Biomass and Bioenergy

Environmental and financial benefits of improved cookstove technologies in the Central Highlands of Ethiopia

--Manuscript Draft--

Manuscript Number:	JBAB-D-20-01287R1
Article Type:	Research paper
Keywords:	Biogas; Controlled Cooking Test, Cookstove; Fuel saving efficiency; greenhouse gases; Kitchen Performance Test
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Response to Reviewers:	

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Abstract

This study assessed the potential contributions of improved cookstoves in enhancing organic fertilizer availability for application to farmland, greenhouse gas emission mitigation and improvement of household finances using the Kitchen Performance Test and Controlled Cooking Test. Substitution of a three-stone open fire with improved cookstoves significantly ($p<0.01$) improved fuel use efficiency by 54% (highest) for the mirt stove together with biogas and 32% (lowest) for the mud stove without biogas. The greenhouse gas emission reductions in carbon dioxide equivalents were 4534(±32) kg y^{-1}, 6370(±42) kg y^{-1}, 6953(±51) kg y^{-1}, 7661(±43) kg y^{-1} for the mud stove, mirt stove, mud stove with biogas and mirt stove with biogas respectively. The average financial savings from the sale of surplus biomass fuel for the improved cookstoves were higher than the summed financial savings from substitution of commercial fertilizer, generation of carbon finance and replacement of kerosene for lighting. This explains why households usually prefer to sell surplus biomass fuels instead of using them as organic fertilizers. This finding suggests that wide scale adoption of fuel-efficient solid biomass stoves can contribute to the financial security of households, and may help to reduce deforestation, but will do little to increase the fertility of soils. By contrast, including biogas stoves will help to improve soil fertility by retaining at least some of the carbon and nutrients in bioslurry that will then be applied to the soil.

Keywords: Biogas; Controlled Cooking Test, Cookstove; Fuel saving efficiency; Greenhouse Gases; Kitchen Performance Test

1. Introduction

Ethiopia is ranked as one of the four countries in the world with the highest per capita biomass fuel consumption, disease burden from indoor air pollution and use of non-renewable biomass fuels [1]. It also has the second highest reliance on traditional fuels of all countries in Africa, only exceeded by Nigeria [2], with ~94% of its total energy demand derived from solid biomass [3].

Biomass fuel consumption rates remain very high since most rural households in Ethiopia are still dependent on inefficient three-stone open fire cooking [4]. As reported by Abebe *et al.* [5], three-stone fires account for 92% of all cooking, while the coverage of improved cookstoves is only 8%. This excessive reliance on biomass fuels, compounded by inefficient combustion technologies, is contributing to increased deforestation, scarcity of fodder and depletion of soil fertility [6, 7]. There is also a high likelihood of future increased demand for biomass fuel and consequent increased rates of deforestation and greenhouse gas (GHG) emissions due to population growth [8]. Under a business-as-usual scenario, biomass fuel demand in Ethiopia is projected to increase by 65% by the year 2030, and this has been linked to deforestation of 9 million ha forest land [9].

High use of biomass fuels also adds to the burden of women hence exacerbating gender inequality by taking away time that could have been used for productive activities [10]. Indoor air pollution from traditional biomass fuels has a disproportionate impact on women and is listed among the top three causes of death in most countries in Sub-Saharan Africa [11]. The global estimate of deaths due to indoor air pollution was as high as 4.3 million each year [11]. In Ethiopia, ~72,400 people die every year due to indoor air pollution [12].

In the Highlands of Ethiopia, rural farm households have been compelled to change their fuel source to agricultural residues due to firewood scarcity [13, 14, 15, 16]. The fuel wood crisis is now widespread in the central and north Highlands of Ethiopia, and many households are struggling to get even enough dung and crop residues to meet their fuel demands [12].

Increasing utilization efficiency of the available biomass fuels and converting to modern energy alternatives are potential approaches to mitigate the detrimental environmental and socio-economic impacts of using biomass resources as fuels [10, 13, 17]. In the short term, substituting traditional biomass fuels with clean and modern energy sources, such as electricity, is unrealistic for the extremely scattered rural villages of the Ethiopian Highlands [5, 9, 18]. Instead, the shift to improved cookstoves and small-scale biogas digesters that have the potential to narrow the gap between energy demand and supply through their increased efficiency could be viable alternatives to traditional biomass burning [19].

Improved cookstoves used in Ethiopia include locally made “mud stoves”, as well as the more efficient, government designed “lakech” (“excellent”) improved charcoal stove and the mirt(“best”) improved biomass [20, 21]. Mud stoves are enclosed stoves made of mud mixed with straw or hay by local artisans [22]. Lakech and mirt stoves were developed by a UK-based company, Energy for Sustainable Development, and the Ethiopian Ministry of Water and Energy in the early and mid-90s (Energy for Sustainable Development (ESD, [23]). The lakech stove is made of ceramic and metal [24], while the mirt stove is made of cement [25]. Mirt stoves are specifically designed for baking the staple food, “injera”, a pancake like thin bread made of teff flour which is native to Ethiopia. Baking injera accounts for ~65% of household fuel consumption [20]. Mirt stoves can also be used to cook and boil food while baking without the use of additional fuel [26].

Improved cookstoves can either be used to burn wood or charcoal, or they can be adapted to burn biogas [27]. Biogas is a clean fuel, produced by anaerobic decomposition of organic wastes, leaving a nutrient rich “bioslurry” residue that can be used as an organic fertilizer [13, 28]. Application of bioslurry to agricultural fields from biogas digesters could also greatly increase the carbon content of the soil, thereby improving soil fertility and crop productivity as well as further reducing net GHG emissions [28].

Through GHG reductions associated with increased biomass fuel use efficiency due to implementation of improved solid biomass fuel cookstoves and biogas, Ethiopia could benefit from carbon financing provided by the Clean Development Mechanism (CDM), Reduced Emission from Deforestation and Forest Degradation (REDD+) and World Bank Forest Carbon Partnership Facility (WB-FCPF) [29].

Despite efforts, since the 1970s, to introduce and disseminate improved cookstoves and small-scale biogas digesters in Ethiopia, adoption has been limited [3]. For instance, by 2014, only 11% of households in Borena woreda of North Central Highlands of Ethiopia were using improved stoves and, of these, 90% were mud stoves [30].

Field–based empirical evidence on potential environmental implications of improved cookstoves and biogas digesters are generally sparse, and field-based evaluation of end-use biomass fuel efficiency is lacking [11, 21, 31, 34]. Therefore, the aim of this work was to assess the potential impact of mud and mirt stoves, with-and-without the use of biogas stoves, on the biomass fuel saving of farm households, and to determine the implications for availability of agricultural residues for soil improvement, mitigation of GHGs emission and household finances.

This was done for the case study of Kumbursa Village in the central Highlands of Ethiopia using the Kitchen Performance Test, the Controlled Cooking Test and household survey.

2. Materials and Methods

2.1. Description of the study site

Ada'a district, where Kumbursa Village is situated, is largely characterized by a cycle of energy-driven deforestation and soil fertility loss, with cattle dung and crop residues constituting 61% and 18% of the total household energy demand, respectively [35].

FIGURE 1 HERE

As elsewhere in Ada'a district, in Kumbursa village, dung cakes and crop residues are the dominant fuels and cooking is usually done using a traditional three-stone open fire [16]. All of the households in Kumbursa use separate kitchens in thatched huts with poor ventilation for cooking. Cooking hearths are located in a corner of the kitchen and they are mostly constructed on a raised level of approximately 1m height. The walls of the kitchens are plastered with mud and the air quality during cooking is poor as the kitchens lack chimneys and windows.

2.2. Types and description of cookstoves used by the households in Kumbursa Village

The major cookstoves currently in use in Kumbursa Village are three stone open fires, mud stoves and mirt stoves (Table 1).

TABLE 1 HERE

2.3. Selection of stove performance testing methods

The three most common methods used to evaluate stove performance are the Water Boiling Test, Controlled Cooking Test and Kitchen Performance Test, also respectively known as efficiency, effectiveness and efficacy tests [36]. Each of these three approaches has its own benefits and limitations.

The Water Boiling Test evaluates stove performance by boiling a measured quantity of water in a standard pot; the shorter the time required and the lower the quantity of fuel used for boiling, the more efficient the stove [11]. The Water Boiling Test is able to control for confounding factors and provides a high degree of replication, but it does not reflect actual cooking performance [31] and is therefore mostly suited to lab-based screening of stove efficiency [36]. The Controlled Cooking Test involves simulation of the real cooking practice by controlling variables like quantity of food prepared, quantity of fuel used and the behaviors of the cook [11, 36]. It is less standardized but more realistic than the Water Boiling Test, but still does not reflect the actual cooking practice in the field. The Kitchen Performance Test involves assessment of fuel consumption by households under a normal cooking practice [37]. It is preferred over both the Water Boiling Test and Controlled Cooking Test for actual in situ stove performance assessment [37] as the results reflect the real cooking situation in a kitchen and so reflect actual cooking practice [36]. Therefore, in this study, the Kitchen Performance Test was used to assess field-based biomass fuel consumption rates of the different stove types in Kumbursa Village.

The Kitchen Performance Test was applied in this study using the protocol set out by Bailis *et al.*[38]. This was also supported by a Controlled Cooking Test and short-term participant observation survey, following the approach used by Granderson *et al*. [37]. The results obtained using both Controlled Cooking Test and participant observation survey methods were then compared and triangulated with those of the Kitchen Performance Test in order to strengthen the reliability of the findings.

2.3.1. The Kitchen Performance Test

The Kitchen Performance Test was done with the same households before and after introduction of improved stoves to measure changes in fuel consumption rates with the improved technology. This is because before and after comparisons yield more accurate results than parallel testing of paired households [37]. The Kitchen Performance Test was carried out under natural conditions in a way that reflects the usual cooking activity in households. Cooking food for the family is mainly done by the mother of the children in the household, so this person with main responsibility for cooking was selected to participate in both the Kitchen Performance Test and Controlled Cooking Test.

The study included 42 sampled households, selected based on recommendations given by the local development agent and village leader. Willingness to participate in the study was also taken into account in the selection process. The participant households were selected to have similar kitchen dimensions, typically thatched huts with plastered walls having a size of $6m^2$ to $10m^2$. The study was limited to only one season but was supplemented by householder interviews and focus groups discussions to compensate for this limitation.

The same types of biomass fuels were supplied to each participant household. The biomass fuel used in this study was composed of the mixture of crop residues, dung cakes and firewood as is normal practice in the study village. The approximate amounts of fuel needed for the Kitchen Performance Test were determined from the mean fuel consumption rate for Kumbursa village

[16] and by a preliminary survey. In this village, 80% by weight of the biomass fuels used were dung cakes, while crop residues and firewood respectively constituted 16% and 2% only. Annual mean fuel consumption per household was 4524 kg y^{-1} for dung cakes, 1885 kg y^{-1} for crop residues and 980 kg y^{-1} for firewood. The amounts of fuel delivered to each household was then increased over these mean consumption rates by 50%, resulting in an amount of fuel given to each household per week of ~131 kg dung cakes, ~54 kg crop residues and ~28 kg firewood; a total of 213 kg of biomass fuels. The participants were told to use only the fuel given to them. After every cooking activity, the participants were asked to immediately extinguish the fire and keep the remaining fuel for the cooking session on the following day.

Initially, all of the 42 selected participant households were instructed to cook their food using the traditional three-stone open fires for seven days (Figures 3a & b). On the last day of the trial (day seven), the remaining fuel was measured to quantify the amounts of fuel consumption using traditional three-stone open fires by each participant household.

Households were then divided into four sub-groups using a random lottery method and new technologies were provided to the groups as follows; 11 members used only mud stoves (Figure 3c) (group 1), 11 members used only mirt stoves (Figure 3d) (group 2), 10 members used mud stoves together with biogas stoves (group 3), and another 10 members used mirt stoves together with biogas stoves (group 4).The same quantity and quality of biomass fuels were provided to all of the study households as during the pre-installation testing, and households were advised to use only the measured and stored biomass fuels during the entire seven days of the test. Again, the amount of fuel that remained after cooking for a week was weighed in order to determine fuel consumption for each household.

FIGURE 2 HERE

2.3.2. The Controlled Cooking Test

The controlled cooking test, also called the standard meal test, was undertaken for baking the staple food, injera. Triplet replications over seven days for each of the three cookstove types (traditional three-stone open fire which served as control, mud stoves and mirt stoves) were compared using the Controlled Cooking Test. Three experienced cooks (women who had fifteen years or more cooking experience) were purposefully selected.

The Controlled Cooking Test was undertaken in the household kitchens so as to simulate normal cooking conditions [14, 31]. Baking was done by the same people (the cook and her assistant), at a similar time and place using similar biomass fuels, griddles and teff dough in order to control variations in fuel consumption rates due to factors other than stove type.

Fuels and dough were weighed using a balance before starting to cook, and the amount of fuel remaining after cooking was weighed in order to determine fuel consumption for each stove type. Immediately after cooking was completed, the unburnt fuel was removed by extinguishing the fire. A cold start was used and cooking was started at 10:00 am for all of the three tested stove types to control for the effects of local weather variation.

2.4. Quantification of the nutrient contents of dung cakes, crop residues and bioslurry

The dry weight of bioslurry produced by the biogas users, dung cakes and crop residues were measured over a period of two weeks and converted into an annual average. Dung cakes, crop residues and bioslurry samples were analyzed in the laboratory to determine the percent of nitrogen (N), phosphorus (P), potassium (K) and organic carbon (OC). The amount of nutrients or OC saved by the household, M_{x}(kg week^{-1}`), was then calculated from the weight of the organic waste saved (dung cakes, crop residues or bioslurry), M_{ow}(kg week^{-1}), as:

$$M_{\mathrm{x}} = M_{\mathrm{ow}} \times {}^{P_{\mathrm{x}}}/_{100} \qquad (1)$$

where P_{x} is the percentage of x (where x = N, P, K or OC) in the dry organic waste.

2.5. Calculation of greenhouse gas emissions

The three most important GHGs; carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), which have global warming potentials of 1, 25 and 298 carbon dioxide equivalents (CO_2e), respectively (IPCC, 2007), were considered in this study. The IPCC [39] default thermal values (MJ kg^{-1} fuel) and emission factors (CO_2e) shown in Table 2 were used to estimate the likely GHG emissions.

TABLE 2 HERE

In order to convert the volume of biogas to the thermal value and weight, a conversion factor of 23 MJ m^{-3}and0.7 kg m^{-3} was used after Mulu *et al.*[6]. The replacement potential of biogas for firewood was determined following the method provided by Pathank *et al.*[40], which assumed that 1m^{3} of biogas provided equivalent heating energy to 5.5 kg of firewood. The GHG reduction potential of typical household biogas digesters with volumes of 6 – 8m^{3} was assumed to be 1.9 t CO_2e per digester per year [12].

The annual mass of GHG emissions from the combustion of fuel type a, $\mathrm{M_{GHG,a}}$ (kg of carbon dioxide equivalents (CO_2e) per household) was calculated as follows:

$$M_{\mathrm{GHG,a}} = E_{\mathrm{a}} \times 10^{-6} \times (EF_{\mathrm{CO2}} + EF_{\mathrm{CH4}} + EF_{\mathrm{N2O}}) \qquad (2)$$

where E_{a} is the annual thermal value of combustion fuel in MJ per household, EF_{CO2} is emission factor for carbon dioxide , EF_{CH4} is emission factor for methane and EF_{N2O} is emission factor for nitrous oxide, all in CO_2e mg MJ^{-1} (Table 2). The annual thermal value of a given fuel of a household (E_{a}) was computed by multiplying the weight of the fuel by its thermal value (MJ kg^{-1}) (Table 2).

The total annual mass of GHG emissions from all fuels, MGHG,tot, in kg of CO_2e per household in the study area was calculated as:

$$M_{\mathrm{GHG,tot}} = E_{\mathrm{a1}} + E_{\mathrm{a2}} + E_{\mathrm{a3}} + E_{\mathrm{a4}} + E_{\mathrm{a5}} \qquad (3)$$

where E_{a1}, E_{a2}, E_{a3}, E_{a4} and E_{a5} are the annual masses of GHG emissions in kg per household from the combustion of wood, dung, crop residue, biogas and kerosene, respectively. Emission reductions were then quantified by subtracting fuel consumed in post-improved cookstove intervention from pre-improved cookstove intervention and then converting into amount of GHGs using their corresponding emission factors for each fuel type.

The amount of methane leakage to the atmosphere from biogas production was calculated as:

$$M_{\mathrm{GHG,dig}} = M_{\mathrm{biogas}} \times p_{\mathrm{CH4}} \times GWP_{\mathrm{CH4}} \times p_{\mathrm{leak}} \qquad (4)$$

where $M_{\mathrm{GHG,dig}}$ is the average annual emission of methane from the biogas digester in kg of CO_2e; M_{biogas} is the average yearly biogas generation of a digester, also in kg of CO_2e (assumed to be 306 kg after Mulu et al., 2016); p_{CH4} is the proportion of methane in biogas (assumed to be 0.6 after Mulu et al. [6]; GWP_{CH4} is the global warming potential of methane (assumed to be 25 after IPCC, 2007); p_{leak} is the proportion of methane produced lost through leakage (assumed to be 0.1 after Mulu *et al. [6]*.

2.6. Replacement cost analysis

The average annual saving of nutrients (N and P in bioslurry) and fuels (firewood, crop residues, dung cakes and kerosene) due to substituting a three-stone open fire with a mud stove or mirt stove, without or with use of a biogas stove, was calculated and valued using the local market monetary values. For determining the value of inorganic fertilizer (diammonium phosphate fertilizer (DAP)), which was dominantly used in the study village, the farm gate price in Kumbursa in 2016 was used.

The carbon financing potential from GHG emission reduction was estimated as 16.4US$ or 360.8 ETB per 1 t CO_2e, based on offset price of the Gold Standard Verified Emission Reduction (VER) of Clean Development Mechanisms [10].

2.7. Statistical analysis

Variation in biomass fuel consumption rates, nutrient savings, GHG emissions and financial savings among the different stoves were analyzed using one-way analysis of variance. Data obtained from pre-intervention stage were compared with that of post-intervention stage fuel saving using paired sample *t*-test. Mean values were used for quantifying GHGs emission and for analyzing the replacement costs.

3. Results

3.1. Biomass fuel saving efficiencies based on results from Kitchen Performance Test

Results from Kitchen Performance Test showed that the mean biomass fuel saving for each household compared to a three stone open fire was 32% (2842(±21) kg y^{-1}) for mud stoves (group 1), 45% (3997(±27) kg y^{-1}) for mirt stoves (group 2), 49% (4352(±33) kg y^{-1}) for the combined use of mud and biogas stoves (group 3), and 54% (4796 (±27) kg y^{-1}) for combined use of mirt and biogas stoves (group 4) (Table 3). The biomass fuel saving was statistically significant (Table 3; $p<0.001$) with the highest fuel saving was for the households using a mirt stove with biogas.

In corroboration with this finding, Amogne [30] obtained biomass fuel savings of 25% and 47% respectively for the "gonzie" stove (another design of improved injera stove) and lakech stoves compared to the three-stone open fires. Mirt stoves saved up to 50% of biomass fuel consumption compared to the three-stone open fire stove [4]. Abera[7] and Dresen *et al*. [41] respectively found 60% and 40% biomass fuel saving efficiencies for the mirt stove compared to the three-stone open fire system.

TABLE 3 HERE

3.2. Biomass fuel saving efficiencies based on results from Controlled Cooking Test

As shown in Table 4, the results from the controlled cooking test are not statistically different within a given technology with (F = 0.679; P = 0.519) for the three stone open fires, (F = 0.894; P = 0.427) for mud stoves, and ((F = 2.222; P = 0.137) for the mirt stoves. This implies that the efficiency test results were consistent and valid, and hence were in agreement with the results obtained using Kitchen Performance Test.

TABLE 4 HERE

FIGURE 3 HERE

3.3. Potential contribution of improved cookstoves to Soil nutrients availability

The lowest nutrient saving was observed for households using mud stove only while the highest was recorded for those households using the mirt stove with biogas; these variations were statistically significant (Table 5; $P<0.001$).

TABLE 5 HERE

3.4. Potentials of improved cookstoves in reduction of greenhouse gas emissions

The potential per household GHG emission reductions in CO_2e were 4534 (±32) kg y^{-1} for mud stoves, 6370 (±42) kg y^{-1} for mirt stoves, 6953 (±51) kg y^{-1} for the mud stoves with biogas and 7661 (±43) kg y^{-1} for mirt stoves with biogas (Table 6).

As shown in Table 6, the use of biogas stoves together with improved solid biomass fuel stoves significantly reduced GHG emissions (Table 6; $P<0.001$). The studies conducted elsewhere also reported similar contributions of biogas and improved cookstoves for the reduction of GHG emissions. For instance, biogas digesters prevented 360 $m^3y^{-1}CO_2$ and 600 m^3y^{-1} CH_4 from being emitted to the atmosphere and saved about 0.562 ha of forest land from being deforested on annual basis [19]. Abera [7] also reported a reduction of CO_2 emissions by 2.145 t y^{-1} per stove as a result of replacing three-stone open fire furnace with a gonzie stove.

TABLE 6 HERE

3.5. Potential contributions of improved cookstoves in saving household finances

The replacement of three-stone open fire with improved cookstoves resulted in significant financial savings (Table 7). The combined financial savings per farm household from reducing expenditure on commercial fertilizer and from carbon financing for the mud stoves and mirt stoves without biogas were 3122(±36) ETB y^{-1} (142(±1.6) US\$ y^{-1}) and 5059 (±45) ETB y^{-1} (230 (±2) US\$ y^{-1}) respectively, while biogas increased this to 7007(±36) ETB y^{-1} (318 (±1.6) US\$ y^{-1}) and 8051 (±45) ETB y^{-1} (366(±2) US\$ y^{-1}). This includes replacement of kerosene by biogas for lighting, which provided a financial saving of 643 ETB y^{-1}(29 US\$ y^{-1}).

These results are consistent with the findings of Abera *et al.* [7] which also reported potential annual financial saving of 3,717 ETB per household as a result of substituting three-stone open fires with mirt stoves. With biogas, Zerihun [42] observed an annual per household savings of ETB 3833, 1243, 129, 266 and 718 from substituting fuel wood, charcoal, dung cake, kerosene and chemical fertilizer.

TABLE 7 HERE

4. Discussions

Although the mud stove was less efficient than the mirt stove and failed to meet the minimum GTZ efficiency requirement of 40% [4], it significantly increased biomass fuel use efficiency when compared to the traditional three-stone open fire. The greater efficiency of the mirt stoves compared to the mud stoves was attributed to the better design and construction of the former. In addition to preparing injera, mirt stoves were used for drying and refreshing stale injera and preparing “firfir” (made by mixing dried injera with hot sauce) using the heat remaining after baking injera. The mirt stove was also used for preparation of sauce (“wot”) on the chimney during injera baking, which, according to the participants, further saved biomass fuel and reduced cooking time.

The biomass fuel saving of the mirt stove over the traditional three-stone open fire was in agreement with the findings by Yosef (2007), who reported a 45% fuel saving for an injera mirt stove compared to a traditional open fire system. However, the result of this study was higher than the findings of Abera [7] Dresen *et al.* [41], and Dagninet *et al.* [43], who reported savings of only 40%, 22% and 33%, respectively. The results from this study are higher because of the probable improvements in the design of the more recent stoves used in this experimental work which were assumed to have better efficiency. Further savings were observed when the solid biomass stoves were used in combination with biogas stoves. This is because biogas was used for cooking activities other than injera baking, such as for wot preparation, making coffee and tea and boiling water.

From the household survey, it was observed that 173 (67%) out of the total 258 households in Kumbursa village had enough feedstock with more than four cows per household, good access to water, i.e. within a distance of less than 2 km from the nearest water source and adequate financial capacity to install biogas digesters (most of them being in the medium and rich farm household wealth groups).

If the full potential of biogas was exploited and used together with mud or mirt stoves, there would be biomass fuel savings of 4352(±33) kg y^{-1} per household and 4796(±27) kg y^{-1} per household respectively (Table 3) while the respective possible biomass fuel savings across all potential users in Kumbursa would be 752.9(±5.7) t y^{-1} and 829.7(±4.6) t y^{-1}).The exhaustive exploitation of the available biogas potential together with use of mud stoves for the entire 258 households of Kumbursa Village could result in potential saving per household of 25.2(±0.13) t y^{-1} N, 7.5(±0.03) t y^{-1}P, 25.9(±0.16) t y^{-1}K and 573.3(±3.50) t y^{-1} OC; if biogas was used together with mirt stoves the nutrients saving potential would be 27.9(±0.10) t y^{-1} N, 7.9(±0.03) t y^{-1} P, 28.1(±0.13) t y^{-1}K and 620.7(±2.84) t y^{-1} OC. The substitution of three-stone open fires with improved cookstoves could also significantly contribute to the mitigation of GHG emissions. Thus, rural farm households can benefit from carbon financing and this could be used to motivate them to switch from the traditional three stone open fires to more fuel-efficient biomass stoves at a larger scale.

As confirmed from the results of both the Kitchen Performance Test and Controlled Cooking Test, substitution of three-stone open fires with mud and mirt stoves both with and without biogas stoves improved nutrient availability for application to farmlands. This implies that saved fuels (cow dung and crop residues) could be used as organic fertilizers. Using improved solid biomass cookstoves together with biogas stoves can substantially increase the availability of nutrients for field application relative to the use of improved solid biomass cookstoves without biogas stoves. Average landholding size for Kumbursa Village is 1.9 ha [16] which requires nearly 190 kg DAP and 190 kg urea based on blanket recommendation, so the extra nutrients potentially supplied to the soil when mirt and biogas stoves are used in combination (N = 117 kg and P = 34 kg) are almost equivalent to the amounts recommended for inorganic fertilizer (122 kg N and 34 kg P).

However, the use of organic fertilizer in the predominantly cereal cropping areas of the Central Highland of Ethiopia, including Kumbursa Village, is very rare. The field survey revealed that farm households prefer to sell the surplus cattle dung as dung cakes instead of applying it to farmland since dung cake demand as fuels is very high near to urban markets. This study demonstrates that the financial savings from the sale of surplus biomass fuel was higher than the potential total financial savings from substituting commercial fertilizer, generation of carbon finance and replacement of kerosene for lighting. This explains why households usually prefer to sell surplus biomass fuels instead of using them as organic fertilizers. This finding suggests that while wide scale adoption of fuel-efficient solid biomass stoves can contribute to the financial security of households, and may help to reduce deforestation, it will do little to increase the fertility of soils. By contrast, including biogas stoves will help to improve soil fertility by retaining at least some of the carbon and nutrients in bioslurry that will be applied to the soil.

Generally, improving biomass fuel use efficiency has the potential to mitigate the adverse environmental and socioeconomic impacts associated with traditional biomass fuel use. Improved cookstoves such as mirt stoves have great potential to improve fuel supply while significantly contributing to mitigation of GHG emissions and improvement of household finance. However, because the dung cakes can be sold for fuel sources at a relatively high price, the availability of dung for soil amendment will only be improved by use of biogas digesters, which prevents it from being sold as dung cakes by turning it into bioslurry.

5. Conclusions

Improving biomass fuel use efficiency has the potential to mitigate the adverse environmental and socioeconomic impacts associated with traditional biomass fuel use. Improved cookstoves such as mirt stoves have great potential to improve fuel supply while significantly contributing to mitigation of GHG emissions and improvement of household finance. However, because the dung cakes can be sold for fuel sources at a relatively high price, the availability of dung for soil amendment will only be improved by use of biogas digesters, which prevents it from being sold as dung cakes by turning it into bioslurry. Therefore, large scale production of more efficient biomass fuel technologies, such as mud stoves and mirt stoves, together with dissemination of biogas digesters, is likely to be a valuable short-term policy intervention.

Acknowledgements

The authors are grateful to the participating households in stove performance test and end-users' stove satisfaction survey without whose assistance the accomplishment of the research undertaking could have been possible. We would like to give our deep gratitude to the African Union Commission (AUC) for funding the installation of biogas digesters and mirt stoves in Kumbursa Village as part of Afriflame project under the adaptation of small-scale biogas digesters for use in rural households in Sub-Saharan Africa. The assistance from Green Heat-Uganda in installing biogas digesters in Kumbursa Village is appreciated. Finally, we are thankful to the staff of Debrezeit Agricultural Research Center for analyzing the nutrient contents of dung cake, crop residues and bioslurry samples.

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Tables

Table 1. Types and description of cookstoves selected for fuel performance assessment at Kumbursa Village

Table 2.Thermal values (MJ kg^{-1}) of fuels (biomass, biogas & kerosene) and greenhouse gas emission factors in carbon dioxide equivalents ($mgMJ^{-1}$); EF_{CO2} is the emission factor for carbon dioxide, $EF\mathrm{CH_4}$ for methane and EF_{N2O} for nitrous oxide [39]

Table 3. Biomass fuel saving efficiencies of mud stoves and mirt stoves with and without biogas stoves as compared to three-stone open fire stoves

Table 4. One way ANOVA among cookstoves and cooks in biomass fuel consumption

Table 5. Nutrient saving potentials of different cookstoves

Table 6. Greenhouse gas (GHG) emission mitigation potentials of the different cookstoves

Table 7. Improvement in household finances due to substitution of the three stone open fires with improvedcookstoves

Table 1. Types and description of cookstoves selected for fuel performance assessment at Kumbursa Village

Cookstove type	Description
Traditional three-stone open fire	A three-stone open fire is made of three-stones, bricks or inverted clay pans. The three-stone open fire forms a circular area with average height of 40 cm, but with varied diameter. Since the stones are not fixed, the area can be set relative to the material that can be used for cooking. This is the most common method used for cooking in Kumbursa. A *mitad* (a circular griddle made from clay with a diameter of approximately 60cm) is used for baking injera.
Mud stove	An enclosed stove, made of mud mixed with straw or hay by the local artisans in the kitchen. The mud stove is fixed with average diameter of 80 cm and height of 65 to 110cm. Mud stoves are mostly used for injera baking, although some households also include a chamber for cooking of *wot* (an Ethiopian stew), making tea and coffee, and boiling water.
Mirt stove	Mirt means 'best' in Amharic [21]. It is a type of improved manufactured stove which has been promoted by GTZ since 1990s. Its design and function is similar to a mud stove. It is usually prepared from cement and sand with an enclosed chamber for combustion having a small opening for adding biomass fuel and to let in air. It is circular in shape with average diameter of 120 cm and height of 75 cm. It has an extra small chamber of 45 cm width, which is used for resting a pan used for cooking wotor kettle used for making coffee.

Biogas stove	A metal stove connected by a biogas pipe to the biogas digester. It is used for cooking wot, boiling water, and making coffee and tea.

Table 2.Thermal values (MJ kg^{-1}) of fuels (biomass, biogas & kerosene) and greenhouse gas emission factors in carbon dioxide equivalents (mgMJ^{-1}); EF_{CO2} is the emission factor for carbon dioxide, EFCH4 for methane and EF_{N2O} for nitrous oxide [39]

Fuel type	Thermal values (MJ kg^{-1})	EF_{CO2}	EFCH4	EF_{N2O}
Air dried fuel wood	15.5	112,000	300	4
Air dried dung fuels	15	100,000	300	4
Air dried crop residues	13.8	100,000	300	4
Biogas	33	54,000	5	0.1
Kerosene	36	71,900	10	0.6

Table 3. Biomass fuel saving efficiencies of mud stoves and mirt stoves with and without biogas stoves as compared to three-stone open fire stoves

Stove types	Mean biomass fuel saving per household		Standard deviation	*t*-value	Df	p-value (2-tailed)
	Absolute (kg y^{-1})	Relative				
Group 1: Mud stove	2842±21	32%	350	19.4	10	.000**
Group 2: Mirt stove	3997±27	45%	441	20.6	10	.000**
Group 3: Mud and biogas stove	4352±33	49%	735	13.7	9	.000**
Group 4:	4796±27	54%	816	13.8	9	.000**

Mirt and biogas stove	

Note: average biomass fuel consumption for three stone open fires = 8891 kg y^{-1} per household

Table 4. One way ANOVA among cookstoves and cooks in biomass fuel consumption

Code	Mean biomass fuel consumption of 7 days performance (kg day^{-1})				Mean square between groups	F-ratio	(P-value)
	3-stone open fire	Mud stove	Mirt stove	Mean			
Cook 1	19.1±0.31	12.3±0.19	10.2±0.13	13.9±0.86	152.5	433.4	0.000**
Cook 2	18±0.33	11.8±0.14	10.7±0.22	13.5±0.73	107.8	259.3	0.000**
Cook 3	18.4±0.47	12.1±0.32	10.4±0.12	13.6±0.80	125.8	159.5	0.000**
Mean	18.5±0.23	12.1±0.13	10.4±0.10				
Mean square within groups	0.800	0.326	0.409				
F-ratio	0.679	0.894	2.222				
(P-value)	0.519	0.427	0.137				

Table 5. Nutrient saving potentials of different cookstoves

Stove types	Average saving potential (kg y^{-1}) per household			
	Nitrogen	Phosphorus	Potassium	Organic carbon
Group 1: Mud stove	43.1±0.32	10.5±0.07	54.2±0.39	1177.9±8.5
Group 2: Mirt stove	60.6±0.41	14.8±0.10	76.2±0.51	1665.4±9.7
Group 3: Mud stove +biogas stove	115.0±0.51	35.4±0.12	109.1±0.63	2427.4±13.5
Group 4: Mirt stove +biogas stove	125.7±0.40	37.0±0.09	117.6±0.51	2611.1±11.0
P-values	0.000**	0.000**	0.000**	0.000**

Table 6. Greenhouse gas (GHG) emission mitigation potentials of the different cookstoves

Stove types	GHGs emissions mitigation potential per household (kg CO_2e y^{-1})			
	CO_2	CH_4	N_2O	Total
Group 1: Mud stove	4173(±31)	310(±20)	50(±3)	4534(±32)
Group 2: Mirt stove	5880(±40)	430(±32)	71(±7)	6370(±42)
Group 3: Mud and biogas stove	10186(±51)	471(±40)	80(±7)	10726(±51)
Group 4: Mirt and biogas stove	10777(±40)	521(±30)	80(±6)	11434(±43)
P-value	0.000**	0.000**	0.000**	0.000*

Table 7. Improvement in household finances due to substitution of the three stone open fires with improvedcookstoves

	Potential financial saving efficiencies per household in ETB y^{-1}			
Stove types	From sale of saved biomass fuel	From reducing expense on inorganic fertilizer	From carbon financing	From replacement of kerosene for lighting
Group 1: Mud stove	6145 (±95)	1488 (±12)	1634 (±24)	-
Group 2: Mirt stove	8630 (±115)	2761 (±15)	2298 (±30)	-
Group 3: Mud stove+biogas stove	9406 (±139)	3308 (±19)	2508 (±35)	643
Group 4: Mirt+biogas stove	10354 (±57)	3450 (±7)	2764 (±168)	643
P-value	0.000**	0.000**	0.000**	

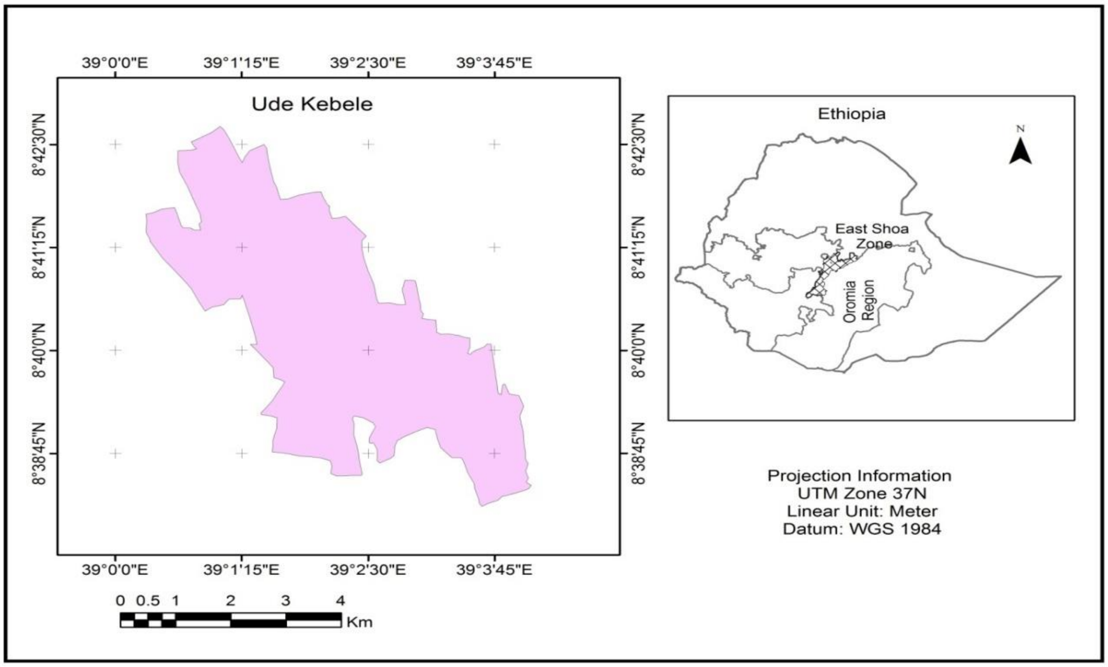
Note:*1USD = 22ETB; dung cakes, crop residues, firewood and charcoal respectively account for 60%, 25%, 13% and 2% of the saved biomass fuel; local market biomass fuel monetary values were 2ETB kg^{-1}for dung cakes, 2.1ETB kg^{-1}for crop residues, 1.8 ETB kg^{-1}for firewood and 10 ETB kg^{-1}for charcoal.*

Figures

Fig.1. Location map of Ude Kebele and East Shoa Zone of Ethiopia

Fig. 2. Baking injera using traditional three stone open fires (a) and (b), a mud stove (c) and a mirt stove (d).

Fig. 3. Comparative biomass fuel consumption rates (t y^{-1}) by the different stove types under Controlled Cooking Test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8°41'15"N
8°40'0"N
8°38'45"N
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N
East Shoa
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Oromia
Region
Projection Information
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Linear Unit: Meter
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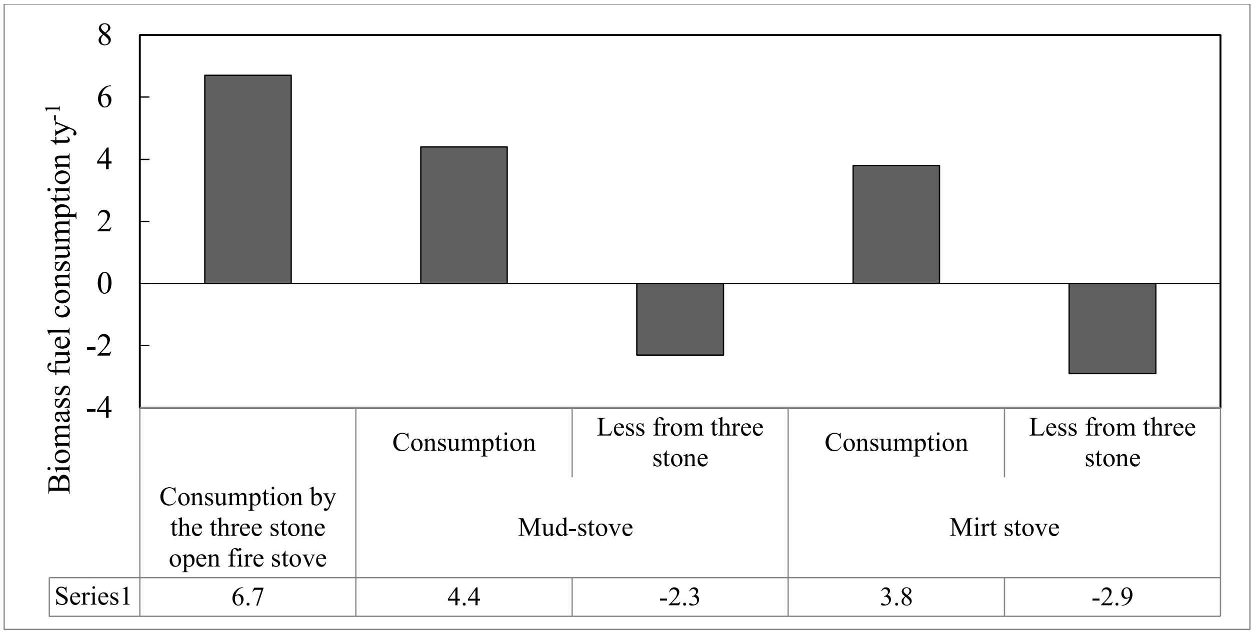
Km

Fig. 1.

Fig. 2.



8
6
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Biomass fuel consumption ty^{-1}
Consumption by the three stone open fire stove
Consumption
Less from three stone
Mud-stove
Consumption
Less from three stone
Mirt stove
Series1
6.7
4.4
-2.3
3.8
-2.9

Fig. 3.

Environmental and financial benefits of improved cookstove technologies in the Central Highlands of Ethiopia

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Abstract

This study assessed the potential contributions of improved cookstoves in increasing organic fertilizer availability for application to farmland, greenhouse gas emission mitigation and improvement of household finances using the Kitchen Performance Test, Controlled Cooking Test, household survey and focus group discussions. Substitution of a three-stone open fire with improved cookstoves significantly ($p<0.01$) improved fuel use efficiency by 54% (highest) for the *mirt* stove with an additional biogas stove and 32% (lowest) for the mud stove without an additional biogas stove. The greenhouse gas emission reductions in carbon dioxide equivalents were 4534 (±32) kg y^{-1}, 6370 (±42) kg y^{-1}, 6953 (±51) kg y^{-1}, 7661 (±43) kg y^{-1} for the mud stove, *mirt* stove, mud stove with an additional biogas stove and mirt stove with an additional biogas stove respectively. The average financial savings from the sale of surplus biomass fuel for the improved cookstoves were higher than the summed financial savings from substitution of commercial fertilizer, generation of carbon finance and replacement of kerosene for lighting. This explains why households usually prefer to sell surplus biomass fuels instead of using them as organic fertilizers. This finding suggests that wide scale adoption of fuel-efficient solid biomass stoves can contribute to the financial security of households, and may help to reduce green gas emissions, but will do little to increase the fertility of soils. By contrast, including biogas stoves will help to improve soil fertility by retaining at least some of the carbon and nutrients in bioslurry that will then be applied to the soil.

Keywords: Biogas; Cookstove; Fuel saving efficiency; Kitchen Performance Test; Controlled Cooking Test; Greenhouse Gases

1. Introduction

Ethiopia is ranked as one of the four countries in the world with the highest per capita biomass fuel consumption, disease burden from indoor air pollution and use of non-renewable biomass fuels [1]. It also has the second highest reliance on traditional fuels of all countries in Africa, only exceeded by Nigeria [2], with ~94% of its total energy demand derived from solid biomass [3].

Biomass fuel consumption rates remain very high since most rural households in Ethiopia are still dependent on inefficient three-stone open fire cooking [4] while kerosene is dominant source of energy for lighting. As reported by Abebe *et al.* [5], three-stone fires account for 92% of all cooking, while the coverage of improved cookstoves is only 8%. This excessive reliance on biomass fuels, compounded by inefficient combustion technologies, is contributing to increased deforestation, scarcity of fodder due to utilization of crop residues for fuel instead of using as livestock feed and depletion of soil fertility as a result of increased shift to cattle dung for fuel [6, 7]. There is also a high likelihood of future increased demand for biomass fuel and consequent increased rates of deforestation and greenhouse gas (GHG) emissions due to population growth [8]. Under a business-as-usual scenario, biomass fuel demand in Ethiopia is projected to increase by 65% by the year 2030, and this has been linked to deforestation of 9 million ha forestland [9].

High use of biomass fuels also adds to the burden of women hence exacerbating gender inequality by taking away time that could have been used for productive activities [10]. The study conducted by Amoah et al. [11] also revealed that females long distance in search of firewood by going long distance wasting much of their time and this compromised their ability to engage in productive work. Indoor air pollution from traditional biomass fuels has a disproportionate impact on women and is listed among the top three causes of death in most countries in Sub-Saharan Africa [12]. The global estimates of deaths due to indoor air pollution was as high as 4.3 million each year [12]. In Ethiopia, ~72,400 people die every year due to indoor air pollution from biomass fuel and kerosene [13].

In the Highlands of Ethiopia, rural farm households have been compelled to change their fuel source to agricultural residues due to firewood scarcity [14, 15, 16, 17]. The fuelwood crisis is now widespread in the central and north Highlands of Ethiopia, and many households are struggling to get even enough dung and crop residues to meet their fuel demands [13].

Increasing utilization efficiency of the available biomass fuels and converting to modern energy alternatives are potential approaches to mitigate the detrimental environmental and socio-economic impacts of using biomass resources as fuels [10, 14, 18]. In the short term, substituting traditional biomass fuels with clean and modern energy sources, such as electricity both for lighting and cooking, is unrealistic for the extremely scattered rural villages of the Ethiopian Highlands [5, 9, 19]. This implies that biomass fuel for cooking and kerosene for lighting continue will continue to dominate the energy source. Thus, the shift to improved cookstoves and small-scale biogas digesters that have the potential to narrow the gap between energy demand and supply through their increased efficiency could be viable alternatives to traditional biomass burning [20].

Improved cookstoves used in Ethiopia include locally made mud stoves as well as the more efficient, government designed *lakech* (excellent) improved charcoal stove and the *mirt* (best) improved biomass stove [21, 22]. Mud stoves are enclosed stoves made of mud mixed with straw or hay by local artisans [23]. *Lakech* and *mirt* stoves were developed by a UK-based company, Energy for Sustainable Development, and the Ethiopian Ministry of Water and Energy in the early and mid-90s (Energy for Sustainable Development (ESD, [24]). The *lakech* stove is made of ceramic and metal [25], while the *mirt* stove is made of cement [26]. *Mirt* stoves are specifically designed for baking the staple food, *injera*, a pancake like thin bread made of *teff* flour which is native to Ethiopia. Baking *injera* accounts for ~65% of household fuel consumption [21]. *Mirt* stoves can also be used to cook and boil food while baking without the use of additional fuel [27].

Improved cookstoves can either be used to burn wood or charcoal, or they can be adapted to burn biogas that may also substitute kerosene for lighting [28]. Biogas is a clean fuel, produced by anaerobic decomposition of organic wastes, leaving a nutrient rich “bioslurry” residue that can be used as an organic fertilizer [14, 29]. Application of bioslurry to agricultural fields from biogas digesters could also greatly increase the C content of the soil, thereby improving soil fertility and crop productivity as well as further reducing net GHG emissions [29]. So additional use of biogas with improved solid biogas could provide multiple environmental and economic benefits.

Through GHG reductions associated with increased biomass fuel use efficiency due to implementation of improved solid biomass fuel cookstoves and biogas, Ethiopia could benefit from carbon financing provided by the Clean Development Mechanism (CDM), Reduced Emission from Deforestation and Forest Degradation (REDD+) and World Bank Forest Carbon Partnership Facility (WB-FCPF) [30, 31].

Despite efforts, since the 1970s, to introduce and disseminate improved cookstoves and small-scale biogas digesters in Ethiopia, adoption has been limited [3]. For instance, by 2014, only

11% of households in Borena woreda of North Central Ethiopia were using improved stoves and, of these, 90% were mud stoves [32].

Field–based empirical evidence on potential environmental implications of improved cookstoves and biogas digesters are generally sparse and field-based evaluation of end-use biomass fuel efficiency is lacking. Mercy Corps [13], for instance focused only on firewood and charcoal as sources of fuel the study being limited to assessing the burning efficiencies of improved biomass cookstoves. Zenebe *et al.* [23, 33] on the other hand, investigated the fuel saving efficiencies as well cooking time and user satisfaction impacts of improved solid biomass cookstoves. Smith et al. [30) evaluated the potential of biogas digesters to improve soil fertility and crop production but did not conduct field based field based practical experiment. Amogne (32) studied factors affecting the adoption of efficient biomass cookstoves. Thus, the studies undertaken so far have tried to assess only limited aspects of improved cookstoves such as the contributions for fuel saving, factors affecting uptake and user satisfaction by primarily focusing on utilization of firewood and/or charcoal for fuel. This study, however, has tried to assess the impacts of improved cookstoves more holistically by considering the multiple potential benefits that can be gained from using improved cookstoves such as greenhouse gas emission reduction and carbon financing, enhancing the availability of agricultural wastes for soil fertility improvement and reduction of expenditure on chemical fertilizers. Unlike the other cookstove tests which have used firewood as source of fuel [23, 29, 32], this study has undertaken the stove efficiency test considering the mixture of local energy sources reflecting the real condition of the study area namely, dung cakes, crop residues and firewood which respectively account for 61.2%, 25.5% and 13.3 of fuel source by weight. Moreover, none of the above previous studies have conducted multiple stove efficiency test and associated environmental and financial benefits including the impact of biogas in improving household finance by substituting kerosene for lighting. Therefore, the aim of this work was to assess the potential impact of mud and *mirt* stoves, with-and-without an additional biogas stove stoves, on the biomass fuel saving of farm households, and to determine the implications for availability of agricultural residues for soil improvement, mitigation of GHGs emission and household finances. This was done for the case study of Kumbursa Village in the Central Highlands of Ethiopia using the Kitchen Performance Test, the Controlled Cooking Test and household survey.

As depicted in Figure 1, substitution of the traditional three stone fires with improved cookstoves and small scale biogas digesters has the potential to increase biomass fuel use efficiency hence reduces fuel consumption rates. The installation of biogas digester can improve household finance by replacing kerosene for lighting. The reduction in biomass fuel consumption implies creating opportunities for increased availability of crop residues and cattle dung for application to farmland while also contributing to the mitigation of GHGs emissions to the atmosphere. Figure 1 also depicts that in order to use livestock manures and crop residues for soil fertility amelioration, the traditional and less efficient biomass burning should be substituted with a sustainable and efficient means of household energy provision should such as small scale biogas digesters and improved solid biomass cook stoves.

FIGURE 1 HERE

2. Materials and Methods

2.1. Description of the study site

Ude *kebele* of Ada'a District, in which Kumbursa Village is situated, is located in East Shoa Zone of Oromia National Regional State of Ethiopia (Figure 2). The Village is found in the

Central Highlands of Ethiopia very close to the western escarpment of the Great East African Rift Valley.

Kumbursa Village is located at about 55 km in the southeast direction from Addis Ababa with astronomical location of 8^0 10’ 45’’ N and 39^0 44’ 12’’ E.

The altitude of Kumbursa Village is ranging between 1878m and 1892m above sea level with flat to slightly undulating topography covering the total area of nearly 1000 ha. Fuel sources are mainly from household owned woodlot plantation, dung and crop residues from household owned livestock and fields. Kumbursa village is not only the source of agricultural produce, it also provides biomass energy for the nearby urban centers.

There is no communal land for livestock grazing or firewood collection in Kumbursa village. Therefore, farm households of the village almost entirely depend on resources collected from their farmlands and homesteads for food, feed, fuel and cash.

Ada’a district of which Kumbursa Village is a part is largely characterized by a cycle of energy-driven deforestation and soil fertility loss, with cattle dung and crop residues constituting 61% and 18% of the total household energy demand, respectively [35].

The farming systems in Kumbursa are denoted by close interdependence and integration of crop cultivation and animal husbandry, where the production and productivity of one is inextricably related to the other. There is no communal land for livestock grazing or firewood collection in Kumbursa Village.

Kumbursa Villages is characterized by very high human and livestock population. There are 258 households with average livestock size of 3.1 TLU and landholding size of 1.9 ha per household [18]. The fact that many urban centers including Addis Ababa are found in close proximity to Kumbursa Village has resulted in extremely high human and animal population pressure on the land. The crop production systems in Kumbursa village are dominated by cereal production with the use of legumes for rotation.

FIGURE 2 HERE

As elsewhere in Ada'a district, in Kumbursa village, dung cakes and crop residues are the dominant fuels and cooking is usually done using a traditional three-stone open fire while the dominant source of energy for lighting the household is kerosene [18]. All of the households in Kumbursa use separate kitchens in thatched huts with poor ventilation for cooking. Cooking hearths are located in a corner of the kitchen and they are mostly constructed on a raised level of approximately 1m height, locally referred to as a *madab*. The walls of the kitchens are plastered with mud and the air quality during cooking is poor as the kitchens lack chimneys and windows.

Kumbursa village was purposively selected for this study because it represents a typical rural village in the Central Highlands of Ethiopia that entirely depend on biomass fuel for cooking purpose. Unlike many rural villages in Ethiopian Highlands that at least partly depend on firewood collected from community forest for firewood, there is neither community forest for firewood collection nor communal grazing land for the livestock. So Kumbursa Village represents the situation that will become widely common in Ethiopian Highlands after depletion of community forest and absence of communal grazing land due to increased population pressure on the available land. Accessibility to asphalt road for transportation and removal of agricultural wastes (dung cakes & crop residues) for sale by taking to the nearby urban centers including Addis Ababa is commonly observed in the area.

2.2. Types and description of cookstoves used by the households in Kumbursa Village

The different stove types used in stove efficiency test are described in Table 1, and the most dominant cookstove currently in use in Kumbursa Village is three stone open fires, and only few of the households are using improved stoves such as mud stoves and *mirt* stoves.

TABLE 1 HERE

2.3. Selection of stove performance testing methods

The three most common methods used to evaluate stove performance are the Water Boiling Test, Controlled Cooking Test and Kitchen Performance Test, also respectively known as efficiency, effectiveness and efficacy tests [36]. Each of these three approaches has its own benefits and limitations but in this study, the Controlled Cooking and Kitchen Performance Tests were used as explained below.

The Water Boiling Test evaluates stove performance by boiling a measured quantity of water in a standard pot; the shorter the time required and the lower the quantity of fuel used for boiling, the more efficient the stove [12]. The Water Boiling Test is able to control for confounding factors and provides a high degree of replication, but it does not reflect actual cooking performance [33], and is therefore mostly suited to lab-based screening of stove efficiency [36]. The Controlled Cooking Test, also called the standard meal test, was undertaken for baking the staple food, *injera*. The Controlled Cooking Test involves simulation of the real cooking practice by controlling variables like quantity of food prepared, quantity of fuel used and the behaviors of the cook [12, 36]. It is less standardized but more realistic than the Water Boiling Test, but still does not reflect the actual cooking practice in the field. The Kitchen Performance Test involves assessment of fuel consumption by households under a normal cooking practice [37]. It is preferred over both the Water Boiling Test and Controlled Cooking Test for actual in situ stove performance assessment [37], as the results reflect the real cooking situation in a kitchen and so reflect actual cooking practice [36]. Therefore, in this study, the Kitchen Performance Test was used to assess field-based biomass fuel consumption rates of the different stove types in Kumbursa Village.

The Kitchen Performance Test was applied in this study using the protocol set out by Bailis *et al.* [38]. This was also supported by a Controlled Cooking Test and short-term participant observation survey, following the approach used by Granderson *et al*. [37]. The results obtained using both Controlled Cooking Test and participant observation survey methods were then compared and triangulated with those of the Kitchen Performance Test in order to strengthen the reliability of the findings.

2.3.1. The Kitchen Performance Test

The Kitchen Performance Test was done with the same households before and after introduction of improved stoves to measure changes in fuel consumption rates with the improved technology. This is because before and after comparisons yield more accurate results than parallel testing of paired households [37]. The Kitchen Performance Test was carried out under natural conditions in a way that reflects the usual cooking activity in households. Cooking food for the family is mainly done by the mother of the children in the household, so this person with main responsibility for cooking was selected to participate in both the Kitchen Performance Test and Controlled Cooking Test.

There were 258 households in Kumbursa Village during the field survey and 42 households (16.3% of the total population) participated in efficiency tests of the cookstoves. Thus, the study included 42 sampled households, selected based on recommendations given by the local development agent and village leader. Willingness to participate in the study was also taken into account in the selection process. Such methods of purposive sampling are widely used when samples with the required characteristics are not easily accessible [39], but the non-random nature of the sampling should be noted when interpreting the results. The participant households were selected to have similar kitchen dimensions, typically thatched huts with plastered walls having a size of 6 m^2 to 10 m^2. The study was limited to only one season i.e., Spring season (first and second weeks of May 2016) but was supplemented by household survey, householder interviews and focus groups discussions to compensate for this limitation. To minimize the effect of variation in time, the cooking tests were conducted within reasonably shorter time (consecutive weeks of the same month; first and second weeks of May 2016).

The same types of biomass fuels were supplied to each participant household. The biomass fuel used in this study was composed of the mixture of crop residues, dung cakes and firewood as is normal practice in the study village. The approximate amounts of fuel needed for the Kitchen Performance Test were determined from the mean fuel consumption rate for Kumbursa village [18] and by a preliminary survey. In this village, 60% and 25% by weight of the biomass fuels used were dung cakes and crop residues respectively while firewood constituted 13% and with charcoal accounting only for 2% of the total energy consumption of household. Annual mean fuel consumption per household was 4524 kg y^{-1} for dung cakes, 1885 kg y^{-1} for crop residues and 980 kg y^{-1} for firewood. The amounts of fuel delivered to each household was then increased over these mean consumption rates by 50%, resulting in an amount of fuel given to each household per week of ~131 kg dung cakes, ~54 kg crop residues and ~28 kg firewood; a total of 213 kg of biomass fuels. The participants were told to use only the fuel given to them. After every cooking activity, the participants were asked to immediately extinguish the fire and keep the remaining fuel for the cooking session on the following day.

Initially, all of the 42 selected participant households were instructed to cook their food using the traditional three-stone open fires for seven days (Figures 3a & b). On the last day of the trial (day seven), the remaining fuel was measured to quantify the amounts of fuel consumption using traditional three-stone open fires by each participant household.

Households were then divided into four sub-groups using a random lottery method. The improved stove types were written on pieces of papers, which were physically similar in shape, size and color and rolled-up. The rolled-up pieces of papers were equal to the sample size. They were placed in a vessel and thoroughly mixed. Then each participant randomly picked a rolled-up paper from the vessel. Finally, new technologies were provided to the groups as follows; 11 members used only mud stoves (Figure 3c) (group 1), 11 members used only *mirt* stoves (Figure 3d) (group 2), 10 member used mud stoves with an additional biogas stove stoves (group 3), and another 10 members used *mirt* stoves with an additional biogas stove stoves (group 4). The same quantity and quality of biomass fuels were provided to all of the study households as during the pre-installation testing, and households were advised to use only the measured and stored biomass fuels during the entire seven days of the test. The participants were told not to use the fuel given to them for unusual occasions such as holidays, ceremonies, etc. Again, the amount of fuel that remained after cooking for a week was weighed in order to determine fuel consumption for each household.

FIGURE 3 HERE

2.3.2. The Controlled Cooking Test

Triplet replications over seven days for each of the three cookstove types (traditional three-stone open fire which served as control, mud stoves and mirt stoves) were compared using the Controlled Cooking Test. Three experienced cooks (women who had fifteen years or more cooking experience) were purposefully selected from the forty two cooks involved in the Kitchen Performance Test.

The Controlled Cooking Test was undertaken in the household kitchens so as to simulate normal cooking conditions [14, 31]. Baking was done by the same people (the cook and her assistant), at a similar time and place using similar biomass fuels, "mitads" and *teff* dough in order to control variations in fuel consumption rates due to factors other than stove type. Every cook had one assistant for tending the fire, feeding biomass fuel into the stove and providing the required materials for cooking.

Fuels and dough were weighed using a weight balance before starting to cook, and the amount of fuel remaining after cooking was weighed in order to determine fuel consumption for each stove type. Immediately after cooking was completed, the unburnt fuel was removed by extinguishing the fire. A cold start was used and cooking was started at 10:00 am for all of the three tested stove types to control for the effects of local weather variation. All cooks and their assistants were strictly instructed to cook only once per day and to start baking *injera* exactly at 10:00am every day of the seven days.

2.4. Quantification of the nutrient contents of dung cakes, crop residues and bioslurry

The dry weight of bioslurry produced by the biogas users, dung cakes and crop residues were measured over a period of two weeks and converted into an annual average. Dung cakes, crop residues and bioslurry samples were analyzed in the laboratory to determine the percent of nitrogen (N), phosphorus (P), potassium (K) and organic carbon (OC). The amount of nutrients saved by the household, M_x (kg week$^{-1`}$), was then calculated from the weight of the organic waste saved (dung cakes, crop residues or bioslurry), Mow (kg week^{-1}), as:

$$Mx=Mow\times Px100 \qquad (1)$$

where P_x is the percentage of x (where x = N, P, K or OC) in the dry organic waste.

2.5. Calculation of greenhouse gas emissions

The three most important GHGs; carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), which have global warming potentials of 1, 25 and 298 carbon dioxide equivalents (CO_2e), respectively [39], were considered in this study. The IPCC [40] default thermal values (MJ kg^{-1} fuel) and emission factors (CO_2e) shown in Table 2 were used to estimate the likely GHG emissions.

TABLE 2 HERE

In order to convert the volume of biogas to the thermal value and weight, a conversion factor of 23 MJ m^{-3} and 0.7 kg m^{-3} was used after Mulu *et al.* [6]. The replacement potential of biogas for firewood was determined following the method provided by Pathank *et al.* [41], which assumed that 1 m^3 of biogas provided equivalent heating energy to 5.5 kg of firewood. The GHG reduction potential of typical household biogas digesters with volumes of 6 – 8 m^3 was assumed to be 1.9 t CO_2e per digester per year [12].

The annual mass of GHG emissions from the combustion of fuel type *a*, $M_{GHG,a}$ (kg of carbon dioxide equivalents (CO_2e) per household) was calculated as follows:

$$M\text{GHG,a}=Ea\times 10-6\times EF\text{CO}_2+EF\text{CH}_4+EF\text{N}_2\text{O} \qquad (2)$$

where E_a is the annual thermal value of combustion fuel in MJ per household, EF_{CO2} is emission factor for carbon dioxide , $EF\text{CH}_4$ is emission factor for methane and EF_{N2O} is emission factor for nitrous oxide, all in CO_2e mg MJ^{-1} (Table 2). The annual thermal value of a given fuel of a household (E_a) was computed by multiplying the weight of the fuel by its thermal value (MJ kg^{-1}) (Table 2).

The total annual mass of GHG emissions from all fuels, $M\text{GHG,tot}$, in kg of CO_2e per household in the study area was calculated as:

$$M\text{GHG,tot}=Ea1+Ea2+Ea3+Ea4+Ea5 \qquad (3)$$

where E_{a1}, E_{a2}, $Ea3$, E_{a4} and E_{a5} are the annual masses of GHG emissions in kg per household from the combustion of wood, dung, crop residue, biogas and kerosene, respectively. Note kerosene is included here as it is widely used in the area as a fuel for lighting, so providing biogas has potential to reduce the requirements for kerosene. Emission reductions were then quantified by subtracting fuel consumed in post-improved cookstove intervention from pre-improved cookstove intervention and then converting into amount of GHGs using their corresponding emission factors for each fuel type.

The amount of methane leakage to the atmosphere from biogas production was calculated as:

$$M\text{GHG,dig}=M\text{biogas}\times p\text{CH4}\times GWP\text{CH4}\times p\text{leak} \qquad (4)$$

where $M_{\text{GHG,dig}}$ is the average annual emission of methane from the biogas digester in kg of CO_2e; M_{biogas} is the average yearly biogas generation of a digester, also in kg of CO_2e (assumed to be 306 kg after Mulu et al., 2016); pCH4 is the proportion of methane in biogas (assumed to be 0.6 after Mulu et al. [6]; GWP_{CH4} is the global warming potential of methane (assumed to be 25 after IPCC[39]; p_{leak} is the proportion of methane produced lost through leakage (assumed to be 0.1 after Mulu *et al. [6]*.

2.6. Replacement cost analysis

The average annual amount of nutrients that can be saved from being burnt (N and P in bioslurry) and the amount of fuels (firewood, crop residues, dung cakes and kerosene) that can be saved due to substituting a three-stone open fire with a mud stove or *mirt* stove, without or with an additional biogas stove, was calculated and valued using the local market monetary values. For determining the value of inorganic fertilizer (diammonium phosphate fertilizer (DAP)), which was dominantly used in the study village, the farm gate price in Kumbursa in 2016 was used. For fertilizers, the farm gate price in Kumbursa in 2016 for diammonium phosphate fertilizer (DAP) was used; 15 Ethiopian Birr (ETB) kg^{-1} (0.72 US$ kg^{-1}). For fuels, local market prices in 2016 were used; for firewood =1.8 ETB kg^{-1} (0.09 US$ kg^{-1}), for crop residues = 2.1 ETB kg^{-1} (0.1US$ kg^{-1}), for dung cakes = 2.0 ETB kg^{-1} (0.1US$ kg^{-1}) and for kerosene = 16.0 ETB dm^{-3} (0.76US$ dm^{-3}).

The carbon financing potential from GHG emission reduction was estimated as 16.4 US$ or 360.8 ETB per 1 t CO_2e, based on offset price of the Gold Standard Verified Emission Reduction (VER) of Clean Development Mechanisms [10].

2.7. Household survey and focus group discussions

A single time cross-sectional survey was carried out to collect data on the resource endowment (landholding size, livestock number, household income) and household energy (sources of energy and consumption rates). A semi-structured interview questionnaire was used for the survey.

Using a participatory wealth ranking method, households of the Village were stratified into three wealth groups (rich, medium and poor). Using a proportionate-stratified-random sampling procedure over the wealth groups, 120 farm households (i.e. 45%) were selected out of the total 258 households of Kumbursa Village.

The four experimental groups participating in stove efficiency test formed four groups for focus group discussions. The issues covered by the focus group discussants constituted sources of biomass fuel as well as the merits and demerits attached to each stove type.

2.8. Sampling crop residues, dung cakes and bioslurry for analysis of nutrient contents

Nine composite samples (each consisting seven sub-samples) were collected each from crop residues, dung cakes and bioslurry for laboratory analysis of nitrogen, phosphorus, potassium and organic carbon contents. The dry weight of bioslurry produced by the biogas digester was measured over a period of two weeks and converted into an annual average. Bioslurry samples were taken after thorough stirring of the slurry in the overflow tank.

2.9. Statistical analysis

Variation in biomass fuel consumption rates, potential availability of nutrients due to reduced consumption of dung and crop residues, GHG emissions and financial savings among the different stoves were analyzed using one-way analysis of variance. Data obtained from pre-intervention stage were compared with that of post-intervention stage fuel saving using paired sample *t*-test. Mean values were used for quantifying GHGs emission and for analyzing the replacement costs.

3. Results

3.1. Biomass fuel saving efficiencies based on results from Kitchen Performance Test

Results from Kitchen Performance Test showed that the mean biomass fuel saving for each household compared to a three stone open fire was 32% (2842 (±21) kg y^{-1}) for mud stoves (group 1), 45% (3997 (±27) kg y^{-1}) for *mirt* stoves (group 2), 49% (4352 (±33) kg y^{-1}) for the mud stove with an additional biogas stoves (group 3), and 54% (4796 (±27) kg y^{-1}) for *mirt* stove with an additional biogas stove (group 4) (Table 3). The potential increase in biomass fuel availability relative to the traditional three stone open fire was statistically significant (Table 3; $p<0.001$) with the highest value for a *mirt* stove with an additional biogas stove.

In corroboration with this finding, Amogne [32] obtained biomass fuel savings of 25% and 47% respectively for the *Gonzie* and *Lakech* stoves compared to the three-stone open fires. *Mirt* stoves saved up to 50% of biomass fuel consumption compared to the three-stone open fire stove [4]. Abera [7] and Dresen *et al.* [42] respectively found 60% and 40% biomass fuel saving efficiencies for the *mirt* stove compared to the three-stone open fire system.

TABLE 3 HERE

3.2. Biomass fuel saving efficiencies based on results from controlled cooking test

As shown in Table 4, the results from the controlled cooking test are not statistically different within a given technology with (F = 0.679; P = 0.519) for the three stone open fires, (F = 0.894; P = 0.427) for mud stoves, and ((F = 2.222; P = 0.137) for the *mirt* stoves. This implies that the efficiency test results were consistent and valid, and hence were in agreement with the results obtained using Kitchen Performance Test.

TABLE 4 HERE

FIGURE 3 HERE

3.3. Potential contribution of improved cookstoves to Soil nutrients availability

The lowest nutrient saving from being burnt was observed for households using mud stove only while the highest was recorded for those households using the *mirt* stove with an additional biogas stove; these variations were statistically significant (Table 5; P<0.001).

TABLE 5 HERE

3.4. Potentials of improved cookstoves in reduction of greenhouse gas emissions

The potential per household GHG emission reductions in CO_2e were 4534 (±32) kg y^{-1} for mud stoves, 6370 (±42) kg y^{-1} for *mirt* stoves, 6953 (±51) kg y^{-1} for the mud stoves with an additional biogas stove and 7661 (±43) kg y^{-1} for *mirt* stoves with an additional biogas stove (Table 6).

As shown in Table 6, the use of biogas stoves together with improved solid biomass fuel stoves significantly reduced GHG emissions (Table 6; P<0.001). The studies conducted elsewhere also reported similar contributions of biogas and improved cookstoves for the reduction of GHG emissions. For instance, biogas digesters prevented 360 m^3 y^{-1} CO_2 and 600 m^3 y^{-1} CH_4 from being emitted to the atmosphere and saved about 0.562 ha of forest land from being deforested on annual basis [19]. Abera [7] also reported a reduction of CO_2 emissions by 2.145 t y^{-1} per stove as a result of replacing three-stone open fire furnace with a *gonziye* stove (another design of improved *injera* stove).

TABLE 6 HERE

3.5. Potential contributions of improved cookstoves in saving household finances

The replacement of three-stone open fire with improved cookstoves resulted in significant financial savings (Table 7). The removal of agricultural wastes for fuel implies reduced application of organic fertilizer and hence lower soil fertility. So the lower the soil fertility the higher the amount of commercial fertilizer for improving soil fertility. Application of more commercial fertilizer implies higher expenditure and reduced household finance. The combined financial savings per farm household from reducing expenditure on commercial fertilizer and from carbon financing for the mud stoves and *mirt* stoves without an additional biogas stove were 3122 (±36) ETB y^{-1} (142 (±1.6) US\$ y^{-1}) and 5059 (±45) ETB y^{-1} (230 (±2) US\$ y^{-1}) respectively, while an additional biogas stove increased this to 7007 (±36) ETB y^{-1} (318 (±1.6) US\$ y^{-1}) and 8051 (±45) ETB y^{-1} (366 (±2) US\$ y^{-1}). Biogas provides not only energy for cooking but also is used for lighting the household. Kerosene is the main source of lighting for the households of Kumbursa Village and biogas has the potential to reduce household expenditure by replacing kerosene for lighting. This includes replacement of kerosene by biogas for lighting, which provided a financial saving of 643 ETB y^{-1} (29 US\$ y^{-1}). The switch from traditional three stone open fire has generally the potential to raise the present average household income of 21109 ETB y^{-1} (959.5 US\$ y^{-1}) for Kumbursa Village to 24321 ETB y^{-1} (1101.4 US\$ y^{-1}) for mud stove, 26168 ETB y^{-1} (1189.5 US\$ y^{-1}) for *mirt* stove, 28116 ETB y^{-1} (1278 US\$ y^{-1}) for mud stove with additional biogas, and 29160 ETB y^{-1} (1325.5 US\$ y^{-1}) for *mirt* stove with additional biogas.

These results are consistent with the findings of Abera *et al.* [7] which also reported potential annual financial saving of 3,717 ETB per household as a result of substituting three-stone open fires with *mirt* stoves. With biogas, Zerihun [43] observed an annual per household savings of ETB 3833, 1243, 129, 266 and 718 from substituting fuel wood, charcoal, dung cake, kerosene and chemical fertilizer.

TABLE 7 HERE

4. Discussions

Although the mud stove was less efficient than the *mirt* stove and failed to meet the minimum GIZ efficiency requirement of 40% [4], it significantly increased biomass fuel use efficiency when compared to the traditional three-stone open fire. The greater efficiency of the *mirt* stoves compared to the mud stoves was attributed to the better design and construction of the former. In addition to preparing injera, *mirt* stoves were used for drying and refreshing stale *injera* and preparing *firfir* (made by mixing *dried* injera with hot sauce) using the heat remaining after baking *injera*. The *mirt* stove was also used for preparation of sauce (*wot*) on the chimney during *injera* baking, which, according to the participants, further saved biomass fuel and reduced cooking time.

The biomass fuel saving of the *mirt* stove over the traditional three-stone open fire was in agreement with the findings by Yosef [22], who reported a 45% fuel saving for an *injera* *mirt* stove compared to a traditional open fire system. However, the result of this study was higher than the findings of Abera [7] Dresen *et al.* [41], and Dagninet *et al.* [44], who reported savings of only 40%, 22% and 33%, respectively. The results from this study are higher because of the probable improvements in the design of the more recent stoves used in this experimental work which were assumed to have better efficiency. Further savings were observed when the solid biomass stoves were used in combination with biogas stoves. This is because biogas was used for cooking activities other than *injera* baking, such as for *wot* preparation, making coffee and tea and boiling water. A three stone open fire can be adjustable and hence can be utilized for many different purposes and this was appreciated as good quality. By contrast, improved cookstoves tend to be used for specific purposes. For instance, the *mirt* stoves and mud stoves are used only for baking *injera* unless special chambers are attached to allow them to be used for other purposes, such as sauce, tea and coffee preparation. On the other hand, biogas stoves are not well adapted for *injera* baking, and are preferred for use for water boiling, sauce preparation, coffee and tea preparation. Therefore, multiple stoves are used in households to serve different purposes.

From the household survey, it was observed that 173 (67%) out of the total 258 households in Kumbursa village had enough feedstock with more than four cows per household, good access to water, i.e. within a distance of less than 2 km from the nearest water source and adequate financial capacity to install biogas digesters (most them being in the medium and rich farm household wealth groups).

If the full potential of biogas was exploited and used together with mud or *mirt* stoves, there would be a total biomass fuel (dung cake, crop residues and firewood according to their respective relative contributions to the total fuel consumptions in the study area i.e., 61.2%, 25.5% and 13.3% of the total dry weight of biomass fuel used for stove efficiency tests) savings of 4352 (±33) kg y^{-1} per household and 4796 (±27) kg y^{-1} per household respectively (Table 3) while the respective possible biomass fuel savings across all potential users in Kumbursa would be 752.9 (±5.7) t y^{-1} and 829.7 (±4.6) t y^{-1}). The exhaustive exploitation of the available biogas potential together with use of mud stoves for the entire 258 households of Kumbursa Village could result in potential nutrient saving from being burnt per household of 25.2 (±0.13) t y^{-1} N, 7.5 (±0.03) t y^{-1} P, 25.9 (±0.16) t y^{-1} K and 573.3 (±3.50) t y^{-1} OC; if biogas was used together with *mirt* stoves, the potential amount of nutrients saving from being burnt would be 27.9 (±0.10) t y^{-1} N, 7.9 (±0.03) t y^{-1} P, 28.1 (±0.13) t y^{-1} K and 620.7 (±2.84) t y^{-1} OC. The substitution of three-stone open fires with improved cookstoves could also significantly contribute to the mitigation of GHG emissions. Thus, rural farm households can benefit from carbon financing and this could be used to motivate them to switch from the traditional three stone open fires to more fuel-efficient biomass stoves at a larger scale.

As confirmed from the results of both the Kitchen Performance Test and Controlled Cooking Test, substitution of three-stone open fires with mud and *mirt* stoves both with and without biogas stoves improved biomass (dung and crop residues) availability that can used for application to farmlands. This implies that saved fuels (cow dung and crop residues) could be used as organic fertilizers. Using improved solid biomass cookstoves together with biogas stoves can substantially increase the availability of nutrients for field application relative to the use of improved solid biomass cookstoves without biogas stoves. Average landholding size for Kumbursa Village is 1.9 ha [18] which requires nearly 190 kg DAP and 190 kg urea based on blanket recommendation, so the extra nutrients potentially supplied to the soil when *mirt* and biogas stoves are used in combination (N = 117 kg and P = 34 kg) are almost equivalent to the amounts recommended for inorganic fertilizer (122 kg N and 34 kg P).

However, the use of organic fertilizer in the predominantly cereal cropping areas of the Central Highland of Ethiopia, including Kumbursa Village, is very rare. The field survey revealed that farm households prefer to sell the surplus cattle dung as dung cakes instead of applying it to farmland since dung cake demand as fuels is very high near to urban markets. This study demonstrates that the financial savings from the sale of surplus biomass fuel was higher than the potential total financial savings from substituting commercial fertilizer, generation of carbon finance and replacement of kerosene for lighting. This explains why households usually prefer to sell surplus biomass fuels instead of using them as organic fertilizers. This finding suggests that while wide scale adoption of fuel-efficient solid biomass stoves can contribute to the financial security of households, and may help to reduce greenhouse gas emission and deforestation in areas where wood fuel provides a significant part of the household energy, it will do little to increase the fertility of soils. By contrast, including biogas stoves will help to improve soil fertility by retaining at least some of the carbon and nutrients in bioslurry that will be applied to the soil.

End-users' satisfaction survey of alternative stoves

From the focus group discussions and interviews with participants, it appeared that the time savings and the smokeless nature of the biogas as a fuel were appreciated by the end users, while the benefits of bioslurry as fertilizer were generally ignored and hence undervalued by the farm households.

End-users favored many of the different traits of the improved cookstoves compared to a traditional three-stone open fires. Traits of *mirt* and mud-stoves that were particularly appreciated by the end users were fuel saving, reduced frequency needed to tend the fire and allowing other household work to be done in parallel with cooking activities, less risk of exposure to burning and cleaner kitchens due to less soot and smoke.

However, there were some focus group discussants that appreciated three stone open fires for cooking purpose. The most commonly favored traits of the three-stone open fires were little or no cost incurred to obtain the stoves, easy adjustability for different activities and easy feeding with fuel through the spaces between the stones. The three-stone open fire was reportedly convenient for different cooking purposes as it is easily adjusted to fit cooking utensils of different sizes.

However, the smoky flavor of *wot*, tea or coffee prepared on a three-stone open fires was disfavored by the observed end users. It was confirmed during the field survey that households with only an improved stove for *injera* cooking presumably used three-stone open fires for other cooking purposes.

The main traits disliked about the three-stone open fire were the higher fuel consumption rates relative to both mud-stoves and *mirt* stoves, higher risk of burning and exposure to smoke, and inability of doing other household tasks due to constant tending of the fire.

The longer lifespan of the *mirt* stoves compared to the mud-stove was favored by the end users. Households liked biomass fuel saving provided by both the mud stoves and *mirt* stoves, while the *mirt* stoves were preferred over the mud-stoves for their durability. Limited supply and consequent increasing prices of biomass fuel were the major factors for prompting some households in Kumbursa Village to adopt fuel efficient cookstoves.

5. Conclusions

Improving biomass fuel use efficiency has the potential to mitigate the adverse environmental and socioeconomic impacts associated with traditional biomass fuel use. Improved cookstoves such as *mirt* stoves have great potential to improve fuel supply while significantly contributing to mitigation of GHG emissions and improvement of household finance. However, because the dung cakes can be sold for fuel sources at a relatively high price, the availability of dung for soil amendment will only be improved by an additional use of biogas digesters, which prevents it from being sold as dung cakes by turning it into bioslurry. Therefore, large scale production of more efficient biomass fuel technologies, such as mud stoves and *mirt* stoves, together with dissemination of biogas digesters, is likely to be a valuable short-term policy intervention.

Acknowledgements

The authors are grateful to the participating households in stove performance test and end-users' stove satisfaction survey without whose assistance the accomplishment of the research undertaking could have been possible. We would like to give our deep gratitude to the African Union Commission (AUC) for funding the installation of biogas digesters and *mirt* stoves in Kumbursa Village as part of Afriflame project under the adaptation of small-scale biogas digesters for use in rural households in Sub-Saharan Africa. The assistance from Green Heat-Uganda in installing biogas digesters in Kumbursa Village is appreciated. Finally, we are thankful to the staff of Debrezeit Agricultural Research Center for analyzing the nutrient contents of dung cake, crop residues and bioslurry samples.

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Tables

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Table 2.Thermal values (MJ kg^{-1}) of fuels (biomass, biogas & kerosene) and greenhouse gas emission factors in carbon dioxide equivalents (mg MJ^{-1}); EF_{CO2} is the emission factor for carbon dioxide, $EFCH_4$ for methane and EF_{N2O} for nitrous oxide [39]

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Cookstove type	Description
Traditional three-stone open fire	A three-stone open fire is made of three-stones, bricks or inverted clay pans. The three-stone open fire forms a circular area with average height of 40 cm, but with varied diameter. Since the stones are not fixed, the area can be set relative to the material that can be used for cooking. This is the most common method used for cooking in Kumbursa. A *mitad* (a circular griddle made from clay with a diameter of approximately 60cm) is used for baking injera.
Mud stove	An enclosed stove, made of mud mixed with straw or hay by the local artisans in the kitchen. The mud stove is fixed with average diameter of 80 cm and height of 65 to 110cm. Mud stoves are mostly used for injera baking, although some households also include a chamber for cooking of *wot* (an Ethiopian stew), making tea and coffee, and boiling water.
Mirt stove	Mirt means 'best' in Amharic [21]. It is a type of improved manufactured stove which has been promoted by GTZ since 1990s. Its design and function is similar to a mud stove. It is usually prepared from cement and sand with an enclosed chamber for combustion having a small opening for adding biomass

	fuel and to let in air. It is circular in shape with average diameter of 120 cm and height of 75 cm. It has an extra small chamber of 45 cm width, which is used for resting a pan used for cooking wot or kettle used for making coffee.
Biogas stove	A metal stove connected by a biogas pipe to the biogas digester. It is used for cooking wot, boiling water, and making coffee and tea.

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Fuel type	Thermal values (MJ kg^{-1})	EF_{CO2}	EFCH4	EF_{N2O}
Air dried fuel wood	15.5	112,000	300	4
Air dried dung fuels	15	100,000	300	4
Air dried crop residues	13.8	100,000	300	4
Biogas	33	54,000	5	0.1
Kerosene	36	71,900	10	0.6

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Stove types	Mean biomass fuel saving per household		Standard deviation	*t*-value	Df	p-value (2-tailed)
	Absolute (kg y^{-1})	Relative				
Group 1: Mud stove	2842 ± 21	32%	350	19.4	10	.000**
Group 2: Mirt stove	3997 ± 27	45%	441	20.6	10	.000**
Group 3: Mud and biogas stove	4352 ± 33	49%	735	13.7	9	.000**

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Note: average biomass fuel consumption for three stone open fires = 8891 kg y^{-1} per household

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Code	Mean biomass fuel consumption of 7 days performance (kg day^{-1})				Mean square between groups	F-ratio	(P-value)
	3-stone open fire	Mud stove	Mirt stove	Mean			
Cook 1	19.1±0.31	12.3±0.19	10.2±0.13	13.9±0.86	152.5	433.4	0.000**
Cook 2	18±0.33	11.8±0.14	10.7±0.22	13.5±0.73	107.8	259.3	0.000**
Cook 3	18.4±0.47	12.1±0.32	10.4±0.12	13.6±0.80	125.8	159.5	0.000**
Mean	18.5±0.23	12.1±0.13	10.4±0.10				
Mean square within groups	0.800	0.326	0.409				
F-ratio	0.679	0.894	2.222				
(P-value)	0.519	0.427	0.137				

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Stove types	Average saving potential (kg y^{-1}) per household			
	Nitrogen	Phosphorus	Potassium	Organic carbon
Group 1: Mud stove	43.1±0.32	10.5±0.07	54.2±0.39	1177.9±8.5
Group 2: Mirt stove	60.6±0.41	14.8±0.10	76.2±0.51	1665.4±9.7
Group 3: Mud stove +biogas stove	115.0±0.51	35.4±0.12	109.1±0.63	2427.4±13.5
Group 4: Mirt stove +biogas stove	125.7±0.40	37.0±0.09	117.6±0.51	2611.1±11.0
P-values	0.000**	0.000**	0.000**	0.000**

Table 6. Greenhouse gas (GHG) emission mitigation potentials of the different cookstoves

Stove types	GHGs emissions mitigation potential per household (kg CO_2e y^{-1})			
	CO_2	CH_4	N_2O	Total
Group 1: Mud stove	4173(±31)	310(±20)	50(±3)	4534(±32)
Group 2: Mirt stove	5880(±40)	430(±32)	71(±7)	6370(±42)
Group 3: Mud and biogas stove	10186(±51)	471(±40)	80(±7)	10726(±51)

Group 4: Mirt and biogas stove	10777(±40)	521(±30)	80(±6)	11434(±43)
P-value	0.000**	0.000**	0.000**	0.000*

Table 7. Improvement in household finances due to substitution of the three stone open fires with improved cookstoves

Stove types	Potential financial saving efficiencies per household in ETB y^{-1}			
	From sale of saved biomass fuel	From reducing expense on inorganic fertilizer	From carbon financing	From replacement of kerosene for lighting
Group 1: Mud stove	6145 (±95)	1488 (±12)	1634 (±24)	-
Group 2: Mirt stove	8630 (±115)	2761 (±15)	2298 (±30)	-
Group 3: Mud stove + biogas stove	9406 (±139)	3308 (±19)	2508 (±35)	643
Group 4: Mirt + biogas stove	10354 (±57)	3450 (±7)	2764 (±168)	643
P-value	0.000**	0.000**	0.000**	

Note:*1USD = 22ETB; dung cakes, crop residues, firewood and charcoal respectively account for 60%, 25%, 13% and 2% of the saved biomass fuel; local market biomass fuel monetary values were 2ETB kg^{-1}for dung cakes, 2.1ETB kg^{-1}for crop residues, 1.8 ETB kg^{-1}for firewood and 10 ETB kg^{-1}for charcoal.*

Figures

Fig.1. Biomass fuel use and livelihood interaction under current situation and after intervention with improved biomass technologies (Modified from Wachera [32])

Fig.2. Location map of Ude Kebele and East Shoa Zone of Ethiopia

Fig. 3. Baking injera using traditional three stone open fires (a) and (b), a mud stove (c) and a mirt stove (d).

Fig. 4. Comparative biomass fuel consumption rates (t y^{-1}) by the different stove types under Controlled Cooking Test

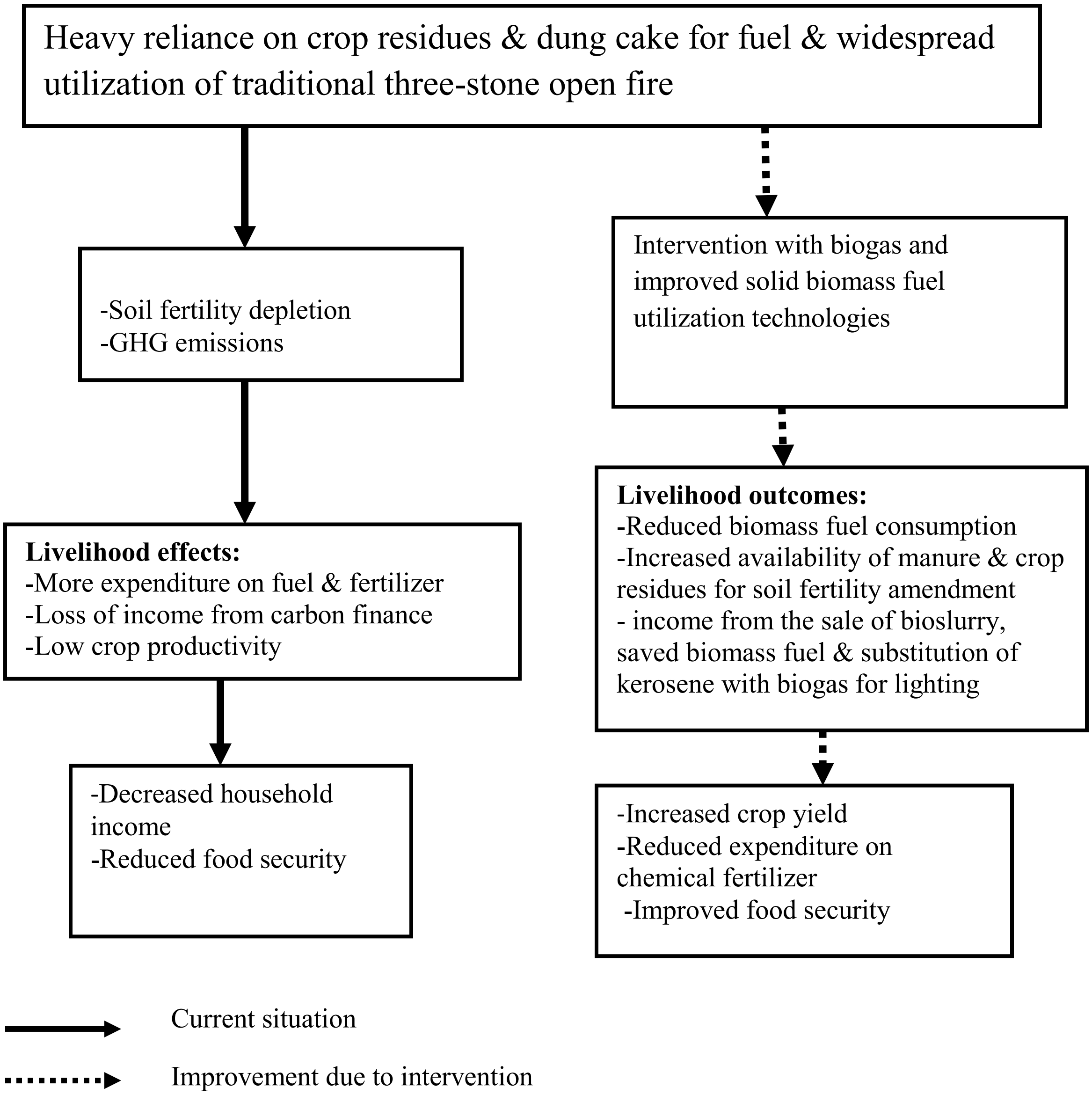
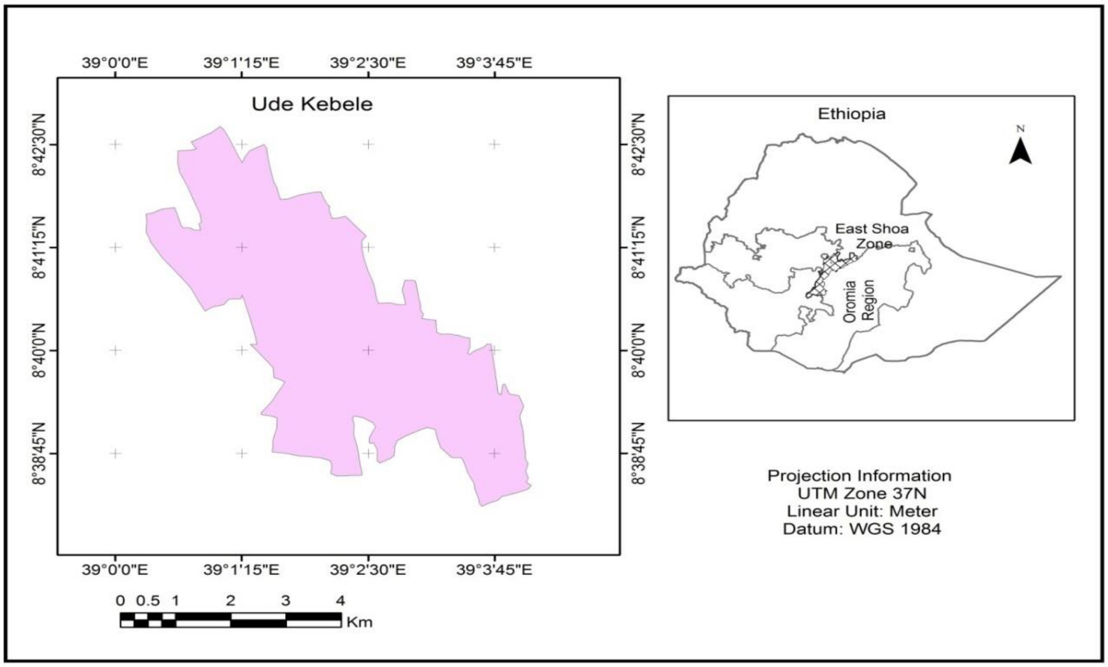


Fig.1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8°38'45"N
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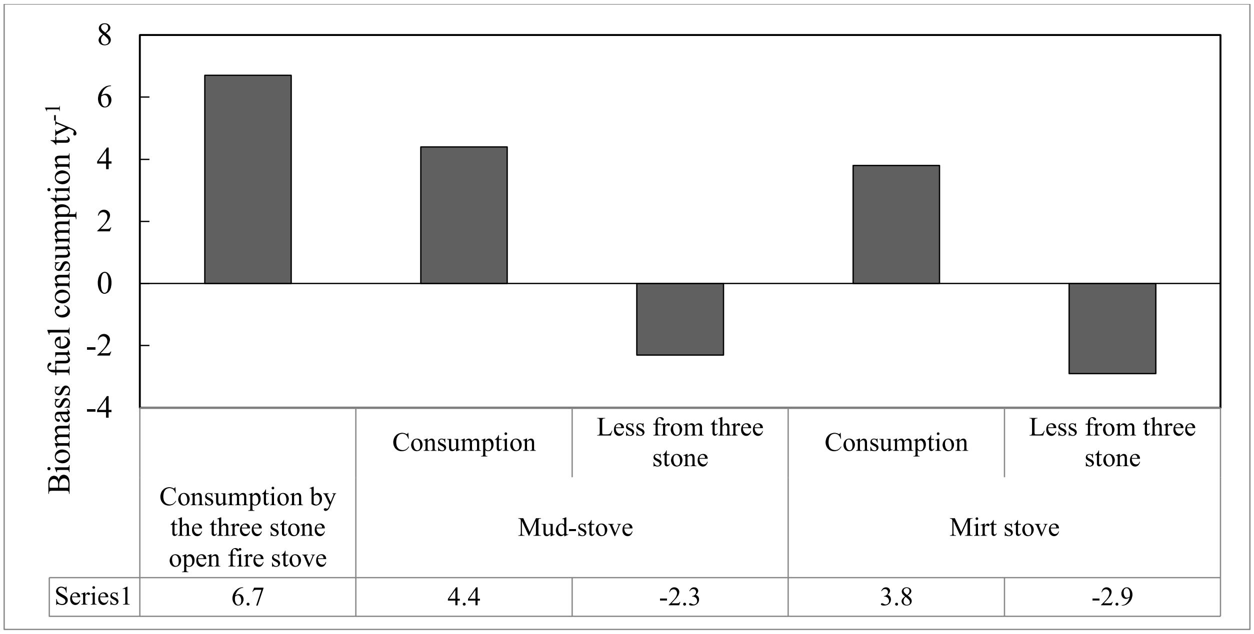
Fig. 2.

Fig. 3.



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Biomass fuel consumption ty^{-1}
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Mud-stove
Consumption
Less from three stone
Mirt stove
Series1
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-2.3
3.8
-2.9

Fig. 4.

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Table 6. Greenhouse gas (GHG) emission mitigation potentials of the different cookstoves

Stove types	GHGs emissions mitigation potential per household (kg CO$_2$e y^{-1})			
	CO$_2$	CH$_4$	N$_2$O	Total
Group 1: Mud stove	4173(±31)	310(±20)	50(±3)	4534(±32)
Group 2: Mirt stove	5880(±40)	430(±32)	71(±7)	6370(±42)
Group 3: Mud and biogas stove	10186(±51)	471(±40)	80(±7)	10726(±51)
Group 4: Mirt and biogas stove	10777(±40)	521(±30)	80(±6)	11434(±43)
P-value	0.000**	0.000**	0.000**	0.000*

Table 7. Improvement in household finances due to substitution of the three stone open fires with improved cookstoves

Stove types	Potential financial saving efficiencies per household in ETB y^{-1}			
	From sale of saved biomass fuel	From reducing expense on inorganic fertilizer	From carbon financing	From replacement of kerosene for lighting
Group 1: Mud stove	6145 (±95)	1488 (±12)	1634 (±24)	-
Group 2: Mirt stove	8630 (±115)	2761 (±15)	2298 (±30)	-
Group 3: Mud stove + biogas stove	9406 (±139)	3308 (±19)	2508 (±35)	643
Group 4: Mirt + biogas stove	10354 (±57)	3450 (±7)	2764 (±168)	643
P-value	0.000**	0.000**	0.000**	

Note:*1USD = 22ETB; dung cakes, crop residues, firewood and charcoal respectively account for 60%, 25%, 13% and 2% of the saved biomass fuel; local market biomass fuel monetary values were 2ETB kg*$^{-1}$*for dung cakes, 2.1ETB kg*$^{-1}$*for crop residues, 1.8 ETB kg*$^{-1}$*for firewood and 10 ETB kg*$^{-1}$*for charcoal.*

Figures

Fig.1. Biomass fuel use and livelihood interaction under current situation and after intervention with improved biomass technologies (Modified from Wachera [32])

Fig.2. Location map of Ude Kebele and East Shoa Zone of Ethiopia

Fig. 3. Baking injera using traditional three stone open fires (a) and (b), a mud stove (c) and a mirt stove (d).

Fig. 4. Comparative biomass fuel consumption rates (t y^{-1}) by the different stove types under Controlled Cooking Test

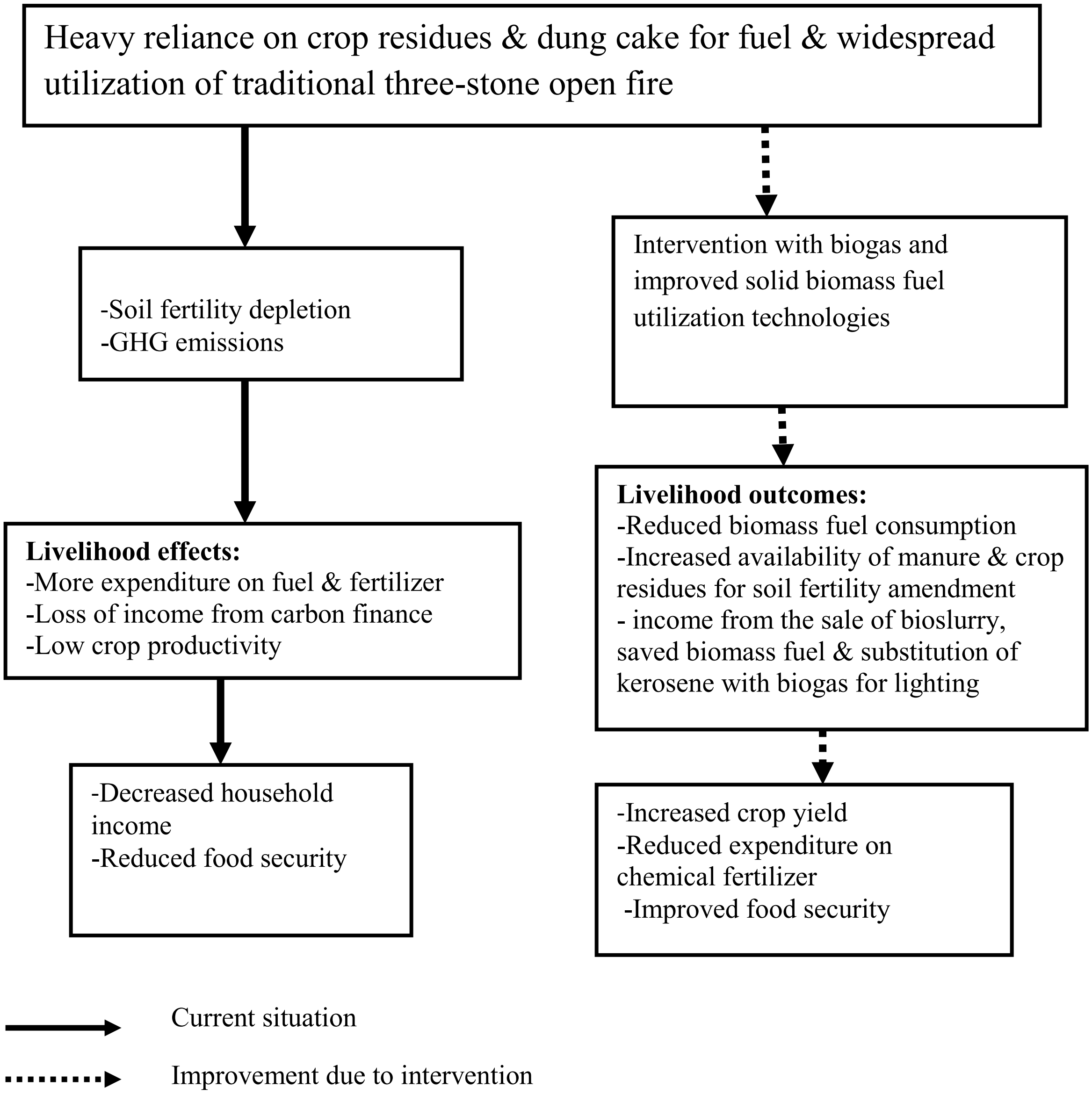
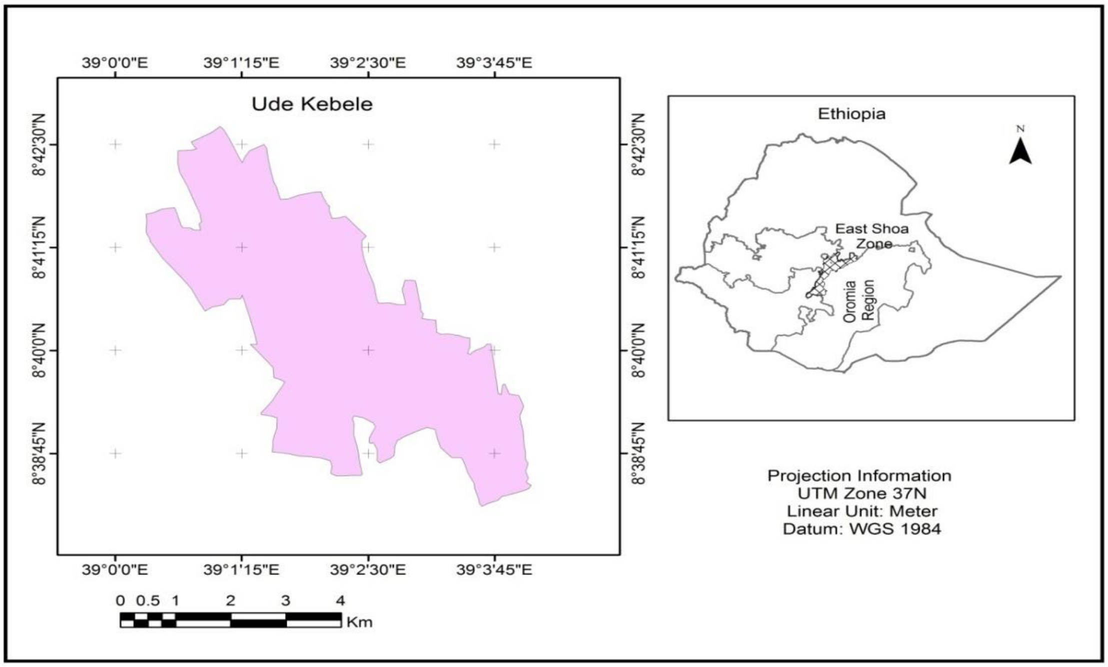

Heavy reliance on crop residues & dung cake for fuel & widespread utilization of traditional three-stone open fire
-Soil fertility depletion
-GHG emissions
Livelihood effects:
-More expenditure on fuel & fertilizer
-Loss of income from carbon finance
-Low crop productivity
-Decreased household income
-Reduced food security
Intervention with biogas and improved solid biomass fuel utilization technologies
Livelihood outcomes:
-Reduced biomass fuel consumption
-Increased availability of manure & crop residues for soil fertility amendment
- income from the sale of bioslurry, saved biomass fuel & substitution of kerosene with biogas for lighting
-Increased crop yield
-Reduced expenditure on chemical fertilizer
-Improved food security
Current situation
Improvement due to intervention

Fig. 1.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Km
Ethiopia
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East Shoa Zone
Oromia Region
Projection Information
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Linear Unit: Meter
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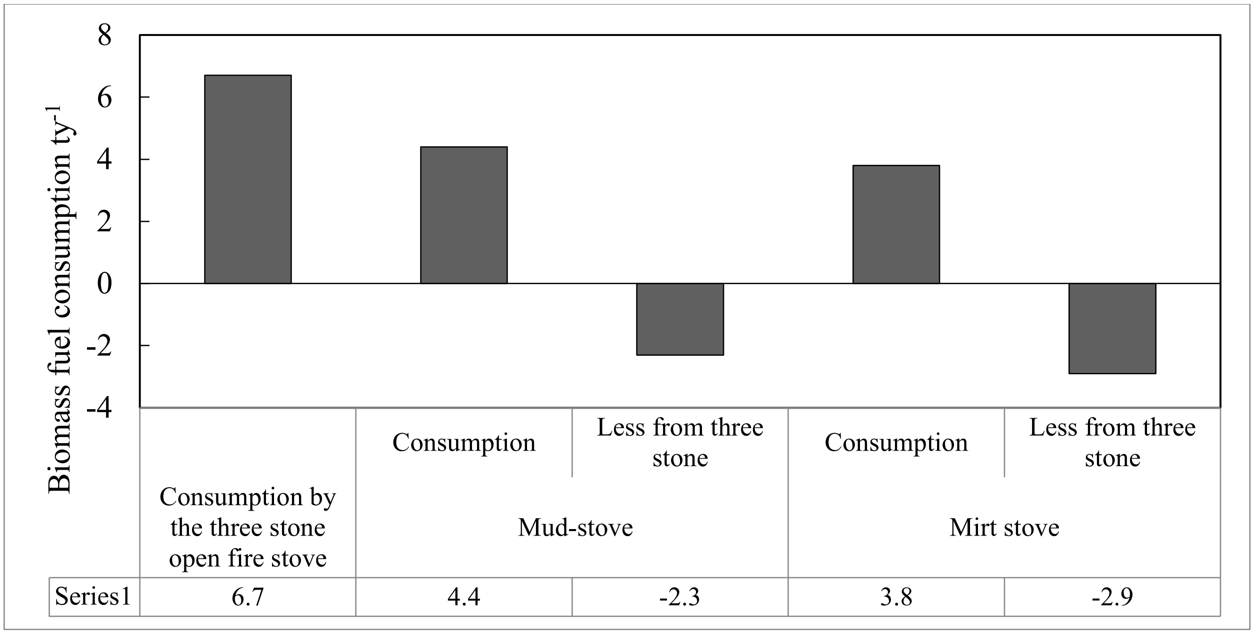
Fig. 2.

Fig. 3.


8
6
4
2
0
-2
-4
Biomass fuel consumption ty^{-1}
Consumption by the three stone open fire stove
Consumption
Less from three stone
Mud-stove
Consumption
Less from three stone
Mirt stove
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6.7
4.4
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3.8
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Fig. 4.

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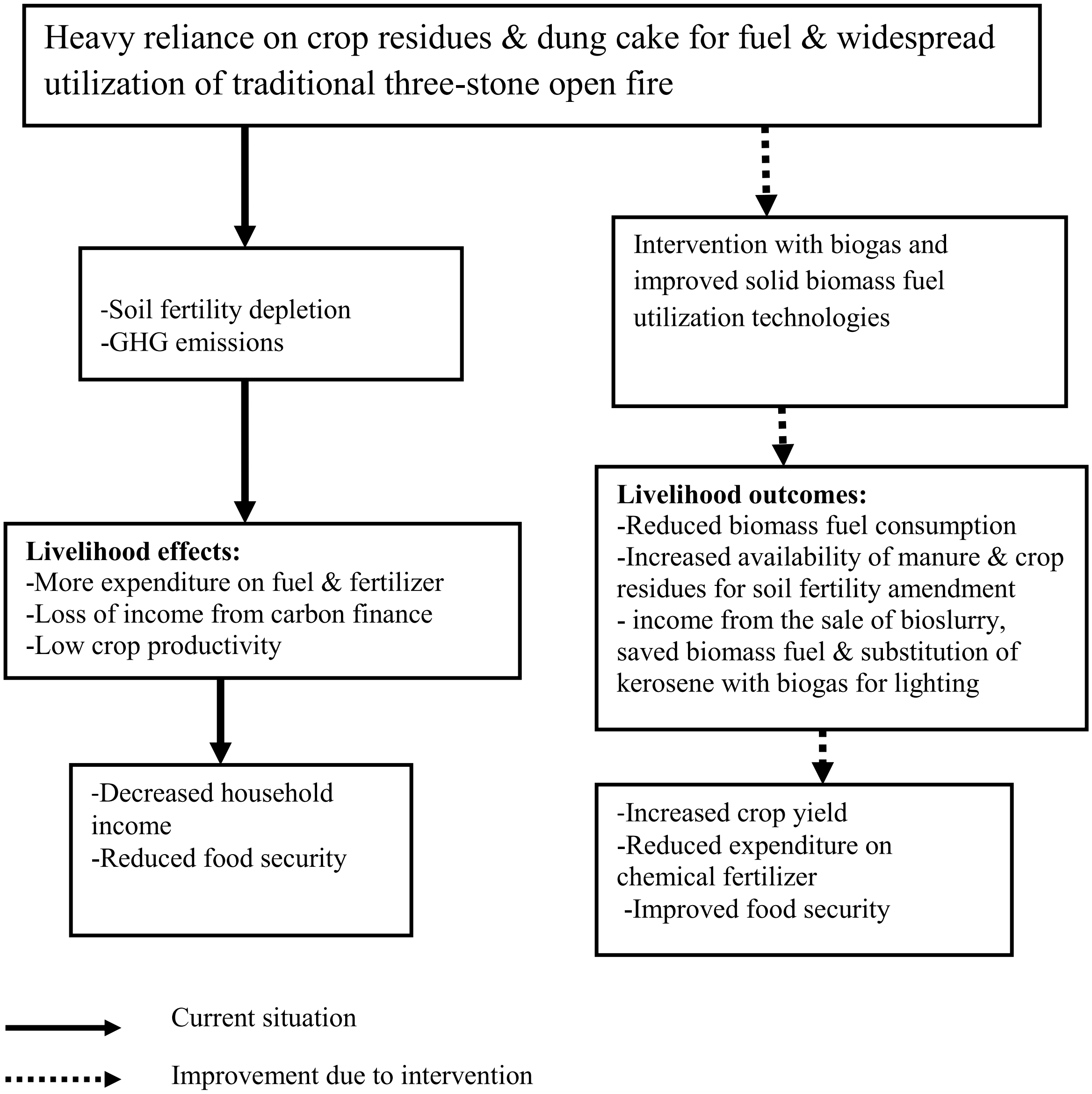
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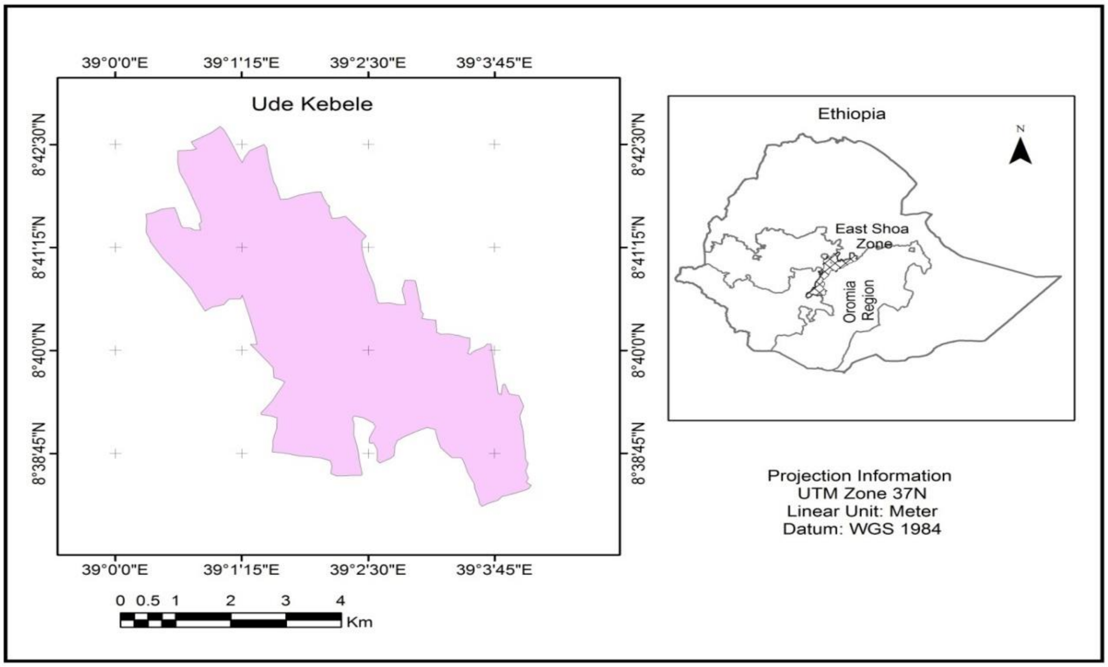

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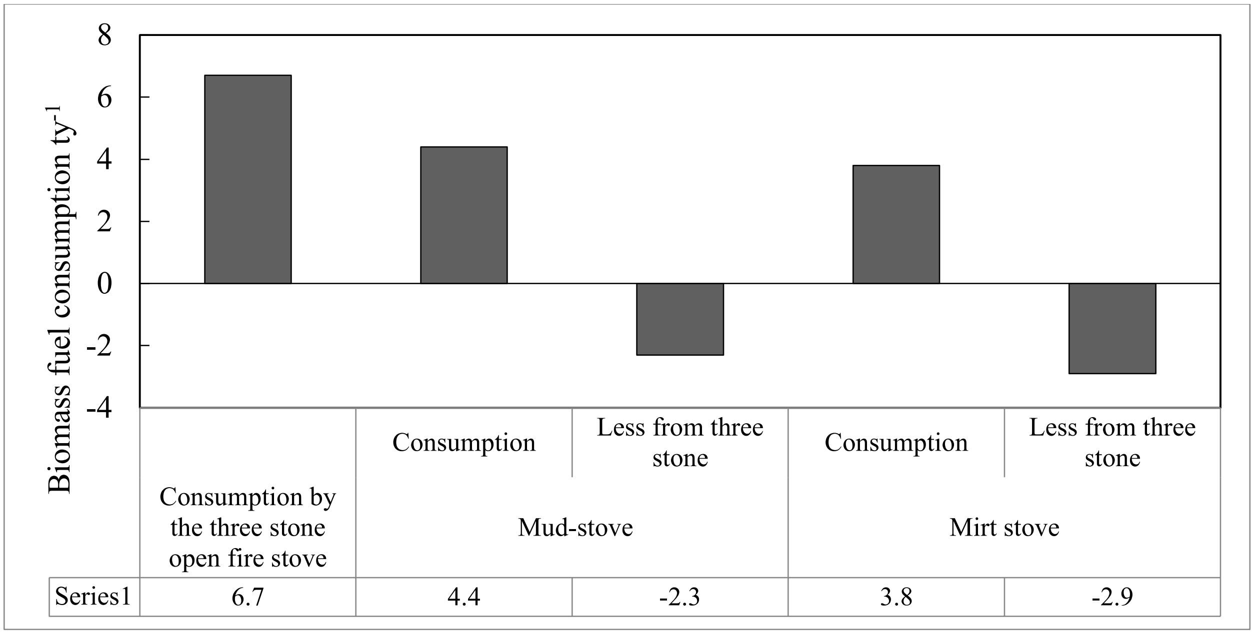
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Fig. 4.