Current Research in Environmental Sustainability 3 (2021) 100072

Contents lists available at ScienceDirect

Current Research in Environmental Sustainability

journal homepage: www.sciencedirect.com/journal/current-research-in-environmental-sustainability

Seasonal variability of resources: The unexplored adversary of biogas use in rural Ethiopia

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A R T I C L E I N F O

Keywords:
Biogas
Sustainability
Season
Ethiopia
Water
Anaerobic digestion

A B S T R A C T

Biogas digester programmes have been rolled out across many countries in sub-Saharan Africa over the past decade with varying levels of success. In Ethiopia, reported success rates have been low, despite high levels of interaction between non-governmental organisations and various levels of government, plus the establishment of practical eligibility criteria. In Halaba, Ethiopia, we investigated physical and social factors affecting feedstock and water availability using a face-to-face questionnaire-based survey ($n = 112$) in four kebeles (local administration areas). We found that practices of fuel use and water collection were markedly different between seasons. Fuel use was almost entirely dependent on season, with wood being burned in the wet season and crop residues and cow dung being used instead in the dry season. A matched pair *t*-test found a significant difference between seasons in terms of water collection times ($p = 7.4 \times 10^{-16}$), with households spending more time and money obtaining clean drinking water in the dry season. Results indicate that seasonal differences in resource availability may reduce the proportion of households that meet the physical characteristics for maintaining a biogas digester by approximately 62% from wet season to dry season. Conversely, the greatest benefits of digester use would be gained in the dry season, when dung could be returned to the soil as a nutrient-rich bioslurry, instead of being combusted as a dirty and inefficient fuel. Seasonality is rarely considered in feasibility studies, so we recommend that these factors should be built into future analyses.

1. Introduction

1.1. Household fuels in rural Ethiopia

Traditionally, rural households in Ethiopia have used a combination of wood, dried cow dung and dried crop residues, such as maize stovers, as fuel for cooking (Tucho and Nonhebel, 2015). While this continues to be the case, with small additional inputs from charcoal and kerosene, the ratio of fuel types is changing. Population growth has led to increasing levels of deforestation, with the past 35 years seeing the clearance of most of the country's forested areas (Kamp and Bermúdez Forn, 2016). This has caused a shift towards increased use of cow dung and crop residues as fuels (Tucho and Nonhebel, 2015; Smith et al., 2013; Negash et al., 2017). These materials hold a valuable nutrient and carbon content, and can be used as fertilisers and soil conditioners when applied to arable land. These soil enhancements are especially important in Ethiopia, where chemical fertiliser use is one of the lowest in sub-Saharan Africa (SSA) (Mekonnen and Köhlin, 2008). The reduction in availability of dung and crop residues for soil amendment due to them being burned as household fuel, is leading to deterioration of soil quality (Tucho et al., 2016), causing increased concern for food security (Tucho and Nonhebel, 2015; Mekonnen and Köhlin, 2008; Roopnarain and Adeleke, 2017), in a region where soil is already classified as degraded (Negash et al., 2017; Byg et al., 2017). There is therefore a conflict between food security and energy provision in Ethiopia (Smith et al., 2015), which is one of the world's most energy poor countries (Negash and Swinnen, 2013). A suggested mitigation measure to this problem is anaerobic digestion (AD) of cow dung. Anaerobic digestion of such organic matter can simultaneously produce biogas as a clean, free energy source for cooking as well as a nutrient-rich organic fertiliser in the form of bioslurry.

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https://doi.org/10.1016/j.crsust.2021.100072
Received 10 December 2020; Received in revised form 15 June 2021; Accepted 13 July 2021
Available online 21 July 2021
2666-0490/

1.2. Benefits of bioslurry to rural communities in Ethiopia

The bioslurry resulting from AD is rich in plant-available nutrients (Coban et al., 2015) and can act as a valuable source of fertiliser. Only 5–10% of the nitrogen in the dung is lost during the AD process and a greater proportion of nutrients are available to plants from the bioslurry than from untreated manure (Smith et al., 2014). Although the digestate retains less carbon from the dung than composting as 20–95% of the carbon contributes to the biogas (Möller, 2015), it has a higher carbon content than synthetic fertilisers and can serve as an excellent soil conditioner (Coban et al., 2015). As the carbon that remains after digestion is more recalcitrant than untreated manure, it is less prone to breakdown in the soil (Möller, 2015). Sandy and silty soils are often found in Ethiopia and large areas of SSA, and the water retention characteristics of these soils increase more than those of other soil types when organic matter is added (Rawls et al., 2003). Water retention of soils is related to organic matter content, so over time, regular application of bioslurry could potentially increase the resilience of these soils to drought as their carbon contents increase (Smith et al., 2019). Soil condition may also be improved indirectly by AD due to reduction in deforestation as homes become less reliant on biomass burning (Landi et al., 2013).

1.3. Benefits of biogas to rural communities in Ethiopia

Sub-Saharan Africa has the largest proportion of people in the world dependent upon biomass for cooking. Cooking is usually done on inefficient three-stone fires in poorly ventilated rooms (Tumwesige et al., 2017). In rural areas 93% of the population is reliant on biomass combustion for household fuel, and the trajectory for the total number of people dependent on biomass combustion is increasing (Maes and Verbist, 2012). Indoor biomass combustion on inefficient stoves has a strong negative impact on respiratory health due to the high quantities of particulate matter and carbon monoxide generated. It is linked to respiratory tract infections, lung inflammation, tuberculosis and eye diseases, with dung combustion having a particularly deleterious effect (Tumwesige et al., 2017; Maes and Verbist, 2012). Incomplete combustion of biomass for cooking is believed to lead to 1.5 million early deaths per annum, with over one-third of those being in Africa (Rupf et al., 2015). This makes it a bigger killer than malaria (Maes and Verbist, 2012). In addition to biomass being a dirty and polluting energy source, when biomass is burned on a three-stone fire it has a thermal efficiency of only 8–12% (Chica and Pérez, 2019) compared to a typical 50–68% thermal efficiency for the cleaner biogas from AD (Tucho et al., 2016). Replacement of three-stone fires with biogas stoves can significantly benefit human health as well as reducing carbon emissions.

1.4. Barriers to biogas production

Household scale AD has been successfully implemented across many countries with approximately 50 million installations in place around the world (Clemens et al., 2018). Asia has dominated the scene with the number of installations reaching over 44 million in China and India alone (Mwirigi et al., 2014). By contrast, uptake in Africa has occurred at a much slower rate with fewer attempts at dissemination (Roopnarain and Adeleke, 2017; Mwirigi et al., 2014; Kelebe et al., 2017). The uptake and continued use of biogas digesters are constrained by a number of physical and cultural issues. The main physical limitations cited are availability of substrate (Puzzolo et al., 2016; Lwiza et al., 2017), adequate funds (Rupf et al., 2015; Mwirigi et al., 2014) and access to water (Tucho et al., 2016; Rupf et al., 2015; Bansal et al., 2017).

Current recommended dilution ratios for cow manure as a substrate for AD are usually one part manure to at least one part water by volume (Kamp and Bermúdez Forn, 2016; Mungwe et al., 2016; Sime, 2020), so uptake may require additional trips to collect water, on top of those currently made for basic household requirements. This may or may not be offset by reduction in time spent collecting wood and/or other fuel sources, making relative values of time perhaps more pertinent than absolute values (Smith et al., 2013). Access to water is listed as a problematic factor in the Development Action Plans of 45 different countries in SSA (Smith et al., 2015) and in drought-prone regions of Ethiopia is likely to be a major constraint, at least in some periods of the year. Lack of water or manure was found to be the reason why 60% of sampled digesters from projects in the 1990s and early 2000s were not operational in Ethiopia (Eshete et al., 2006). Similar small-scale projects with low success rates were typical across other SSA countries including Tanzania (Rupf et al., 2015), Uganda, Zambia and Kenya at the time (Mwirigi et al., 2014).

1.5. Implementation of anaerobic digesters in Ethiopia

Despite the lack of success of past installations, over the last decade, further pushes have been made to disseminate the technology in SSA. This was initiated after feasibility analyses concluded that millions of people could successfully use AD for fuel and slurry production (Landi et al., 2013; Eshete et al., 2006). The largest biogas initiative in SSA to date is the African Biogas Partnership Program (ABPP), which includes Ethiopia, Kenya, Tanzania, Uganda and Burkina Faso. Funders and technical partners, including the Netherlands Development Organisation (SNV), Hivos and the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), work together with the respective national governments to conduct feasibility analyses and develop the most appropriate structure for dissemination within that country. The Ethiopian branch of the ABPP, the National Biogas Program of Ethiopia (NBPE), conducted installations between 2008 and 2017 (Kamp and Bermúdez Forn, 2016). The NBPE established eligibility criteria to restrict installations to those households deemed capable of adequate biogas production. As dung and water availability are the key physical determinants of biogas production, the main criteria summarised by SNV were that households must own a minimum of four cattle, be within 20 min walking distance of a water source and have available land space (SNV, Personal correspondence, 2017). These ABPP criteria can differ slightly between countries according to the livestock management systems in place, which determine the proportion of dung that is likely to be collectable from around the homestead. A more detailed version of the feasibility criteria created for SNV for the NBPE can be seen on p.44 of the report by Eshete et al. (2006). Despite such criteria to select the most suitable households, many biogas projects continue to fail. A recent study in Southern Ethiopia found that over 80% of recently installed digesters were abandoned or malfunctioning due to shortage of water, and that problems were worse during dry season (Sime, 2020). Here, we look beyond these basic eligibility criteria to identify practical factors which may be involved in the failure of digesters to run for sustained periods.

We aim to gain insight into the potential benefits and drawbacks of low-tech household scale AD to subsistence farmers in rural Ethiopia. We synthesise information collected from questionnaires in conjunction with physical measurements of organic resource use in a sub-set of households to assess trade-offs between fuel and water collection. Our study focuses on one single district, Halaba in the southern part of Ethiopia, to allow us to cover a higher percentage of households and gain a higher resolution perspective than would be available over a larger area.

Interestingly, to date, no studies or feasibility analyses have investigated how temporal variation of water or dung availability can impact adoption, sustained use or benefits gained from household biogas digesters. As we will show, this could be an important oversight considering the seasonality of rainfall, crops and available organic matter in subsistence communities of SSA and beyond.

2. Materials and methods

2.1. Study area

The Halaba Special Woreda, a district level administration unit, is situated in the Southern Nations, Nationalities and Peoples' Region of Ethiopia. The district capital, Halaba Kulito lies at 7°18′46 N, 38°05′20 E at an altitude of 1780 m. Soil degradation is a known problem and is perceived to have been caused by deforestation associated with population growth and the transition from livestock to arable farming (Byg et al., 2017). According to the most recent census in 2007, 37,442 of the 41,110 rural households of Halaba kept livestock inside the house (Ethiopia Population Census Commision, 2007). In this area, the wet season known as keremt, was considered by villagers to be from May to December. Rainfall and temperature data for Halaba can be seen as Appendix 1.

2.2. Survey

A face-to-face questionnaire-based study ($n = 112$) was conducted with subsistence farmers between September and November 2017. The key aims of the questionnaire were i) to quantify and establish current uses of organic matter, exploring the benefits of each, and ii) to quantify the demand and collection times for water and fuel, considering seasonal differences in water availability. The Cochran's formula determines that the sample number of 112 is sufficient to provide 95% confidence that answers are representative of the larger population with a worst-case margin of error of ±9%. Prior to beginning data collection, two days were spent piloting the questionnaires in two of the kebeles, resulting in amendments being made at the end of each day. If respondents gave more information than requested, e.g. long answers to Yes/No questions, the whole answer was noted for qualitative insight and later simplified for quantitative purposes. Most questions elicited numeric data, e.g. quantities of dung collected. Within the four focal kebeles (local administration areas, typically made up of a few villages), households were randomly selected by choosing every *n*th household on the kebele list. Two of the kebeles, Wanja and 2nd Choroko (named to distinguish it from the original Choroko), were located close to the River Bilate (Fig. 1). River Bilate runs throughout the year and is a reliable source of water. The other two kebeles, Gofesa and Galeto, approximately 7 km and 20 km from River Bilate to central point respectively, were chosen to compare travelling times and strategies to obtain water. Gofesa is situated around a seasonal stream, with kebele representatives claiming it had a pond which provided water throughout the year. Galeto has no known large sources of water and suffers from seasonal water scarcity.

In addition to the estimates collected through the questionnaire, in Wanja and 2nd Choroko, the mass of wood and crop residue bundles was measured using hand-held scales. Animal dung quantities were estimated based on the volume of the baskets used to clear dung out of the homes in the early morning.

2.3. Statistical methods

All data was checked for normality of distribution, independence and homogeneity of variance before deciding the most appropriate statistical tests. Data visualisation and analysis was done in the R version 4.0.2 with parametric tests being used when appropriate. Assumptions of

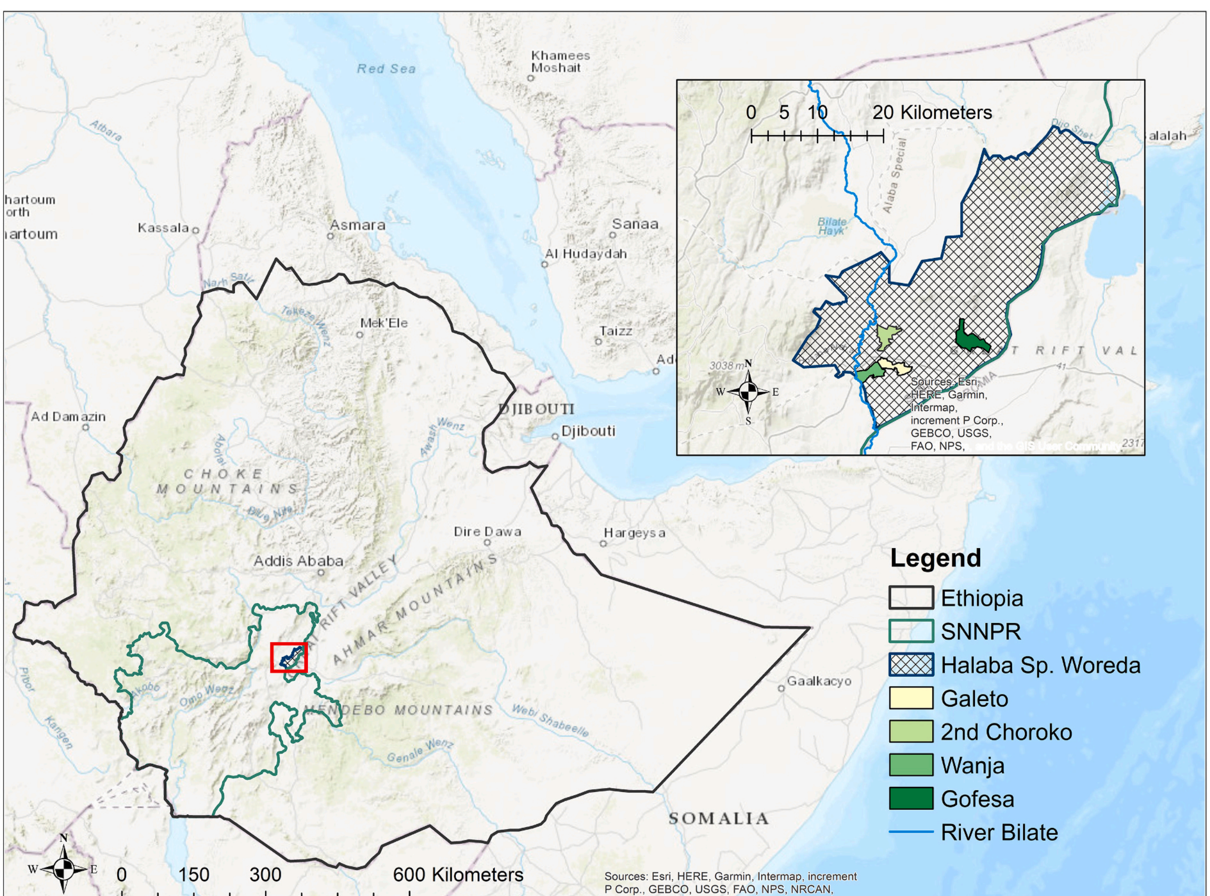

Fig. 1. Study areas of Halaba (Map showing geographical location of Halaba within the context of Ethiopia and the Southern Nations Nationalities and Peoples' Region).

normality of distribution were not always met, but when the Levene's test for homogeneity of variance between groups yielded *p*-values of over 0.05, and sample sizes were over 30, parametric tests which are robust to non-normality were used. Transformations of data to attempt to gain normal distributions were not applied due to values of zero being meaningful values in the data. Paired *t*-tests were used to compare factors such as collection time for wood compared to water so each household's relative time was considered.

3. Results

3.1. Use of organic matter

The pilot interviews revealed that organic "waste" was not a locally understood concept as organic material was highly valued and utilised. The first use of crop residues was to feed it to the livestock in quantities that were difficult to estimate, as they were fed in small amounts frequently throughout the day. We therefore modified the questions to establish the main uses of crop residues after animal feed, and found that it was for fuel (Fig. 2).

Of the 112 households surveyed, 54% had four or more cattle, so meeting the SNV criterion for having sufficient dung for substrate. An analysis of variance test found there was no significant difference in the number of cattle between kebeles ($F = 0.75$, $p = 0.53$). The overall mean was 4.5, (SD 3.4) cattle per household; looking only at those households with at least four cattle which may be eligible for a digester, the mean was considerably higher at 6.7 (SD 3.3). The mean quantity of manure per head of cattle collected per day by those with four or more cattle *and* whose manure removal containers were measured was 7.9 l (SD 3.2). Interviewees responded with the amount of manure they collected at that time of year, which was the wet season. Some interviewees reported that the quantity was less during the dry season when livestock were fed from dried, stored fodder rather than wet grass and fresh crop residues. As most households kept their livestock in the family home at night and cleared dung frequently, collection for biogas digesters should not create additional work.

3.2. Seasonal use of fuel

A significant finding from this research was that the majority of households switched fuel sources between seasons due to practical factors. During the wet 'keremt' season dung was wet and crops were still growing, making them unavailable for fuel use. In keremt the main fuel source was wood which had usually been cut from trees earlier in the year. In this area, the villagers considered the wet season to be from May to December. Conversely, in the dry 'baga' season, households preferred to burn the dried crop residues saved from the harvest, and cow dung which could be sun-dried in absence of the rain. The information about changes to fuel sources between seasons was not fully established until after completion of the first 20 household interviews as we initially focussed on quantity of fuel use. Therefore, the first 20 households are omitted from seasonal analysis of fuel provided below. This leaves 92 households in the data set for that question. All households burned crop residues during the dry season but only 16.3% burned dung as well. Reasons for not burning dung included needing it all as manure for the land and having received education about the damage to their respiratory health. Table 1 summarises the fuel consumption patterns of households according to season. It shows the difference between the kebele mean quantities per household in addition to the mean value only for the households which use the fuel type in that season. It can be seen that using generalised figures can obscure usage within particular households which may be important when assessing the suitability of new cooking methods, e.g. the rate of dung burning in wet season is over 30 times higher in user households than across the kebele as a whole.

3.3. Time spent on fuel and water collection by season

There is a potential trade-off between wood collection and water

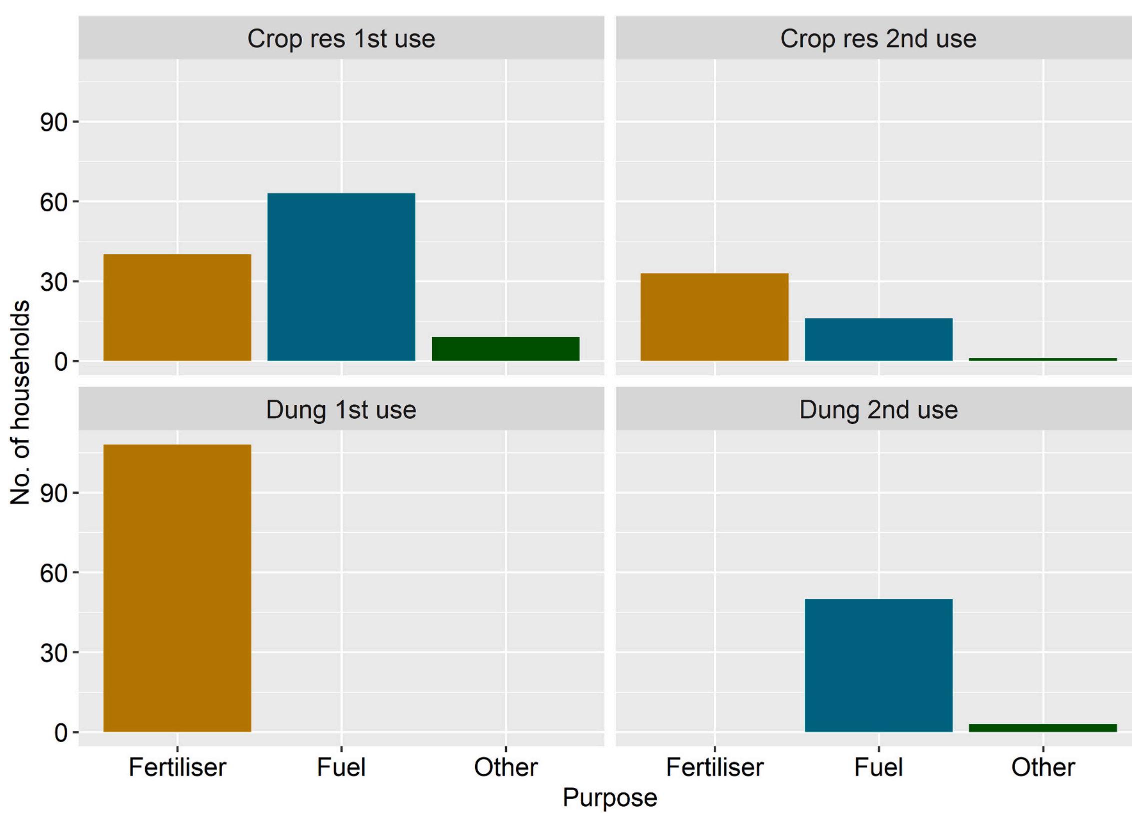

Fig. 2. Main uses of crop residues and animal dung (Multiple column charts showing the primary and secondary uses of dung and crop residues).

Table 1
Seasonal use of fuel by fuel type.

Fuel & season	% households using fuel type	Mean quantity (all 92 households)	SD	Mean quantity (user households only)	SD
Wood - wet	100.0	14.9 kg day^{-1}	8.2	14.9 kg day^{-1}	8.2
Wood - dry	10.9	1.4 kg day^{-1}	4.9	12.9 kg day^{-1}	8.9
Crop res - wet	13.0	0.5 bundles $week^{-1}$	1.5	3.6 bundles $week^{-1}$	2.3
Crop res - dry	100.0	8.3 bundles $week^{-1}$	5.4	8.3 bundles $week^{-1}$	5.4
Dung - wet	3.3	3.2 l $week^{-1}$	23.4	99.2 l $week^{-1}$	102.8
Dung - dry	16.3	22.5 l $week^{-1}$	77.7	138.2 l $week^{-1}$	148.8

collection time that may result from adopting biogas technology due to the perceived need for substrate dilution. We therefore quantified the possible impacts on user time that could arise from digester installations. The underlying assumption was that there must be an incentive of labour-time reduction for digesters to be maintained by households. A matched pair *t*-test found no significant difference between wood collection time and water collection time during the wet keremt season in Wanja and Gofesa ($p = 0.14$ and 0.33 respectively). By contrast, in 2nd Choroko and Galeto there was a significant difference ($p = 9.2 \times 10^{-3}$ and 0.04×10^{-2} respectively), with the water collection time being lower than wood collection time in Choroko but significantly higher in Galeto. A Wilcoxon test was used for the Galeto data as the variance between the wood and water collection times was significant ($p = 2.2 \times 10^{-16}$). A Kruskal-Wallis test showed a highly significant difference in water collection times between the kebeles in both wet season (chi-squared = 40.0, $p = 1.1 \times 10^{-8}$) and dry season (chi-squared = 42.3, $p = 3.5 \times 10^{-9}$) (Fig. 3).

The mean daily water collection times in wet season (keremt) by kebele are 0.80 (SD 0.7), 2.9 (SD 1.6), 2.4 (SD 1.9) and 0.9 (SD 0.9) hours for 2nd Choroko, Galeto, Gofesa and Wanja respectively. Although the figure is high for Galeto, this kebele also has a high wood collection time. These figures represent the overall time for all sources of collection which include tap water, river water, pond water and harvested water. Of the overall time, 50.9% of households took one hour or less to make a return trip with water. Considering collection, waiting time and return journey, this roughly equates to the 20 min to water source used when assessing eligibility criteria. Combined with the criteria of having four or more cattle, 34 households met the eligibility criteria in wet season. When water collection is narrowed down to rainwater harvesting from building roofs during rain events, of the 70 households that harvested rainwater, 47 claimed that it took no time at all as they merely positioned their jerry cans and left them to fill. The mean time for rainwater harvesting was 0.2 h. The main limitation to rainwater harvesting was lack of containers.

During the dry (baga) season, rainwater harvesting was not possible and water collection time was significantly higher than in the wet season (*t*-test paired: $t = 9.4$, $p = 7.4 \times 10^{-16}$) with a mean of 4 h compared to 1.7 h. This was largely due to pond water being more limited and the decrease in water quality leading to more people purchasing water from taps for which they had to queue. The mean time taken for piped water collection was three hours, compared to 0.9 h from a pond. Ponds used throughout the wet season often became parched in dry season and were used sparingly in an attempt to maintain the source for a longer period. Therefore, respondents did not generally allow their animals to drink from the ponds. The river was the only free source of relatively unlimited water for many households, but in dry season it was mainly only used for livestock to drink from. Most livestock were herded to the river while donkeys were taken elsewhere to carry potable water back to the homestead. This time was variable as sometimes the nearest tap stations were not functional. An exception to this was in 2nd Choroko where people switched from pond water collection to river water collection. Despite 2nd Choroko being in close proximity to the river, there was a significant increase in time taken to obtain water in dry season compared to wet season (*t*-test paired: $t = 4.9$, $p = 3.2 \times 10^{-5}$) with the mean increasing from 0.8 (SD 0.7) hours to 2.2 (SD 1.3) hours. Whereas the wet season water collection time was lower than that of wood collection time in 2nd Choroko (1.3 h, SD 0.9), in dry season the mean

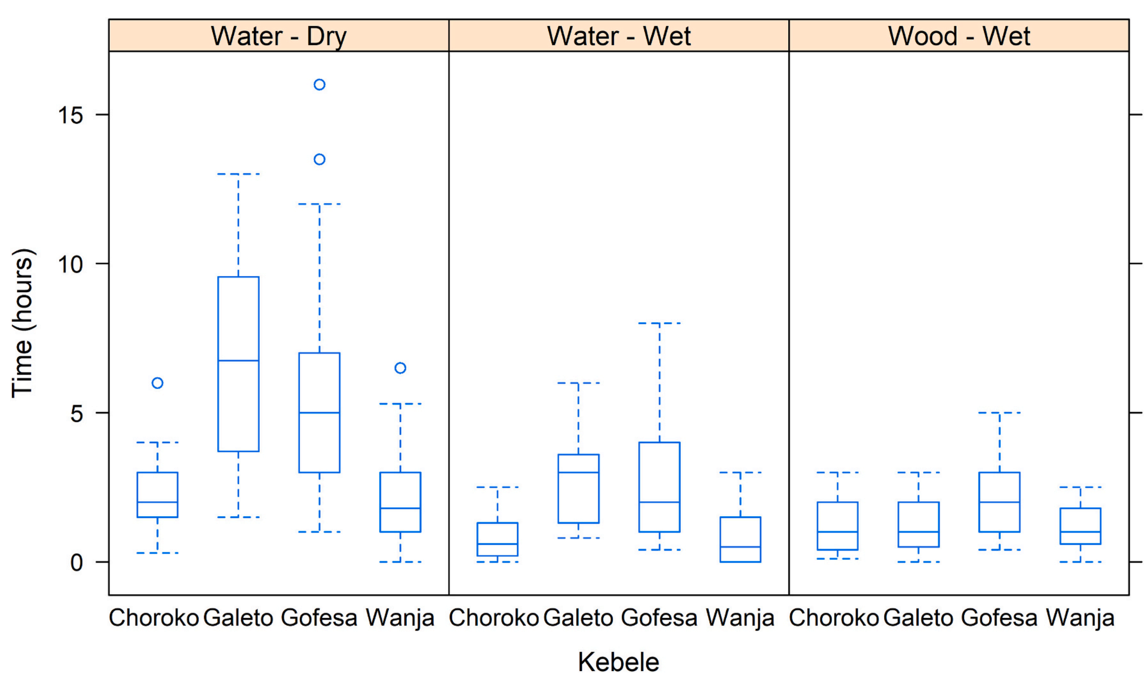

Fig. 3. Water and wood collection times by season and kebele N.B. Wood is not used in dry season, Choroko = 2nd Choroko (Boxplots showing the time used for collecting water and wood according to season).

water collection time was almost an hour longer than wood collection time.

In the dry season, only 16% of households were able to collect water in less than one hour, with only 8% of households collecting water from the river within that time. The proportion of households which had four or more cattle *and* took one hour or less to collect water decreased from 30.4% in wet season to 11.6% in dry season.

4. Discussion

4.1. Seasonal availability of water

The essential physical resources required to produce biogas in rural areas of SSA are sufficient animal dung and an adequate supply of water. In the wet season in Halaba, biogas appears to have reasonable potential with approximately 30% of households having four or more cattle to supply substrate and being able to obtain water within one hour. As water could be harvested and poured directly into the digester mixing trough, the availability of containers, which was the biggest constraint on water harvesting, need not be a limiting factor. Nor would maintaining digesters be a burden on time or effort as most people perceived water harvesting as not taking up time and already collected dung from the home to take outside. This is an important factor as additional labour requirements associated with collecting and transporting water and feedstock can be a major deterrent to the uptake of AD (Tucho et al., 2016).

The study found, however, that there was a significant difference in water collection time between wet and dry seasons; in the dry season, the proportion of households within a one hour water collection time and having enough cattle decreased to approximately 12%. From conversations with villagers in Halaba and the NBPE eligibility criteria, seasonal differences do not appear to be factored into feasibility analyses. There may be an assumption that locations within a given walking time of a permanent water source can collect water with the same ease throughout the year. We found that during the dry season, people used alternative sources of water and had different approaches for obtaining sufficient water for their family and livestock. In addition, anecdotal evidence suggested there were different views on what constituted a permanent water source, with some interviewees stating allegedly permanent ponds were dry for approximately a month per year.

It was acknowledged that as well as water decreasing in quantity during the dry season, with fewer sources available, it was also of declining quality with particulates becoming more concentrated in a smaller volume of water. This caused households to change strategies, spending more time and money to obtain purchased tap-water for purposes other than drinking. In the wet season, livestock were fed on fresh wet grass and wet crop residues, which provided their daily water demands. During the dry season, cattle, sheep and goats were taken to the river to drink, but water was not collected for use at home as these are not load-bearing animals. Therefore, water provision was more intensive on human resources in the dry season as it required herding the animals to the river. Apart from in 2nd Choroko, donkeys, the water-bearers, were commonly used to collect potable water from rural tap stations elsewhere. Collection time for piped water was unpredictable as the nearest sources could be dry. As small-scale farmers have very little disposable income, which is also subject to seasonality (Rupf et al., 2015), it is unlikely that households would be willing to pay for water to put into a digester. The collection of free water for a biogas digester in the dry season would consequently require an additional journey to other water sources after returning from purchasing potable water. The distance to potable water may therefore render proximity to a permanent river or pond less significant than is currently assumed, as clean water collection was a priority for human and animal resource use. It is also notable that even in 2nd Choroko, which is relatively close to the River Bilate, there would be a disincentive to collect water for anaerobic digestion in the dry season as the collection time was almost an hour longer than that of wood (Fig. 3).

4.2. Availability of feedstock

Some households volunteered information that animals produced a larger quantity of wetter dung in the wet season when fresh feed and water were abundant, than in the dry season when livestock were fed on reserves of dried crop residues. This was also found by Sime (2020) in other areas of Southern Ethiopia. As the water for anaerobic digesters is used to create an optimal consistency, this drier dung would require more dilution than in the wet season, thus increasing the water requirement at the time it is least available. Furthermore, the dung produced by animals while travelling to the water source is not collected, so a higher proportion is lost to the households. As lack of dung is often cited as a barrier to the functioning of biogas digesters (Rupf et al., 2015; Berhe et al., 2017), successfully running a biogas digester may be limited to wet season conditions and practices. Kabera et al. (2016) briefly mention this to be the case when assessing the effectiveness of Rwanda's National Domestic Biogas Program, although there is a distinct lack of information on this topic.

4.3. Seasonal change of fuel sources

An important finding from the study is that there was an almost complete seasonal change in fuel type used by households. The primary fuel type used by all households in the wet season was wood, while the primary fuel type in dry season was crop residues, supplemented in some households by dung. Previous research has established that quantitative differences in fuel use between seasons are often overlooked due to field evaluations being conducted over a short time period (Lam et al., 2017). However, a complete switch in fuel type between seasons does not appear to have been reported in the literature. This fundamental physical factor may be more pertinent to the likelihood of households maintaining use of digesters than the frequently assessed socio-economic factors, such as educational level, age and sex (Kelebe et al., 2017; Mengistu et al., 2016). Indeed elsewhere, it has been found that socio-economic factors are influential in the uptake of digester installations, but more practical issues exert a higher degree of influence regarding continued use (Ruiz-Mercado et al., 2011).

Wood is not typically used in the dry season, so does not regularly consume time for preparation or collection. As dung and crop residues are already collected for manure and animal feed or field clearance, time attributed to collection of these materials specifically for cooking is inevitably less than for water collection during dry season. The requirement for an additional trip specifically to collect digester water would exacerbate this further. Increasing household labour does not encourage uptake of new technologies (Tucho et al., 2016), (Bansal et al., 2017) and may render use of biogas digesters throughout the dry season more unlikely, even for those households in close proximity to water. Such was the case in Rwanda, where it was found women and children preferred to collect firewood than additional water in the dry season (Kabera et al., 2016). Studies from different countries have found that the reduction in the quantity of firewood used by households that use AD is typically 45–60% (Kelebe and Olorunnisola, 2016). It is not stated whether this reduction is achieved from year-round fuel stacking, the practice of using new sources of energy in combination with existing sources of energy (Negash et al., 2017; Puzzolo et al., 2016), or seasonal changes in fuel type. More knowledge about this is required in order to assess the likelihood of continued use of the digesters.

4.4. Impact on abundance of trees

Results indicate that sufficient water for digestion may only be available to most households at the time of year they burn wood. The practical limitations of seasonal digester use are discussed in section 4.7. Assuming digester use is feasible on this basis; it could have a significant impact on reducing wood burning. The mean quantity of firewood used per household in the wet season was 14.9 kg per day, with 34 households meeting the eligibility criteria for biogas installation at that time of year. Approximately 80% of cooking time is spent on cooking food other than injera, the traditional Ethiopian staple fermented flatbread. Injera cannot easily be cooked on a normal biogas stove, so this is not included in the following calculations. Replacement of 80% of wood fuel with biogas over an eight-month wet season for 30% of the sampled households would provide a saving in firewood of 100.5 t at a rate of 2.96 t per household. If this is scaled up to 30% of the 41,000 households in Halaba, the total firewood savings from cooking would sum up to 36,400 t per annum. Mengistu et al. (2016) found regional differences in attitudes and practices within the state of Tigray were significant in the adoption of biogas. There could therefore be a high level of uncertainty involved in further upscaling of these estimates.

In Halaba, most households obtained firewood from trees distributed around their own land rather than a forested area. If the main purpose of trees is to provide firewood, reducing the demand for firewood may not equate to more trees as farmers may stop planting them. A third of farmers did not want to plant trees on their land as they felt that they drained precious water and nutrients from the soil and outcompeted their crops. Only 15% of farmers did not experience any problems from tree planting. Other farmers stated they simply had no motivation to plant trees or did not know how to. In the Tigray region of northern Ethiopia, however, the typical fuel source is from communal forests (Kelebe et al., 2017), as is the case in many areas of SSA. In this situation, reduced use of wood fuel could have a more positive impact on reforestation. This can also be the case where financial incentives from wood sales is a motivational factor (Mengistu et al., 2016).

4.5. Impact on indoor air quality

In the dry season, the primary household fuel switches from firewood to crop residues and dried dung. Using crop residues and dung as a fuel source has the most negative impact upon human health in terms of respiratory health. Emissions of carbon monoxide, hydrocarbons and particulate matter from dung are 64, 115 and 63 times higher in relation to a clean baseline fuel, whereas wood performs considerably better at 19, 17 and 26 times higher than the baseline (Smith, 2006). This is reflected by dung and crop residues being placed on the bottom rung of the energy ladder (Maes and Verbist, 2012; Mengistu et al., 2015). Adoption of digesters could therefore have a considerably lower impact on respiratory health than anticipated, as the dirtiest, least efficient fuels are the ones that are combusted in dry season when digesters are more likely to be non-operational. A previous study in Uganda and Cameroon found that when households partially converted to biogas with 54% wood use and 46% biogas use, carbon monoxide levels fell to within World Health Organisation limits, but small particulate matter ($PM_{2.5}$) concentration did not (Tumwesige et al., 2017).

4.6. Impact on food security

One of the key motivations for introducing anaerobic digesters to rural areas of SSA is to deter small-scale farmers from burning dung, crop residues and other biomass (Roopnarain and Adeleke, 2017). Combustion of these organic resources reduces the quantity of organic matter available for soil improvement (Negash et al., 2017). As bioslurry from AD can serve as a fertiliser and soil conditioner, AD has the potential to increase food security through improved agricultural production. In Halaba we found that AD may have little impact on the quantity of dung and crop residues being returned to the soil, as they are only used as a fuel source in the dry season, when the digester may not be functional. In wet season, access to the land is restricted by the growing crops meaning optimal use of the bioslurry may not be possible. Benefits to soil fertility and carbon content will only be gained if seasonal variations in water and organic matter availability are considered in eligibility criteria, and only households that benefit from water collection year-round receive installations.

4.7. Potential impact of seasonal viability

If digester use was restricted to wet season, practicalities of re-establishing the digester could prove problematic as the digestion process would need to be started over again. Feedstock left in the digester without movement since the last wet season could dry out or separate into liquid and solid components, changing the physical, chemical and biological characteristics required for biogas production. In an environment where lack of technical help is widely reported (Rupf et al., 2015; Lwiza et al., 2017; Kabera et al., 2016), full abandonment of digesters may be an unintended consequence of seasonal dis-adoption as users tend to return to former practices if the technology is not working (Sime, 2020; Barry et al., 2011).

Few studies on energy use changes between seasons exist from the global south (Lam et al., 2017). The authors can find no literature on this topic of seasonally dormant continuous flow digesters, although the abandonment or malfunction of new digesters is widely reported from projects in Eastern Africa (Kelebe et al., 2017; Lwiza et al., 2017; Sime, 2020; Shallo and Sime, 2019). Monitoring and reporting on this topic needs to be established, as technologies for improved cooking efficiencies are not sustainable or beneficial without long-term use which enables the embedded energy to be recovered. Failure of project plans to include monitoring of sustained use was previously due to absence of suitable metrics for doing so, but this is no longer the case (Ruiz-Mercado et al., 2011). Although monitoring and technical support were features which were theoretically built into the NBPE, the few studies published report their absence (Kamp and Bermúdez Forn, 2016; Sime, 2020); a situation shared with other biogas projects in SSA (Rupf et al., 2015; Kabera et al., 2016). Interestingly, Ruiz-Mercado et al. (2011) argue that there is a dis-incentive for monitoring technologies that promise to increase household efficiencies due to technology promotions being based on unrealistic efficiencies of up to 100%, meaning some degree of failure is almost inevitable.

5. Conclusions

Ease of obtaining water may render biogas a feasible fuel source only in specific seasons in Ethiopia, the wider SSA, and elsewhere. The proportion of households in Halaba that meet NBPE eligibility criteria in wet season was 30% ($\pm$9), but was reduced by 62% to only 12% ($\pm$6) in dry season. Although 36,400 t of firewood per annum could be saved in Halaba based on the 8-month wet season practices, this would have no direct impact on nutrients and carbon from dung and crop residues being returned to the soil as fertilisers and conditioners. From this we conclude that anaerobic digesters contribute less towards food security than anticipated. The impacts of this should be considered in analyses of household costs, soil health, human health and other environmental gains from reduced biomass burning. The switch between fuels could introduce large errors in estimates of potential reductions in indoor air pollution and carbon emissions associated with digester use, as the least efficient and dirtiest fuels are the ones most likely to remain in use for direct combustion.

Our primary recommendation is that feasibility analyses and eligibility assessments for household-scale AD should be more robust and place more emphasis on sustained use over the long-term than the initial adoption conditions, which are currently focused upon. Such assessments need to be repeated in different seasons, or at least contain separate questions about dry and wet season water and fuel collection and consumption patterns. Open-ended questions should be included to establish if water transportation is available from free sources, if those sources are reliable, and if there is more competition for human and animal resources between seasons. The effect of reduced water and fodder availability on dung quantity should not be overlooked.

We also recommend a rigorous investigation into whether or not seasonally dormant digesters can be easily recovered before further household-scale digester programs are implemented. Establishing whether digester use is feasible over a period of several years is at least as important as the initial adoption conditions to the success of household-scale AD as a sustainable technology. Essentially, more resources from implementation programmes should be diverted towards ensuring that installations are limited to households with long term potential for sustained use and that the selected households are monitored and better supported through technical difficulties. Although factors including lifestyle, culture, weather and geographical characteristics vary, findings from such a study will be applicable to household-scale AD for subsistence livelihoods across SSA.

Funding

This project was funded by (BBSRC BB/M010996/1) and the University of Aberdeen. AF's contribution was supported by UKRI (ES/P002501/1). JS's contribution was supported by UKRI (ES/P002501/1) and DFID NEXUS (NE/P004830).

Ethical statement

All questionnaire respondents gave their informed consent for inclusion before they participated in the study. The protocol was approved by the Ethics Committee of the University of Aberdeen [CERB/2017/5/1477].

Declaration of Competing Interest

None.

Acknowledgements

We would like to thank Hawassa University and the Southern Agricultural Research Institute for their support with organisation, data collection and translation.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.crsust.2021.100072.

References

Bansal, V., Tumwesige, V., Smith, J.U., 2017. Water for small-scale biogas digesters in sub-Saharan Africa. GCB Bioenergy 9 (2), 339–357.
Barry, M., Steyn, H., Brent, A., 2011. Selection of renewable energy technologies for Africa : Eight case studies in Rwanda, Tanzania and Malawi. Renew. Energy 1–8.
Berhe, T.G., Tesfahuney, R.G., Desta, G.A., Mekonnen, L.S., 2017. Biogas Plant Distribution for Rural Household Sustainable Energy Supply in Africa. Energy Policy Res. 4 (1), 10–20.
Byg, A., et al., 2017. Trees, soils, and warthogs – Distribution of services and disservices from reforestation areas in southern Ethiopia. For. Policy Econ. 84, 112–119. June.
Chica, E., Pérez, J.F., March, 2019. Development and performance evaluation of an improved biomass cookstove for isolated communities from developing countries. Case Stud. Therm. Eng., vol 14.
Clemens, H., Bailis, R., Nyambane, A., Ndung'u, V., 2018. Africa Biogas Partnership Program: A review of clean cooking implementation through market development in East Africa. Energy Sustain. Dev. 46, 23–31.
Coban, H., Miltner, A., Elling, F.J., Hinrichs, K.U., Kästner, M., 2015. The contribution of biogas residues to soil organic matter formation and CO2 emissions in an arable soil. Soil Biol. Biochem. 86, 108–115.
Eshete, G., Sonder, K., Heegde, F., 2006. Report on the feasibility study of a national programme for domestic biogas in Ethiopia.
Ethiopia Population Census Commision, 2007. 2007 Population and Housing Census.
Kabera, T., Nishimwe, H., Imanantirenganya, I., Mbonyi, M.K., 2016. Impact and effectiveness of Rwanda's National Domestic Biogas programme. Int. J. Environ. Stud. 73 (3), 402–421.
Kamp, L.M., Bermúdez Forn, E., 2016. Ethiopia's emerging domestic biogas sector: Current status, bottlenecks and drivers. Renew. Sust. Energ. Rev. 60, 475–488.
Kelebe, H.E., Olorunnisola, A., 2016. Biogas as an alternative energy source and a waste management strategy in Northern Ethiopia. Biofuels 7 (5), 479–487.
Kelebe, H.E., Ayimut, K.M., Berhe, G.H., Hintsa, K., 2017. Determinants for adoption decision of small scale biogas technology by rural households in Tigray, Ethiopia. Energy Econ. 66, 272–278.
Lam, N.L., et al., 2017. Seasonal fuel consumption, stoves, and end-uses in rural households of the far-western development region of Nepal. Environ. Res. Lett. 12 (12).
Landi, M., Sovacool, B.K., Eidsness, J., 2013. Cooking with gas: Policy lessons from Rwanda's National Domestic Biogas Program (NDBP). Energy Sustain. Dev. 17 (4), 347–356.
Lwiza, F., Mugisha, J., Walekhwa, P.N., Smith, J., Balana, B., 2017. Dis-adoption of Household Biogas technologies in Central Uganda. Energy Sustain. Dev. 37, 124–132.
Maes, W.H., Verbist, B., 2012. Increasing the sustainability of household cooking in developing countries: Policy implications. Renew. Sust. Energ. Rev. 16 (6), 4204–4221.
Mekonnen, A., Köhlin, G., 2008. Biomass Fuel Consumption and Dung Use as Manure. Environ. Dev. - Discuss. Pap. Ser. 08–17, 1–19 no. April.
Mengistu, M.G., Simane, B., Eshete, G., Workneh, T.S., 2015. A review on biogas technology and its contributions to sustainable rural livelihood in Ethiopia. Renew. Sust. Energ. Rev. 48, 306–316.
Mengistu, M.G., Simane, B., Eshete, G., Workneh, T.S., 2016. Factors affecting households' decisions in biogas technology adoption, the case of Ofla and Mecha Districts, northern Ethiopia. Renew. Energy 93, 215–227.
Möller, K., 2015. Effects of anaerobic digestion on soil carbon and nitrogen turnover, N emissions, and soil biological activity. A review. Agron. Sustain. Dev. 35 (3), 1021–1041.
Mungwe, J.N., Colombo, E., Adani, F., Schievano, A., 2016. The fixed dome digester: An appropriate design for the context of Sub-Sahara Africa? Biomass and Bioenergy 95, 35–44 no. December.
Mwirigi, J., et al., 2014. Socio-economic hurdles to widespread adoption of small-scale biogas digesters in Sub-Saharan Africa: A review. Biomass Bioenergy 70, 17–25.
Negash, M., Swinnen, J.F.M., 2013. Biofuels and food security: Micro-evidence from Ethiopia. Energy Policy 61, 963–976.
Negash, D., Abegaz, A., Smith, J.U., Araya, H., Gelana, B., 2017. Household energy and recycling of nutrients and carbon to the soil in integrated crop-livestock farming systems: a case study in Kumbursa village, Central Highlands of Ethiopia. GCB Bioenergy 9 (10), 1588–1601.
Puzzolo, E., Pope, D., Stanistreet, D., Rehfuess, E.A., Bruce, N.G., 2016. Clean fuels for resource-poor settings: A systematic review of barriers and enablers to adoption and sustained use. Environ. Res. 146, 218–234.
Rawls, W.J., Pachepsky, Y.A., Ritchie, J.C., Sobecki, T.M., Bloodworth, H., 2003. Effect of soil organic carbon on soil water retention. Geoderma 116 (1–2), 61–76.
Roopnarain, A., Adeleke, R., 2017. Current status, hurdles and future prospects of biogas digestion technology in Africa. Renew. Sust. Energ. Rev. 67, 1162–1179.
Ruiz-Mercado, I., Masera, O., Zamora, H., Smith, K.R., 2011. Adoption and sustained use of improved cookstoves. Energy Policy 39 (12), 7557–7566.
Rupf, G.V., Bahri, P.A., De Boer, K., McHenry, M.P., 2015. Barriers and opportunities of biogas dissemination in Sub-Saharan Africa and lessons learned from Rwanda, Tanzania, China, India, and Nepal. Renew. Sust. Energ. Rev. 52, 468–476.
Shallo, L., Sime, G., 2019. Determinants of functional status of family size bio-digesters: empirical evidence from southern Ethiopia. Int. J. Sustain. Energy 38 (5), 493–510.
Sime, G., 2020. Technical and socioeconomic constraints to the domestication and functionality of biogas technology in rural areas of southern Ethiopia. Cogent Eng. 7 (1), 0–18.
Smith, K.R., 2006. Health impacts of household fuelwood use in developing countries. Unasylva 57 (224), 41–44.
Smith, J., Apsley, A., Avery, L., Baggs, E., Balana, B., Yongabi, K., 2013. The potential of small-scale biogas digesters to alleviate poverty and improve long term sustainability of ecosystem services in Sub-Saharan Africa. 1st World Sustain. Forum 5 (10), 2911–2942.
Smith, J., et al., 2014. What is the potential for biogas digesters to improve soil fertility and crop production in Sub-Saharan Africa? Biomass Bioenergy 70 (3), 58–72.
Smith, J.U., et al., 2015. Sustainable use of organic resources for bioenergy, food and water provision in rural Sub-Saharan Africa. Renew. Sust. Energ. Rev. 50, 903–917.
Smith, J., Nayak, D., Albanito, F., Balana, B., Black, H., Phimister, E., 2019. Treatment of organic resources before soil incorporation in semi-arid regions improves resilience to El Nino, and increases crop production and economic returns. Environ. Res. Lett. 14 (8).
Tucho, G.T., Nonhebel, S., 2015. Bio-wastes as an alternative household cooking energy source in Ethiopia. Energies 8 (9), 9565–9583.
Tucho, G.T., Moll, H.C., Schoot Uiterkamp, A.J.M., Nonhebel, S., 2016. Problems with biogas implementation in developing countries from the perspective of labor requirements. Energies 9 (9).
Tumwesige, V., Okello, G., Semple, S., Smith, J., 2017. Impact of partial fuel switch on household air pollutants in sub-Sahara Africa. Environ. Pollut. 231, 1021–1029.