digester is the treatment of the water so that it is more suitable for re-use in irrigation after being used in the house. Storage tanks or ponds can collect rainwater from roofs and other large surfaces [36], and can be used to provide an additional source of income in the form of fish ponds, as often seen for example in Vietnam [37]. Here the liquid from the biogas digester is directed back into a fish pond to fertilize plankton in the ponds, which in turn is the food for fresh water fish, such as Tillapia [38]. Therefore, although investment in water harvesting technology requires additional financial input that could be used elsewhere on the farm, in time it can provide a financial return from the fish. Water from the fish ponds can subsequently be used for irrigation. The largest fraction of the nutrients fed to ponds accumulates in the sediment, which contain nitrogen and potassium, but only small amounts of soluble reactive phosphorus [39,40]. Therefore, pond sediments, supplemented with phosphorus, can also be used as a highly effective organic fertiliser.

Widespread collection and storage of water can impact other water users in the area; this effect may be positive, for instance if it prevents excessive runoff resulting in erosion, or negative if it removes water from downstream water users. Dry anaerobic digestion technologies may become more widespread in the future, although these can introduce problems of long retention times and so also increased size requirements for digestion tanks [7].

In many cases not enough water can be collected for a fish pond and some cultures would not use the fish. If this is the case, the design of the holistic farming system should include direct use of biogas slurry for plants, giving farmers the opportunity to include nutrient hungry cash crops in their farming systems [41]. In some cases, even after optimising water use across the farm, the water supply is so limited that it is not feasible to include a biogas digester within the farming system. Areas of SSA where biogas digestion is not a realistic option should be identified and biogas extension programmes should only target areas where water availability allows a year-round supply of biogas without the requirement for excessively high labour input to collect the additional water needed.

2.3. Nutrients and carbon

If nutrients are limiting the productivity of the farm, the extra labour required to collect water and feed the digester may become more worthwhile to the householder because the digestion process converts nutrients in organic residues into a more available form. Release of carbon as methane increases the concentration of immediately available and rapidly released nutrients in the feedstock [42]. Because anaerobic digestion is usually limited by oxidation potential rather than nutrients, typical concentrations in anaerobically digested materials of inorganic nitrogen in the form of immediately available ammonium are 50-75% of the total nitrogen [43,44]; similarly, inorganic phosphorus constitutes a major portion of the total phosphorus, although much of this is usually insoluble due to precipitation of inorganic phosphates [45]. Smith et al [41] argue that because the bioslurry produced by biogas digesters provides a source of immediately available nitrogen that can be used as and when it is needed, the risks of nitrogen loss from the necessary early application of untreated organic residues are very much reduced. Because losses of nutrients during anaerobic digestion are less than in other methods of organic residue treatment (such as composting or pyrolysis), Smith et al [41] also suggest that where crop production is not limited by other factors, anaerobic digestion can provide the more efficient means of retaining nutrients in the farming system. Improving crop yields will also increase carbon sequestration from plant inputs to the soil [46].

In contrast to soil nutrients, anaerobic digestion is not a good method of increasing soil carbon because a lower proportion of the carbon is lost and the carbon remaining is more stabilised during pyrolysis than during anaerobic digestion [47]. Therefore, significantly more carbon is sequestered in the soil by incorporating the biochar produced by pyrolysis rather than the bioslurry produced by anaerobic digestion [47]. Development of commercially available small-scale pyrolysis cook-stoves is in its very early stages, but this technology has the potential in future to sequester significantly more carbon than sequestered by other treatment methods [48]. Therefore strategies to optimise recycling of nutrients and carbon should use a combination of anaerobic digestion of wet, nutrient rich materials, mixed to achieve the optimum carbon to nitrogen ratio for methane production of 25:1 [44], and pyrolysis of the dry, carbon rich materials that remain [47].

The use of these differently treated residues to fertilise crops and fish ponds, and to improve the soil structure and water holding capacity can then be optimised within the farming system in order to produce the greatest increase in overall productivity. Fields within a farming system can be categorised as (1) fertile fields that hold sufficient nutrients in the soils so crops are unresponsive to fertiliser, (2) intermediate fields that are nutrient limited and so crops are highly responsive to fertilisers, and (3) infertile fields that limited by other factors in addition to nutrients so crops are unresponsive to fertilisers [4]. Optimum use of nutrients requires that the valuable immediately available nutrients in the bioslurry be applied first to the fields that are most responsive to the applications. In nutrient deficient systems in SSA, fields that are fertile and unresponsive to fertilisers are likely to be rare. Infertile fields of category 3 provide a low yield response to bioslurry applications. Crop productivity is intimately linked to the soil organic matter content, which influences soil physical, chemical and biological properties, as well as indigenous soil nutrient supply [49]. Therefore, the bioslurry from anaerobic digestion should be applied to the intermediate fields in category 2 first, while the biochar from pyrolysis should be used to improve the soil in the infertile fields in category 3. Alternatively, bioslurry can be used to make high quality compost by mixing the bioslurry with other organic materials. Compost must be stored to allow the compost to mature, and so can be applied at a time when it is most useful to the crop [50] and convenient to the farmer. Farmers may need advice from extension workers as to how best to do this, as the optimum time to apply the compost will depend of climate, soil and types of crops. Further research is also needed to quantify the potential increase in losses of ammonia from compost heaps treated with bioslurry.

The use of bioslurry, biochar or compost rather than untreated manure requires adaptation in the farming system to accommodate the processing of organic residues. Additional labour will be required to process the residues, to use it to produce fish or to apply it to fields. Combining different treatment processes allows greater flexibility in the use of the energy produced, but would require further investment in a pyrolysis cook stove as well as a biogas digester. The short and long term economic returns from such an investment and the extra labour requirement for processing organic residues should be included in the whole farm analysis used to design the holistic system.

3. Socioeconomic constraints

3.1. Energy

In Sub-Saharan Africa 90-100% of the household energy demand is for cooking fuel [51], and the percentage of the cooking fuel obtained from fuel wood is between 75 and 100%, depending on country [52,53]. If fuel wood is in short supply, labour requirements for fuel collection can be very high, and alternatives, such as charcoal, can introduce a high economic burden to the household [54]. Recycling of organic residues has potential to supply a high proportion of the household energy demand.

The main methods currently available to obtain energy from organic residues at the small scale are by burning, pyrolysis or anaerobic digestion. Burning and pyrolysis require organic wastes to be dry [55]. Burning cow dung, firewood and charcoal have thermal efficiencies of 11%, 17% and 28% respectively [52]. Pyrolysis may yield between 38% and 50% of the energy contained in the feedstock, depending on the quality of the feedstock, the reaction conditions, and on whether the biochar produced is burnt as a fuel or incorporated in the soil [56]. By contrast, anaerobic digestion requires the organic residues to be wet. The energy yield from anaerobic digestion is highly variable, depending on the conditions and composition of the feedstock [57], but can be between 60% [28] and 75% [58]. Therefore if energy is the most limiting resource in the farming system, the optimum use of the organic residue might be as a fuel for anaerobic digestion. If, however, water is limiting, energy production by burning or pyrolysis is a good option.

Omer and Fadalla [52] presented estimates for the biogas required for different purposes in Sudan. Cooking in Sudan requires approximately 425 dm^3 $caput^{-1}$ d^{-1} of biogas, and a 2 mantle burner for lighting will require 140 dm^3 $caput^{-1}$ d^{-1} of biogas. Therefore, depending on the requirements for lighting, the biogas requirement might be expected to be in the region of ~500 dm^3 $caput^{-1}$ d^{-1}. The per capita energy requirement varies across countries. The typical rural energy requirement can be obtained for example using values provided by the African Development Bank [59] assuming 45 GJ t^{-1} of energy equivalent to oil and ranges from 7.65 GJ $caput^{-1}$ y^{-1} in Senegal to 17.55 GJ $caput^{-1}$ y^{-1} in Botswana, equivalent to 1000 to 2100 dm^3 $caput^{-1}$ d^{-1} assuming an energy content of ~0.022 GJ m^{-3} biogas [52,60]. The energy use depends on the time taken for cooking, which differs across countries due to different cooking traditions. Assuming biogas has a heating equivalence of 1.5 kWh m^{-3} [61], if a single gas plate, typically equivalent to 0.75 kWh electrical energy [61] is used to cook food for 1 hour, the biogas requirement will be ~500 dm^3. If the cooking tradition is for slow cooking stews, requiring 2-3 hours of cooking, biogas requirement will clearly be much greater than where cooking uses rapid techniques such as stir fry that may be completed in a few minutes.

3.2. Labour

While labour required for some aspects of the farming system will be reduced by including a biogas digester in the farming system (e.g. collection of domestic fuel), for other aspects labour requirements may be increased, at least during part of the year (e.g. water collection, mixing residues into a slurry suitable for anaerobic digestion, making and transporting slurry and composts to the fields, transporting residues to the digester).

The labour needed to feed the digester, mix organic residues, and to make and transport slurry and composts to the fields, can be partly accounted for as work that would need to be done to care for livestock and crops, and maintain the area around the household. Good design and layout of animal housing and the biogas unit can ensure that additional labour needed to feed and process the organic residues is small. If labour is limiting, it is particularly important that the design of the farming system is well thought out to minimise any additional labour needed to process the organic residues on a daily basis (e.g. positioning of the digester to minimise work needed to move residues to the digester). Advisory services can make a big difference to successful adaptation to biogas. If animals are not stall fed, additional labour may be needed to collect manure from the fields. Therefore, biogas digesters are most suitable for use with stall-fed animal production systems.

Depending on the location of the household, the extra labour required to collect the additional water needed to feed the digester can be significant. The average distance that women in “developing countries” walk to collect water every day is 6.5 km and the average weight that women carry on their heads is approximately 20 kg [62]. Depending on the weight of the water container, this is equivalent to 15-20 dm^3 water. As discussed in section 2.2, for a typical household in SSA, an extra 60-70 dm^3 water per day is required to feed the digester. This equates to 3-4 extra trips and, if water is collected from distant sources, can require a large input of additional labour. The average time spent collecting water in a number of studies in SSA was quoted by Rosen and Vincent [29] to be 134 minutes each day. If this is for a 4 person household with an average water use of 10 dm^3 $caput^{-1}$ d^{-1} [30], the time required to collect the additional water would be equivalent to 200 - 235 minutes (3 - 4 hours) per household per day. The majority of household water is collected by women and girls [63-65]. This has impacts on health [66], calorific requirement [32,63,67], and the amount of time available for other activities on the farm.

The additional labour needed to collect water must be balanced against the reduced labour needed to collect fuel wood. If 3-4 trips are required per day to collect the extra water needed to run the biogas digester, assuming the household relies on wood fuel collected in just 1 trip per day, a biogas digester will reduce the labour needed each day only if the source of wood fuel is 3-4 times more distant from the household than the water source. As forest reserves become depleted at their margins [54], the balance between labour needed for wood and water collection may shift to favour installation of small-scale biogas digesters.

Tittonell et al [68] proposed a categorisation of household diversity based on a functional typology of livelihood strategies, and observed consistent patterns in the number of months in the year when the household was food self-sufficient with respect to the land:labour ratio of the household; households with a lower land:labour ratio being observed to have less months of food self-sufficiency. They also observed a relationship between the carbon and nutrient stocks of the farm and the livelihood strategy, with larger wealthier farms that grow cash crops having carbon and nutrient stocks 2-3 times higher than medium to low income households that rely partly, or entirely, on off-farm employment for income. By impacting the land:labour ratio, as well as the carbon and nutrients available for recycling, it is likely that a biogas digester will strongly impact food self-sufficiency as well as the carbon and nutrient status of the farm.

3.3. Feedstock

For small farmers in Asia and Africa, the feedstock for biogas production is mainly excreta from livestock e.g. cattle, sheep, goats, horses, donkeys, rabbits and chickens but also from humans if culturally acceptable [12]. In many areas of Asia, livestock are kept close to houses, sometimes below the house as seen in Cambodia (Fig.1). In a so called cut and carry system, animal feeds are mainly by-products from crops for human food e.g. straw, groundnut and cassava leaves etc. If so, animals will be stall fed and so the manure is easily collected for biogas. If the cattle are grazing for part of the day, manure can be collected from the fields, but this requires extra labour.

FIGURE 1 HERE

Assuming optimum conditions for biogas production (temperature 30-35 °C; pH 6.8-7.5; carbon to nitrogen ratio 20-30; solid content 0.07-0.09 kg kg^{-1} kg fresh waste and retention time 20-40 days [44]), biogas production is dependent on the proportion of volatile solids in the organic residues [69]. Table 2 provides estimates of biogas production for a range of different organic residues. Cow manure, rice straw and water hyacinth all yield high amounts of biogas, producing over 100 dm^3 kg^{-1} of fresh residue.

TABLE 2 HERE

The amount of biogas produced per head depends on food intake and the size and breed of the animal. Housed dairy and beef cattle are estimated to produce more manure than feedlot cattle, which results in a higher potential for biogas production from dairy and beef cattle (over 2000 dm^3 d^{-1} per head) than from feedlot beef (less than 1700 dm^3 d^{-1} per head). Brown [70] suggested that 1-2 cows or 5-8 pigs would supply adequate feedstock for a single 4 person household biogas digester. The estimates of biogas production given in table 2 suggest this would equate to 830 to 1400 dm^3 $caput^{-1}$ d^{-1} from 2 cows (or 160 dm^3 $caput^{-1}$ d^{-1} from cattle in Sudan), and only 370 dm^3 $caput^{-1}$ d^{-1} from 8 pigs. Comparison against the estimated biogas requirements given in section 3.1 (500 - 2100 dm^3 $caput^{-1}$ d^{-1}) shows consistency with Brown's estimate of the number of cows needed, but suggests that a higher number of some breeds of pigs would be needed to provide a biogas yield sufficient for a 4 person household.

From the results of nationally representative household surveys in Ethiopia, Kenya, Rwanda, Mozambique and Zambia, Jayne et al [71] concluded that farm sizes in Africa are declining over time, with approximately 25% of agricultural households being virtually landless, controlling less than 0.1 ha caput^{-1}, the largest part of the variation in farm sizes occurring within, rather than between villages. Households controlling such a low area of land may be limited in the livestock they can manage, which may in turn limit their potential to run a biogas digester. A system based on human faeces alone would produce only 20 dm^3 caput^{-1} d^{-1} of biogas, which is not enough biogas to meet cooking needs. The system could be supplemented by vegetable material; for instance, sufficient biogas could be produced from 1.5 – 6.3 kg caput^{-1} d^{-1} rice straw or 2.6 – 11.0 kg caput^{-1} d^{-1} water hyacinth. In households controlling such small areas of land, consideration would also need to be given to the possibilities for productive use of the bioslurry produced.

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

3.4. Finance

Investment in a biogas digester requires financial input, not only for the digester itself, but also for cooking and lighting appliances, modified cooking equipment, and if water is limiting, equipment for water collection including a water tank or fish pond. Finances and the design of the holistic farming system are strongly interrelated. The strategy used to finance the digester impacts the economic returns on the digester and the profits that can be achieved from the farm. Similarly, the environment and design of the farm impact the finances needed to establish efficient operation of the digester.

One strategy to finance the digester minimises costs by selecting the cheapest digester designs and avoiding additional infrastructure associated with optimum use of the digester, such as water collection tanks and insulation. This strategy may reduce the efficiency of biogas production, increase the labour needed for daily operation of the digester, and reduce the potential profits from the farm by missing opportunities for income, such as fish production. Where limited funds are diverted to the purchase of equipment, they are not available for other materials that may be required on the farm, such as fertilisers and other agrochemicals. The impact of not buying fertilisers may be alleviated by improved retention of nutrients in bioslurry, but the implications of reductions in other agrochemicals on crop productivity must also be accounted for.

A second strategy draws on a community fund to establish the digester, paying back the money saved on fuel and fertilisers at regular intervals, so not requiring any initial outlay from the farmer. Such a fund might be pump-primed by a local benefactor, initiated by small upfront payments from members of a community group who then take turns to benefit from the fund. Another possible method for obtaining funding is by new internet-based approaches such as crowd-sourcing [72]; an approach where very small amounts of money are pledged by a large number of donors, so allowing the required sum to be pledged with very little cost to each individual. A similar strategy obtains the upfront payment for the equipment through micro-financing [73]. This strategy, however, involves considerable risk to the householder. Rockström [33] discussed how severe crop reductions in semi-arid regions, caused by dry periods occurring one or two out of five years and total crop failure caused by annual droughts once every ten years, results in reluctance in poor farmers to take entrepreneurial risks to improve crop productivity. As a result, despite the potential payback period of only a few years [74], many farmers have been reluctant to invest in relatively expensive biogas units. The prices can vary from about 100 to about 2000 dollars. The cheapest designs are the balloon digesters, as seen for example in Indonesia (Fig. 2), but these are also most vulnerable to damage by birds or sharp materials. The more expensive designs are more reliable and can last for many years.

FIGURE 2 HERE

If farmers are living closely together, another strategy is to form a co-operative and share the biogas produced and the initial cost of the digester. The co-operation may involve biogas being transferred in different proportions depending on contribution to the production of the biogas. Small scale cooperatives often function well in urban areas where the people are living closer together than in rural areas (Fig.3). This is a subject that needs further consideration as many different solutions can be achieved through cooperation.

FIGURE 3 HERE

4. Cultural Constraints

4.1. Requirement for products

Incorporating a biogas digester in the farming system changes the products that can be generated on the farm. In order for the farm to benefit from these changes, there needs to be a demand for the products, and this is dependent on location and on culture.

The location of the farm has a profound impact on the requirement for products. The rich organic fertiliser output from the digester presents opportunities for producing nutrient hungry cash crops and for aquaculture. Bioslurry can also be mixed with other organic residues to produce a compost that can be used directly or sold to other farmers. Farmers, especially in peri-urban areas where market gardening of cash crops tends to dominate, are often keen to obtain composts to fertilise their crops [75]. A farm located close to the market will also be able to profit from growing cash crops; a farm with a more remote location will need to overcome difficulties in transport of crops to market before the potential profit can be realised.

Cultural factors have, perhaps, an even more profound impact on requirement for products than location. In Vietnam, a valued output from holistic farming systems built around biogas digesters is freshwater fish that can be eaten by the family or sold at market. The food provided to the fish through plankton growing on bioslurry makes the biogas digester an important component of the holistic system. In Vietnam the fish are so valued that, in a survey of 54 pig farms, 20% of farmers reported that they raised pigs just to provide a nutrient input to their fish ponds [37]. By contrast, there is no tradition of eating fish in Ethiopia, so a holistic system including a biogas digester and fish pond is not an attractive proposition.

Through their impact on the requirement for products, the location of a farm and culture determine the elements that can be included in the farm design. This strongly impacts value of the biogas digester to the household, and so determines the likelihood of successful uptake of the technology.

4.2. Local attitudes to the technology

Location specific problems may arise affecting the prospects of biogas technology in a particular area. For example, biogas was blamed for increased prevalence of mosquitoes in some communities in Nepal, causing adverse publicity about the technology [76] and resulting in reduced uptake. The way organic residues are handled changes when a biogas digester is included in the farming system. Traditionally manure is used directly as a fertilizer. This must change to use of bioslurry, applied both directly and following composting with other organic materials that are not suitable for anaerobic digestion (eg. bagasse from sugar cane). Whether the increased handling involved in this processing of organic residues is acceptable is influenced by culture and religion. Religious beliefs may influence the types of manures that can be included in the biogas digester. For instance, pig manure is a popular feedstock for biogas digesters, but cannot be used by many Jewish or Muslim farmers due to their religious beliefs [28]. Such factors must be considered when determining whether there is sufficient feedstock to maintain an efficient digestion process.

3.7. Gender issues

Introduction of biogas may also affect the work allocated to women and men. Depending on country, Parikh [77] observed that the energy supplied by women in “developing countries” ranges from 10 to

80% of the total national energy supply; this is in the form of gathered fuel (biomass, animal dung, fuelwood) and the production of charcoal, bricquettes and dungcakes. The proportion of energy supplied by women is highest in rural areas, where availability of commercial fuels is low [78]. Often women in Africa and Asia collect wood for fuel far from where they live. Using biogas for cooking can reduce their workload and so be an attractive option for women. However, if men are responsible for animal husbandry, their workload will be increased by the extra handling needed to process the organic residues. If men control the household finances, this shift in workload may inhibit the uptake of biogas [79].

4. Conclusions

Design of holistic farming systems is becoming a highly formalised process, involving participatory research, farm typologies, data-mining, experiments and modelling tools [4,13]. These approaches allow the farm to be planned to optimise the use of available resources, within the socio-economic and cultural constraints of the household. Biogas digesters impact all of the most limiting resources, and so their incorporation on the farm can have a profound impact on the optimum farm design. However, usually a digester is incorporated into an existing system, so the questions posed are more limited: is it possible to include a biogas digester on this farm; how will it impact resource use; what additional practices can be used to improve resource use efficiency?

The conditions potentially constraining biogas use are summarised in Table 3. Biogas digesters can readily be incorporated in holistic farming systems in tropical and sub-tropical regions at low altitude where the water supply is not limiting. In cooler regions, to avoid heat loss, the design of the digester may be constrained to the more expensive floating drum and fixed dome digesters, rather than the cheaper flexible balloon design [9,10]. In dry conditions, additional investment in pools or tanks for rainwater harvesting may be required. The process of anaerobic digestion can improve the composition of water recycled from household uses, the collection of water to run the digester then providing opportunities for fish production and irrigation of crops that can further improve the overall productivity of the farm. The farming systems should be planned to apply bioslurry from anaerobic digestion to the fertile fields and fields that are responsive to nutrient inputs, while compost and biochar produced by pyrolysis should be used to improve the soil in the unresponsive infertile fields [4]. If energy and nutrients are the most limiting resources in the farming system, the optimum use of the organic residues might be as a fuel for anaerobic digestion, whereas if water and soil organic matter are limiting, energy production by burning or pyrolysis might be a better option. If labour is limiting, it is particularly important that the design of the farming system minimises additional labour needed to process the organic residues. If animals are stall fed, manure is easily collected for biogas, whereas manure from cattle that are grazing for part of the day must be collected from the fields. This requires more labour, but the farming system will benefit from the import of nutrients from surrounding areas. Investment in a biogas digester requires financial input, not only for the digester itself, but also for cooking and lighting appliances, modified cooking equipment, and if water is limiting, equipment for water collection. Where limited funds are diverted to the purchase of equipment, they are not then available for other materials that may be required on the farm. The implications of the consequent reduction in other inputs to the farm must be accounted for.

TABLE 3 HERE

Table 4 provides a qualitative assessment of the impact of different uses of organic residues on the livelihood assets of a smallholder farm in SSA. As discussed in section 2.2, anaerobic digestion requires input of water, but in some cases, this can have a positive impact on water use by treating water before it is applied to crops. Other uses of organic residues do not directly impact water use. The nutrient status of a farm is improved by feeding suitable organic residues to animals, composting and by using residues to produce biogas, anaerobic digestion having the most potential of the methods considered to increase nutrient availability. Pyrolysis of organic residues may also indirectly improve the nutrient status of the farm by reducing the losses of nutrients from the soil. The carbon content of the soil is improved by applying compost, bioslurry or biochar; bioslurry is likely to increase the carbon content of the soil less than compost or biochar. Energy is provided by producing biogas, by burning or by pyrolysis of the organic residues; if suitable residues for anaerobic digestion is available, this is likely to provide the highest return of energy per unit weight of organic residues. Composting requires more input of labour than not using the organic residues, whereas burning and pyrolysis require less input of labour as time required to collect fuel wood is reduced. Using organic residues to produce biogas can decrease the input of labour by reducing the time spent collecting wood, but if the water source is distant, labour input might be increased. All uses of organic residues are likely to increase household finances; further work is needed to fully quantify and compare the impact of different applications of organic residues on finances. If conditions are such that biogas digestion has a positive impact on water use and labour, biogas can improve availability of all livelihood assets on the farm, whereas other uses of organic residues only improve availability of some of the livelihood assets.

TABLE 4 HERE

In this paper we have attempted to quantify the constraints, benefits and tradeoffs of incorporating biogas digesters into farming systems. This analysis has necessarily been limited, as there is very little data available on which to base such assessments. Further quantification and analysis of the factors determining the impact of biogas digesters on the livelihood assets available in small scale farms in SSA is urgently needed. This should be done as a comparison to other potential uses of organic residues, so that the full implications of using organic residues to produce biogas can be determined. There is little doubt that the use of biogas digesters will increase rapidly in the years ahead. Already Asian countries (e.g. Vietnam, India and China) have millions of units. However, scientists, extension services and farmers all need to participate in developing our understanding of which type of digester is most suitable for different areas, how to set up co-operatives of small farmers to fund installations and how best to use bioslurry [80]. This is an aspect of total resource management where all outputs are considered to be resources and there is minimum waste from the system.

Acknowledgements

We are very grateful to the UK Department for International Development (DFID) New and Emerging Technologies Research Call for funding this work.

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Tables

Table 1 – Manure production from different types of livestock in Sub-Saharan Africa and the consequent water requirement for anaerobic digestion. Note, actual values are highly dependent on breeding and diet, but typical values are presented here as an approximate guide to water requirements for anaerobic digestion. The moisture content, M, is assumed to be 75% after Polprasert [27].

Table 2 – Biogas production from different types of livestock in Sub-Saharan Africa. Note, actual values are highly dependent on breeding and diet, but typical values are presented here as an approximate guide to water requirements for anaerobic digestion.

Table 3 – Potential constraints to application of biogas digesters in Sub-Saharan Africa.

Figures

Fig. 1 – Keeping livestock below living accommodation

Fig. 2 – Balloon digester in Uganda

Fig. 3 – Cooperative use of anaerobic digesters in urban areas

Fig. 1 – Keeping livestock below living accommodation

Photo: Bob Orskov, Cambodia, 2011

Fig. 2 – Balloon digester in Uganda

Photo: Vianney Tumwesige, Kabanyolo, Uganda, 2012

Fig. 3 – Cooperative use of anaerobic digesters in urban areas

Photo: Els Keunen (BTC Kampala), Kibera, Kenya, 2011

Table 1 – Manure production from different types of livestock in Sub-Saharan Africa and the consequent water requirement for anaerobic digestion. Note, actual values are highly dependent on breeding and diet, but typical values are presented here as an approximate guide to water requirements for anaerobic digestion. The moisture content, M, is assumed to be 0.75 dm^{3} kg^{-1} waste after Polprasert [27].

	[a] W = Wet weight produced (% live weight per day)	[b] D = Dry weight manure production (% live weight per day)	A = Average weight of animal (kg per head)	[e] P = Manure production each day (kg d^{-1} of dry weight per head)	[f] Water requirement for anaerobic digestion (dm^{3} d^{-1} per head)
Pork pigs	5.1	1.275	[a] 45	0.57	11
Laying hens	6.6	1.65	[c] 1.5	0.02	0.5
Feedlot sheep	3.6	0.9	[d] 25	0.23	5
Feedlot beef	4.6	1.15	[c] 217	2.50	50
Dairy cattle	9.4	2.35	[a,c] 356	8.36	167

[a] Polprasert [27]

[b] Calculated as (W x (1 - M))

[c] Omer and Fadalla [28]

[d] Rey et al. [29]

[e] Calculated as ((D/100) x A)

[f] Calculated as (P x (200/10)) [25]

Table 2 – Biogas production from different types of livestock in Sub-Saharan Africa. Note, actual values are highly dependent on breeding and diet, but typical values are presented here as an approximate guide to biogas production.

Type of feedstock	*V* = Volatile Solids per unit dry solids (kg kg^{-1})	*M* = Moisture content of fresh waste (dm^{3} kg^{-1})	*B* = Biogas production per unit weight of volatile solids (dm^{3} kg^{-1})	*W* = Total fresh waste produced per head (kg d^{-1})	*P* = Biogas production per unit weight of fresh waste = (*V* x (1-*M*) x *B*) (dm^{3} kg^{-1})	Biogas production per head = *W* x *P* (dm^{3} d^{-1})
Human faeces	[a] 0.856	[a] 0.823	[c] 380	[f] 0.37	58	21
Pork pigs	[e] 0.856	[a] 0.75	[e] 380	[a] 2.30	81	187
Laying hens	[e] 0.85	[a] 0.75	[d] 130	[b] 0.10	27	3
Feedlot sheep	[b] 0.85	[a] 0.75	[d] 170	[a] 0.90	36	33
Cow (Sudan)	[e] 0.85	[a] 0.75	[b] 150	[b] 9.98	32	318
Feedlot beef cattle	[e] 0.85	[a] 0.75	[d] 470	[a,g] 16.56	100	1656
Dairy cattle	[e] 0.85	[a] 0.75	[d] 470	[a,h] 28.00	100	2800
Beef cattle	[e] 0.85	[a] 0.75	[d] 470	[a] 22.50	100	2250
Rice straw	[a] 0.773	[a] 0.141	[a] 500		332	
Water Hyacinth	[a] 0.68	[a] 0.437	[a] 500		191	

[a] Polprasert [27]

[b] Omer and Fadalla [28]

[c] Nas [70]

[d] Austin [71]

[e] Estimated from similar materials

[f] Gotaas [72]; Feacham et al [73]

[g] Taiganides [74]

[h] Volger [75]

Table 3 – Potential constraints to application of biogas digesters in Sub-Saharan Africa.

Constraint	Biogas not favoured	Biogas favoured
Environmental		
Temperature	Average air temperature below ~20°C	
Water	Water available to run digester less than ~20 dm^3 per person per day	
Nutrients		Nutrients limiting crop production. Rapidly available nutrients provided in bioslurry
Carbon	Soil organic matter content limiting crop production. Incorporate compost or biochar to improve crop production	
Socioeconomic		
Energy	Fuel wood plentiful	
Labour	Animals not stall-fed	Wood fuel source 3-4 times more distant than water source
Feedstock	Feedstock limited (less than 1 cow or 5 pigs for a 4 person household)	
Finance		Savings attributed to biogas digester are sufficient to pay quickly back funding for digester
Cultural		
Requirement for products		Demand for the food produced using bioslurry
Local attitudes to technology	Use of gas or manure culturally unacceptable	

Table 4 – Qualitative assessment of the impact of different uses of organic wastes on the livelihood assets of a smallholder farm in Sub-Saharan Africa

	Options for use of organic wastes				
Livelihood asset	Feed to animals	Compost	Biogas	Burnt	Pyrolsis Cookstove
Water			+ / -		
Nutrients	+	+	+		?
Carbon		+	+		+
Energy			+	+	+
Labour		-	+ / -	+	+
Finance	+	+	+	+	+

+	uses that provide a net increase in the availability of the asset compared to not using organic waste
-	uses that provide a net decrease in the availability of the asset compared to not using organic waste
+ / -	uses that provide a net increase in the availability of the asset in some conditions and a net decrease in others
?	uses for which the impact on assets is unknown

Highlights

- Holistic farming aims to make long term sustainable use of all resources
- A biogas digester could be a central component of many holistic systems
- It uses organic residues to produce energy, recycling digested materials
- Environmental, socioeconomic and cultural factors influence use on the farm