

Biomass and Bioenergy

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

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Abstract:	<p>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 $4534(\pm 32) \text{ kg y}^{-1}$, $6370(\pm 42) \text{ kg y}^{-1}$, $6953(\pm 51) \text{ kg y}^{-1}$, $7661(\pm 43) \text{ kg y}^{-1}$ 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.</p>
Response to Reviewers:	

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4 22 ***Abstract***

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6 23 This study assessed the potential contributions of improved cookstoves in enhancing organic
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10 25 improvement of household finances using the Kitchen Performance Test and Controlled Cooking
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16 28 (lowest) for the mud stove without biogas. The greenhouse gas emission reductions in carbon
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34 37 will do little to increase the fertility of soils. By contrast, including biogas stoves will help to
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38 39 then be applied to the soil.

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40 40 *Keywords:* Biogas; Controlled Cooking Test, Cookstove; Fuel saving efficiency; Greenhouse
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42 41 Gases; Kitchen Performance Test

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4 **44 1. Introduction**

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7 45 Ethiopia is ranked as one of the four countries in the world with the highest per capita biomass
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9 46 fuel consumption, disease burden from indoor air pollution and use of non-renewable biomass
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11 47 fuels [1]. It also has the second highest reliance on traditional fuels of all countries in Africa,
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13 48 only exceeded by Nigeria [2], with ~94% of its total energy demand derived from solid biomass
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15 49 [3].

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20 50 Biomass fuel consumption rates remain very high since most rural households in Ethiopia are
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22 51 still dependent on inefficient three-stone open fire cooking [4]. As reported by Abebe *et al.* [5],
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24 52 three-stone fires account for 92% of all cooking, while the coverage of improved cookstoves is
25
26 53 only 8%. This excessive reliance on biomass fuels, compounded by inefficient combustion
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28 54 technologies, is contributing to increased deforestation, scarcity of fodder and depletion of soil
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30 55 fertility [6, 7]. There is also a high likelihood of future increased demand for biomass fuel and
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32 56 consequent increased rates of deforestation and greenhouse gas (GHG) emissions due to
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34 57 population growth [8]. Under a business-as-usual scenario, biomass fuel demand in Ethiopia is
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36 58 projected to increase by 65% by the year 2030, and this has been linked to deforestation of 9
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38 59 million ha forest land [9].

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45 60 High use of biomass fuels also adds to the burden of women hence exacerbating gender
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47 61 inequality by taking away time that could have been used for productive activities [10]. Indoor
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49 62 air pollution from traditional biomass fuels has a disproportionate impact on women and is listed
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51 63 among the top three causes of death in most countries in Sub-Saharan Africa [11]. The global
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53 64 estimate of deaths due to indoor air pollution was as high as 4.3 million each year [11]. In
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55 65 Ethiopia, ~72,400 people die every year due to indoor air pollution [12].

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4 66 In the Highlands of Ethiopia, rural farm households have been compelled to change their fuel
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6 67 source to agricultural residues due to firewood scarcity [13, 14, 15, 16]. The fuel wood crisis is
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9 68 now widespread in the central and north Highlands of Ethiopia, and many households are
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12 69 struggling to get even enough dung and crop residues to meet their fuel demands [12].
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15 70 Increasing utilization efficiency of the available biomass fuels and converting to modern energy
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17 71 alternatives are potential approaches to mitigate the detrimental environmental and socio-
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20 72 economic impacts of using biomass resources as fuels [10, 13, 17]. In the short term, substituting
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22 73 traditional biomass fuels with clean and modern energy sources, such as electricity, is unrealistic
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25 74 for the extremely scattered rural villages of the Ethiopian Highlands [5, 9, 18]. Instead, the shift
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27 75 to improved cookstoves and small-scale biogas digesters that have the potential to narrow the
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30 76 gap between energy demand and supply through their increased efficiency could be viable
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32 77 alternatives to traditional biomass burning [19].
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35 78 Improved cookstoves used in Ethiopia include locally made “mud stoves”, as well as the more
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38 79 efficient, government designed “lakech” (“excellent”) improved charcoal stove and the
39
40 80 mirt(“best”) improved biomass [20, 21]. Mud stoves are enclosed stoves made of mud mixed
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43 81 with straw or hay by local artisans [22]. Lakech and mirt stoves were developed by a UK-based
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45 82 company, Energy for Sustainable Development, and the Ethiopian Ministry of Water and Energy
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48 83 in the early and mid-90s (Energy for Sustainable Development (ESD, [23]). The lakech stove is
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50 84 made of ceramic and metal [24], while the mirt stove is made of cement [25]. Mirt stoves are
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53 85 specifically designed for baking the staple food, “injera”, a pancake like thin bread made of teff
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55 86 flour which is native to Ethiopia. Baking injera accounts for ~65% of household fuel
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58 87 consumption [20]. Mirt stoves can also be used to cook and boil food while baking without the
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60 88 use of additional fuel [26].
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89 Improved cookstoves can either be used to burn wood or charcoal, or they can be adapted to burn
90 biogas [27]. Biogas is a clean fuel, produced by anaerobic decomposition of organic wastes,
91 leaving a nutrient rich “bioslurry” residue that can be used as an organic fertilizer [13, 28].
92 Application of bioslurry to agricultural fields from biogas digesters could also greatly increase
93 the carbon content of the soil, thereby improving soil fertility and crop productivity as well as
94 further reducing net GHG emissions [28].

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

100 Despite efforts, since the 1970s, to introduce and disseminate improved cookstoves and small-
101 scale biogas digesters in Ethiopia, adoption has been limited [3]. For instance, by 2014, only
102 11% of households in Borena woreda of North Central Highlands of Ethiopia were using
103 improved stoves and, of these, 90% were mud stoves [30].

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

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

112 **2. Materials and Methods**

113 *2.1. Description of the study site*

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

117 **FIGURE 1 HERE**

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

124 *2.2. Types and description of cookstoves used by the households in Kumbursa Village*

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

127 **TABLE 1 HERE**

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4 128 2.3. Selection of stove performance testing methods
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7 129 The three most common methods used to evaluate stove performance are the Water Boiling Test,
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9 130 Controlled Cooking Test and Kitchen Performance Test, also respectively known as efficiency,
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11 131 effectiveness and efficacy tests [36]. Each of these three approaches has its own benefits and
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14 132 limitations.

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18 133 The Water Boiling Test evaluates stove performance by boiling a measured quantity of water in
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20 134 a standard pot; the shorter the time required and the lower the quantity of fuel used for boiling,
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23 135 the more efficient the stove [11]. The Water Boiling Test is able to control for confounding
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25 136 factors and provides a high degree of replication, but it does not reflect actual cooking
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27 137 performance [31] and is therefore mostly suited to lab-based screening of stove efficiency [36].
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30 138 The Controlled Cooking Test involves simulation of the real cooking practice by controlling
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32 139 variables like quantity of food prepared, quantity of fuel used and the behaviors of the cook [11,
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34 140 36]. It is less standardized but more realistic than the Water Boiling Test, but still does not reflect
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37 141 the actual cooking practice in the field. The Kitchen Performance Test involves assessment of
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39 142 fuel consumption by households under a normal cooking practice [37]. It is preferred over both
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41 143 the Water Boiling Test and Controlled Cooking Test for actual in situ stove performance
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43 144 assessment [37] as the results reflect the real cooking situation in a kitchen and so reflect actual
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46 145 cooking practice [36]. Therefore, in this study, the Kitchen Performance Test was used to assess
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49 146 field-based biomass fuel consumption rates of the different stove types in Kumbursa Village.

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53 147 The Kitchen Performance Test was applied in this study using the protocol set out by Bailis *et*
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55 148 *al.*[38]. This was also supported by a Controlled Cooking Test and short-term participant
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57 149 observation survey, following the approach used by Granderson *et al.* [37]. The results obtained
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4 150 using both Controlled Cooking Test and participant observation survey methods were then
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6 151 compared and triangulated with those of the Kitchen Performance Test in order to strengthen the
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9 152 reliability of the findings.

12 153 *2.3.1. The Kitchen Performance Test*

15 154 The Kitchen Performance Test was done with the same households before and after introduction
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18 155 of improved stoves to measure changes in fuel consumption rates with the improved technology.
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20 156 This is because before and after comparisons yield more accurate results than parallel testing of
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23 157 paired households [37]. The Kitchen Performance Test was carried out under natural conditions
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25 158 in a way that reflects the usual cooking activity in households. Cooking food for the family is
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28 159 mainly done by the mother of the children in the household, so this person with main
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30 160 responsibility for cooking was selected to participate in both the Kitchen Performance Test and
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33 161 Controlled Cooking Test.

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36 162 The study included 42 sampled households, selected based on recommendations given by the
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39 163 local development agent and village leader. Willingness to participate in the study was also taken
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41 164 into account in the selection process. The participant households were selected to have similar
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43 165 kitchen dimensions, typically thatched huts with plastered walls having a size of 6m² to 10m².
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46 166 The study was limited to only one season but was supplemented by householder interviews and
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48 167 focus groups discussions to compensate for this limitation.

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51 168 The same types of biomass fuels were supplied to each participant household. The biomass fuel
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54 169 used in this study was composed of the mixture of crop residues, dung cakes and firewood as is
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57 170 normal practice in the study village. The approximate amounts of fuel needed for the Kitchen
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59 171 Performance Test were determined from the mean fuel consumption rate for Kumbursa village

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4 172 [16] and by a preliminary survey. In this village, 80% by weight of the biomass fuels used were
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6 173 dung cakes, while crop residues and firewood respectively constituted 16% and 2% only. Annual
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9 174 mean fuel consumption per household was 4524 kg y⁻¹ for dung cakes, 1885 kg y⁻¹ for crop
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11 175 residues and 980 kg y⁻¹ for firewood. The amounts of fuel delivered to each household was then
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14 176 increased over these mean consumption rates by 50%, resulting in an amount of fuel given to
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16 177 each household per week of ~131 kg dung cakes, ~54 kg crop residues and ~28 kg firewood; a
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19 178 total of 213 kg of biomass fuels. The participants were told to use only the fuel given to them.
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21 179 After every cooking activity, the participants were asked to immediately extinguish the fire and
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24 180 keep the remaining fuel for the cooking session on the following day.

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27 181 Initially, all of the 42 selected participant households were instructed to cook their food using the
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29 182 traditional three-stone open fires for seven days (Figures 3a & b). On the last day of the trial (day
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32 183 seven), the remaining fuel was measured to quantify the amounts of fuel consumption using
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34 184 traditional three-stone open fires by each participant household.

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38 185 Households were then divided into four sub-groups using a random lottery method and new
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40 186 technologies were provided to the groups as follows; 11 members used only mud stoves (Figure
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42 187 3c) (group 1), 11 members used only mirt stoves (Figure 3d) (group 2), 10 members used mud
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45 188 stoves together with biogas stoves (group 3), and another 10 members used mirt stoves together
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47 189 with biogas stoves (group 4). The same quantity and quality of biomass fuels were provided to all
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50 190 of the study households as during the pre-installation testing, and households were advised to use
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52 191 only the measured and stored biomass fuels during the entire seven days of the test. Again, the
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55 192 amount of fuel that remained after cooking for a week was weighed in order to determine fuel
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57 193 consumption for each household.

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194 **FIGURE 2 HERE**

195 *2.3.2. The Controlled Cooking Test*

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

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

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

210 *2.4. Quantification of the nutrient contents of dung cakes, crop residues and bioslurry*

211 The dry weight of bioslurry produced by the biogas users, dung cakes and crop residues were
212 measured over a period of two weeks and converted into an annual average. Dung cakes, crop
213 residues and bioslurry samples were analyzed in the laboratory to determine the percent of
214 nitrogen (N), phosphorus (P), potassium (K) and organic carbon (OC). The amount of nutrients

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4 215 or OC saved by the household, $M_x(\text{kg week}^{-1})$, was then calculated from the weight of the
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6 216 organic waste saved (dung cakes, crop residues or bioslurry), $M_{ow}(\text{kg week}^{-1})$, as:

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$$M_x = M_{ow} \times P_x / 100 \quad (1)$$

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14 218 where P_x is the percentage of x (where x = N, P, K or OC) in the dry organic waste.

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17 219 *2.5. Calculation of greenhouse gas emissions*

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21 220 The three most important GHGs; carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O),
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23 221 which have global warming potentials of 1, 25 and 298 carbon dioxide equivalents (CO₂e),
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25 222 respectively (IPCC, 2007), were considered in this study. The IPCC [39] default thermal values
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27 223 (MJ kg⁻¹ fuel) and emission factors (CO₂e) shown in Table 2 were used to estimate the likely
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29 224 GHG emissions.

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34 225 **TABLE 2 HERE**

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38 226 In order to convert the volume of biogas to the thermal value and weight, a conversion factor of
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40 227 23 MJ m⁻³ and 0.7 kg m⁻³ was used after Mulu *et al.*[6]. The replacement potential of biogas for
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42 228 firewood was determined following the method provided by Pathank *et al.*[40], which assumed
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44 229 that 1m³ of biogas provided equivalent heating energy to 5.5 kg of firewood. The GHG reduction
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46 230 potential of typical household biogas digesters with volumes of 6 – 8m³ was assumed to be 1.9 t
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48 231 CO₂e per digester per year [12].

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52 232 The annual mass of GHG emissions from the combustion of fuel type a, $M_{GHG,a}$ (kg of carbon
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54 233 dioxide equivalents (CO₂e) per household) was calculated as follows:

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$$M_{GHG,a} = E_a \times 10^{-6} \times (EF_{CO_2} + EF_{CH_4} + EF_{N_2O}) \quad (2)$$

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4 235 where E_a is the annual thermal value of combustion fuel in MJ per household, EF_{CO_2} is emission
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6 236 factor for carbon dioxide, EF_{CH_4} is emission factor for methane and EF_{N_2O} is emission factor for
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9 237 nitrous oxide, all in CO₂e mg MJ⁻¹ (Table 2). The annual thermal value of a given fuel of a
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12 238 household (E_a) was computed by multiplying the weight of the fuel by its thermal value (MJ kg⁻
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14 239 ¹) (Table 2).

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17 240 The total annual mass of GHG emissions from all fuels, $M_{GHG,tot}$, in kg of CO₂e per household
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20 241 in the study area was calculated as:

$$23 \quad 242 \quad M_{GHG,tot} = E_{a1} + E_{a2} + E_{a3} + E_{a4} + E_{a5} \quad (3)$$

24
25
26 243 where E_{a1} , E_{a2} , E_{a3} , E_{a4} and E_{a5} are the annual masses of GHG emissions in kg per household
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29 244 from the combustion of wood, dung, crop residue, biogas and kerosene, respectively. Emission
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32 245 reductions were then quantified by subtracting fuel consumed in post-improved cookstove
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34 246 intervention from pre-improved cookstove intervention and then converting into amount of
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36 247 GHGs using their corresponding emission factors for each fuel type.

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40 248 The amount of methane leakage to the atmosphere from biogas production was calculated as:

$$43 \quad 249 \quad M_{GHG,dig} = M_{biogas} \times p_{CH_4} \times GWP_{CH_4} \times p_{leak} \quad (4)$$

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46 250 where $M_{GHG,dig}$ is the average annual emission of methane from the biogas digester in kg of
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49 251 CO₂e; M_{biogas} is the average yearly biogas generation of a digester, also in kg of CO₂e (assumed
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52 252 to be 306 kg after Mulu et al., 2016); p_{CH_4} is the proportion of methane in biogas (assumed to
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54 253 be 0.6 after Mulu et al. [6]; GWP_{CH_4} is the global warming potential of methane (assumed to be
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57 254 25 after IPCC, 2007); p_{leak} is the proportion of methane produced lost through leakage
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59 255 (assumed to be 0.1 after Mulu *et al.* [6]).

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256 *2.6. Replacement cost analysis*

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

263 The carbon financing potential from GHG emission reduction was estimated as 16.4US\$ or
264 360.8 ETB per 1 t CO₂e, based on offset price of the Gold Standard Verified Emission Reduction
265 (VER) of Clean Development Mechanisms [10].

266 *2.7. Statistical analysis*

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

272 **3. Results**

273 *3.1. Biomass fuel saving efficiencies based on results from Kitchen Performance Test*

274 Results from Kitchen Performance Test showed that the mean biomass fuel saving for each
275 household compared to a three stone open fire was 32% (2842(±21) kg y⁻¹) for mud stoves
276 (group 1), 45% (3997(±27) kg y⁻¹) for mirt stoves (group 2), 49% (4352(±33) kg y⁻¹) for the

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277 combined use of mud and biogas stoves (group 3), and 54% (4796 (± 27) kg y⁻¹) for combined
278 use of mirt and biogas stoves (group 4) (Table 3). The biomass fuel saving was statistically
279 significant (Table 3; $p < 0.001$) with the highest fuel saving was for the households using a mirt
280 stove with biogas.

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

287 **TABLE 3 HERE**

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

289 As shown in Table 4, the results from the controlled cooking test are not statistically different
290 within a given technology with ($F = 0.679$; $P = 0.519$) for the three stone open fires, ($F = 0.894$;
291 $P = 0.427$) for mud stoves, and ($F = 2.222$; $P = 0.137$) for the mirt stoves. This implies that the
292 efficiency test results were consistent and valid, and hence were in agreement with the results
293 obtained using Kitchen Performance Test.

294 **TABLE 4 HERE**

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8 298 *3.3. Potential contribution of improved cookstoves to Soil nutrients availability*

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11 299 The lowest nutrient saving was observed for households using mud stove only while the highest
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14 300 was recorded for those households using the mirt stove with biogas; these variations were
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16 301 statistically significant (Table 5; $P < 0.001$).

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22 303 *3.4. Potentials of improved cookstoves in reduction of greenhouse gas emissions*

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25 304 The potential per household GHG emission reductions in CO₂e were 4534 (± 32) kg y⁻¹ for mud
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27 305 stoves, 6370 (± 42) kg y⁻¹ for mirt stoves, 6953 (± 51) kg y⁻¹ for the mud stoves with biogas and
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29 306 7661 (± 43) kg y⁻¹ for mirt stoves with biogas (Table 6).

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33 307 As shown in Table 6, the use of biogas stoves together with improved solid biomass fuel stoves
34
35 308 significantly reduced GHG emissions (Table 6; $P < 0.001$). The studies conducted elsewhere also
36
37 309 reported similar contributions of biogas and improved cookstoves for the reduction of GHG
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39 310 emissions. For instance, biogas digesters prevented 360 m³y⁻¹CO₂ and 600 m³y⁻¹ CH₄ from being
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41 311 emitted to the atmosphere and saved about 0.562 ha of forest land from being deforested on
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43 312 annual basis [19]. Abera [7] also reported a reduction of CO₂ emissions by 2.145 t y⁻¹ per stove
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45 313 as a result of replacing three-stone open fire furnace with a gonzie stove.
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51 314 **TABLE 6 HERE**

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55 315 *3.5. Potential contributions of improved cookstoves in saving household finances*

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57 316 The replacement of three-stone open fire with improved cookstoves resulted in significant
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59 317 financial savings (Table 7). The combined financial savings per farm household from reducing
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318 expenditure on commercial fertilizer and from carbon financing for the mud stoves and mirt
319 stoves without biogas were 3122(±36) ETB y⁻¹ (142(±1.6) US\$ y⁻¹) and 5059 (±45) ETB y⁻¹ (230
320 (±2) US\$ y⁻¹) respectively, while biogas increased this to 7007(±36) ETB y⁻¹ (318 (±1.6) US\$ y⁻¹)
321 and 8051 (±45) ETB y⁻¹ (366(±2) US\$ y⁻¹). This includes replacement of kerosene by biogas
322 for lighting, which provided a financial saving of 643 ETB y⁻¹(29 US\$ y⁻¹).

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

328 [TABLE 7 HERE](#)

329 **4. Discussions**

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

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

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

354 If the full potential of biogas was exploited and used together with mud or mirt stoves, there
355 would be biomass fuel savings of 4352(±33) kg y⁻¹ per household and 4796(±27) kg y⁻¹ per
356 household respectively (Table 3) while the respective possible biomass fuel savings across all
357 potential users in Kumbursa would be 752.9(±5.7) t y⁻¹ and 829.7(±4.6) t y⁻¹.The exhaustive
358 exploitation of the available biogas potential together with use of mud stoves for the entire 258
359 households of Kumbursa Village could result in potential saving per household of 25.2(±0.13) t
360 y⁻¹ N, 7.5(±0.03) t y⁻¹P, 25.9(±0.16) t y⁻¹K and 573.3(±3.50) t y⁻¹ OC; if biogas was used together
361 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,

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362 28.1(\pm 0.13) t y⁻¹K and 620.7(\pm 2.84) t y⁻¹ OC. The substitution of three-stone open fires with
363 improved cookstoves could also significantly contribute to the mitigation of GHG emissions.
364 Thus, rural farm households can benefit from carbon financing and this could be used to
365 motivate them to switch from the traditional three stone open fires to more fuel-efficient biomass
366 stoves at a larger scale.

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

378 However, the use of organic fertilizer in the predominantly cereal cropping areas of the Central
379 Highland of Ethiopia, including Kumbursa Village, is very rare. The field survey revealed that
380 farm households prefer to sell the surplus cattle dung as dung cakes instead of applying it to
381 farmland since dung cake demand as fuels is very high near to urban markets. This study
382 demonstrates that the financial savings from the sale of surplus biomass fuel was higher than the
383 potential total financial savings from substituting commercial fertilizer, generation of carbon
384 finance and replacement of kerosene for lighting. This explains why households usually prefer to

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385 sell surplus biomass fuels instead of using them as organic fertilizers. This finding suggests that
386 while wide scale adoption of fuel-efficient solid biomass stoves can contribute to the financial
387 security of households, and may help to reduce deforestation, it will do little to increase the
388 fertility of soils. By contrast, including biogas stoves will help to improve soil fertility by
389 retaining at least some of the carbon and nutrients in bioslurry that will be applied to the soil.

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

397 **5. Conclusions**

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

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413 digesters for use in rural households in Sub-Saharan Africa. The assistance from Green Heat-
414 Uganda in installing biogas digesters in Kumbursa Village is appreciated. Finally, we are
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417 References

418 [1] R. Bailis, A. Drigo, O. Ghilardi, Masera, The carbon footprint of traditional wood fuels,
419 Nature Climate Change; 5(2015)266-272.

420 [2] D. J. Idiata, M. Ebiogbe, H. Oriakhi, H. Iyalekhue, Wood fuel usage and the challenges on
421 the environment. International Journals of Engineering Sciences, 2(4) (2013)110-114.

422 [3] S. H. Kooser, Clean cooking: The value of clean cookstoves in Ethiopia. Journal of
423 Environment and Resource Economics at Colby, Vol 01, Iss. 01, Article 03(2014).
424 Available at <http://digitalcommons.colby.edu/jerec/vol01/iss10/3>.

425 [4] GIZ, Energizing development (EnDev) Ethiopia: Improved cookstoves (ICS). Bonn and
426 Escoborn (2014). Available at: <http://endev.info/ethiopia>.

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[5] B. Abebe, R. Bluffstone, G.Zenebe, P. Martinsson, M. Alemu, F. Vieider, Do improved biomass cookstoves reduce fuel consumptions and carbon emissions? Evidence from rural Ethiopia using a randomized treatment trial with electronic monitoring. Policy Research Working Paper 7324(2015).

[6] M.G. Mulu, S. Belay, E. Getachew, W.S. Tilahun, The environmental benefits of domestic biogas technology in rural Ethiopia. *Biomass Bioenergy*, 90 (2016), 131-138.

[7] A.B. Abera, The implication of wood-burning stove efficiency for environment, health and CO₂ emissions in the Jogo Gudedo Watershed, Ethiopia. *Academic Research Journal of Agricultural Science and Research*, 4(4) (2016)154-163.

[8] T. Lemlem, Biogas technology adoption in rural Ethiopia: Its effect on the crisis of deforestation. *Journal of Energy Technologies and Policy*, 6/1(2016).

[9] FDRE [Federal Democratic Republic of Ethiopia], *Ethiopia's Climate Resilient Green Economy (CRGE)*, Addis Ababa, Ethiopia (2011).

[10] SEI [Stockholm Environment Institute], *Assessing the climate impacts of cookstove projects: Issues in Emissions Accounting*. SEI Working Paper Series No. 201301, Sweden, Stockholm (2013).

[11] F. Lambe, M. Jürisoo, H. Wanjiru, J.Senyagwa, *Bringing clean, safe, affordable cooking energy to households across Africa: an agenda for action*, Prepared by the Stockholm Environment Institute, Stockholm and Nairobi, for the New Climate (2015).

[11] Mercy Corps, *Basic guide to fuel efficient stoves and emission testing*. Portland OR 97204, USA; Edinburgh, EH9 1NJ, UK (2010).

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448 [12] M.G. Mulu, Biogas technology adoption and its contribution to rural livelihood and
449 environment in Northern Ethiopia, the case of Ofla and Mecha Woredas. Thesis
450 submitted to Center for Environment and Development, presented in fulfillment of the
451 requirements for the Degree of Doctor of Philosophy in Development Studies (Center
452 for Environment and Development), Addis Ababa University, Addis Ababa, Ethiopia
453 (2016).

454 [13] S. G. Gwavuya, S. Abele, I. Barfuss, M. Zeller, J. Muller, Household energy economics in
455 rural Ethiopia: A cost-benefit analysis of biogas energy, *Renew Energy*, 48 (2012)202-
456 209.

457 [14] N. Abebe, T.W. Kuyper, A. de Neergaard, Agricultural waste utilization strategies and
458 demand for urban waste compost: Evidence from smallholder farmers in Ethiopia.
459 *Waste Management*, 4, (2015) 82-93.

460 [15] M. Dawit, B. Elizabeth, A. Tekie, C. Ringler, Food versus Fuel: Examining tradeoffs in the
461 allocation of biomass energy sources to domestic production uses in Ethiopia. Paper
462 presented at Agricultural and Applied Economics Association and Western Agricultural
463 Economics Association Annual Meeting, Sanfrancisco, CA, July 26-28(2015).

464 [16] N. Dugassa, A. Assefa, J.U. Smith, A. Hailu, G. Bogale, Household energy and recycling of
465 nutrients and carbon to the soil in integrated crop-livestock farming systems; a case
466 study in Kumbursa village, Central Highlands of Ethiopia. *GCB Bioenergy*, 9 (2017)
467 1588-1601, doi:10.1111/gcbb.12459.

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468 [17] B. Kassahun, H. Hager, K. Mekonnen, Woody and non-woody biomass utilization for fuel
469 and implications on plant nutrients availability in Mukehantuta Watershed in Ethiopia.
470 *African Crop Science Journal*, 21, (2013) 625-636.

471 [18] L. Hilawe, T. Getenet, Y. Asrat , Low carbon Africa: Leap-frogging to a green future.
472 Ethio-Resource Group and Christian Aid Ethiopia (2011). Available at
473 christianaid.org.uk/low-carbon-africa.

474 [19] Y. Seid, Y. Bezabih, O. Sahu, Biogas production using geomembrane plastic digesters as
475 alternative rural energy source and soil fertility management, *sustainable energy* 2(1)
476 (2014)12-19.

477 [20] A. B. Yosef, Assessing environmental benefits of mirt stove with particular reference to
478 indoor air pollution (carbon monoxide and suspended particulate matter) and energy
479 conservation. Thesis submitted to the School of Graduate Studies of Addis Ababa
480 University in partial fulfillment of the requirements of Master of Science in
481 Environmental Science, Addis Ababa, Ethiopia (2007).

482 [21] G. Zenebe, B. Abebe, R. Bluffstone, P. Martinsson, M. Alemu, M. Toman, Fuel saving,
483 cooking time and user satisfaction with improved biomass cookstoves: Evidence from
484 Controlled Cooking Tests in Ethiopia. *Resource and Energy Economics* 52 (2018),
485 [10.1016/j.reseneeco.2018.01.006](https://doi.org/10.1016/j.reseneeco.2018.01.006).

486 [22] Accenture, Enhancing market for delivery of improved cookstove development and
487 promotion support in Ethiopia: Market analysis, recommendations and program plan
488 final. Accenture Development Partnerships, UK (2015).

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[23] ESD (Energy for Sustainable Development), Mirte, Ethiopia (2017). Available online at:
<http://stoves.bioenergylists.org/stovesdoc/Bess/Mirte.htm>.

[24] Hedon Lakech stove (2017). Available online at:
<http://support.hedon.info/View+Stove&itemId=11487>.

[25] Energypedia, List of Stoves in Ethiopia (2017). Available online at:
https://energypedia.info/wiki/List_of_Stoves_in_Ethiopia.

[26] Kindu Trust, Mirt stove distribution project (2017). Available online at:
<https://kindustrust.org/projects/mirt-stove-distribution-project/>.

[27] V. Tumwesige, D. Fulford, G.C. Davidson, Biogas appliances in Sub-Sahara Africa. Biomass and Bioenergy, 70 (2014) 40-50.

[28] J. Smith, A. Abegaz, R. Matthews, M. Subedi, B. Orskov, V. Tumwesige, P. Smith, What is the potential for biogas digesters to improve soil fertility and crop production in Sub-Saharan Africa? Biomass and Bioenergy, 70 (2014) 73–86.

[29] G. Zenebe, M. Alemu, T. Adane, S. Assefa, Carbon markets and mitigation strategies for Africa/Ethiopia: Literature review and the way forward. EDRI report 14. Addis Ababa: Ethiopian Development Research Institute(2012).

[30] A. Amogne, Factors affecting the adoption of fuel efficient stoves among rural households in Borena woreda: North central Ethiopia. International Journal of Energy Science (IJES), 4 (5)(2014) 141-154.

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508 [31] E. Adkins, E. Tyler, J. Wang, D. Siriri, V. Modi, Field testing and survey evaluation of
509 household biomass cookstoves in rural Sub-Saharan Africa. *Energy for Sustainable*
510 *Development*, 14/ 2010 172-185.

511 [32] V. Arthurson, Closing the global energy and nutrient cycles through application of biogas
512 residue to agricultural land – potential benefits and drawbacks, *energies*, 2, (2009), 226
513 – 242.

514 [33] L. T. C. Bonten, K.B. Zwart, R.P.J.J. Rietra, R. Postma, M.J.G. Haas de, Bio-slurry as
515 fertilizer; Is bio-slurry from household digesters a better fertilizer than manure? A
516 literature review. Wageningen, Alterra Wageningen UR (University & Research
517 Centre), Alterra report 2519(2014).

518 [34] R.W. Wachera, Assessing the challenges of adopting biogas technology in energy provision
519 among dairy farmers in Nyeri County, Kenya. MSC Thesis, School of Environmental
520 Studies of Kenyatta University (2014).

521 [35] I. Campbell, Environmental assessment and screening report on the project: Improving
522 productivity and market success (IPMS) of Ethiopian farmers; pilot learning woreda:
523 Ada'a, IPMS Environmental Screening Report (2005).

524 [36] R. Bailis, V. Berrueta, C. Chengappa, K. Dutta, B. Edwards *et al.*, Performance testing for
525 monitoring improved biomass stove interventions: Experiences of the household
526 energy and health project. *Energy for Sustainable Development*, Vol. XI, No 2 (2007).

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[37] J. Granderson, S. J. Sandhu, D. Vasquez, E. Ramirez, K.R. Smith, Fuel use and design analysis of improved wood burning stoves in the Guatemalan Highlands. *Biomass Bioenergy*, 33, (2008), 306-315.

[38] R. Bailis, K.R. Smith, R. Edwards, The kitchen performance test, version 1.5, household Energy and health program. Shell Foundation(2004).

[39] IPCC [Intergovernmental Panel on Climate Change],Climate change: the physical science basis, in: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge and New York (2007).

[40] H. Pathank, N. Jain, A. Bhatia, S. Mohanty, N. Gupta, Global warming mitigation potential of biogas plants in India. *Environmental Monitoring and Assessment*, 157/ 1-4:(2009) 407-418.

[41] E. Dresen, B. DeVries, M. Herold, L. Verchot, R. Müller, Fuelwood Savings and carbon emission reductions by the use of improved cooking stoves in an Afromontane Forest, Ethiopia. *Land*, 3, (2014) 1137-1157.

[42] Y. A. Zerihun, The benefits of the use of biogas energy in rural areas in Ethiopia: A case study from Amhara National Regional State, Fogera District. *African Journal of Environmental Science and Technology*, 9, 4(2015), 332-345.

[43] A. Dagninet, A. Endeblhatu, M. Awole, Enhancing biomass energy efficiency in rural households of Ethiopia. *Journal of Energy and Natural Resources*, 4 (2015) (27-33).

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548 Tables

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

551 Table 2. Thermal values (MJ kg⁻¹) of fuels (biomass, biogas & kerosene) and greenhouse gas
552 emission factors in carbon dioxide equivalents (mgMJ⁻¹); EF_{CO_2} is the emission factor for carbon
553 dioxide, EF_{CH_4} for methane and EF_{N_2O} for nitrous oxide [39]

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

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

557 Table 5. Nutrient saving potentials of different cookstoves

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

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

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4 568 Table 1. Types and description of cookstoves selected for fuel performance assessment at
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6 569 Kumbursa Village
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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 <i>mitad</i> (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 <i>wot</i> (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.

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571
572
573 Table 2. Thermal values (MJ kg⁻¹) of fuels (biomass, biogas & kerosene) and greenhouse gas
574 emission factors in carbon dioxide equivalents (mgMJ⁻¹); *EF_{CO2}* is the emission factor for carbon
575 dioxide, *EF_{CH4}* for methane and *EF_{N2O}* for nitrous oxide [39]

Fuel type	Thermal values (MJ kg ⁻¹)	<i>EF_{CO2}</i>	<i>EF_{CH4}</i>	<i>EF_{N2O}</i>
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

576
577 Table 3. Biomass fuel saving efficiencies of mud stoves and mirt stoves with and without biogas
578 stoves as compared to three-stone open fire stoves

Stove types	Mean biomass fuel saving per household		Standard deviation	<i>t</i> -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

579 *Note: average biomass fuel consumption for three stone open fires = 8891 kg y⁻¹ per household*

580 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				

581

582 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**

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584 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*

585
586 Table 7. Improvement in household finances due to substitution of the three stone open fires with
587 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**	

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

592 Figures

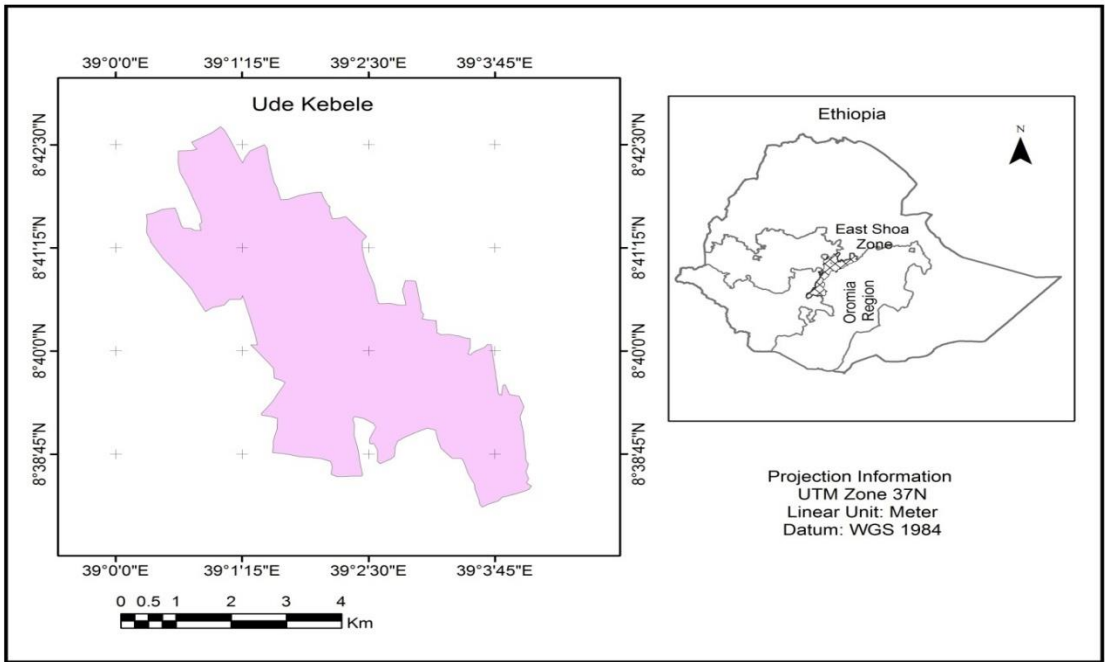
593 Fig. 1. Location map of Ude Kebele and East Shoa Zone of Ethiopia

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

596 Fig. 3. Comparative biomass fuel consumption rates (t y⁻¹) by the different stove types under

597 Controlled Cooking Test

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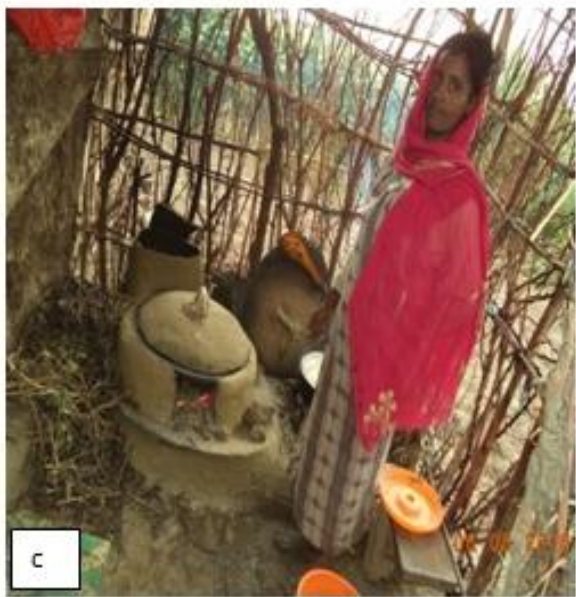
599 Fig. 1.

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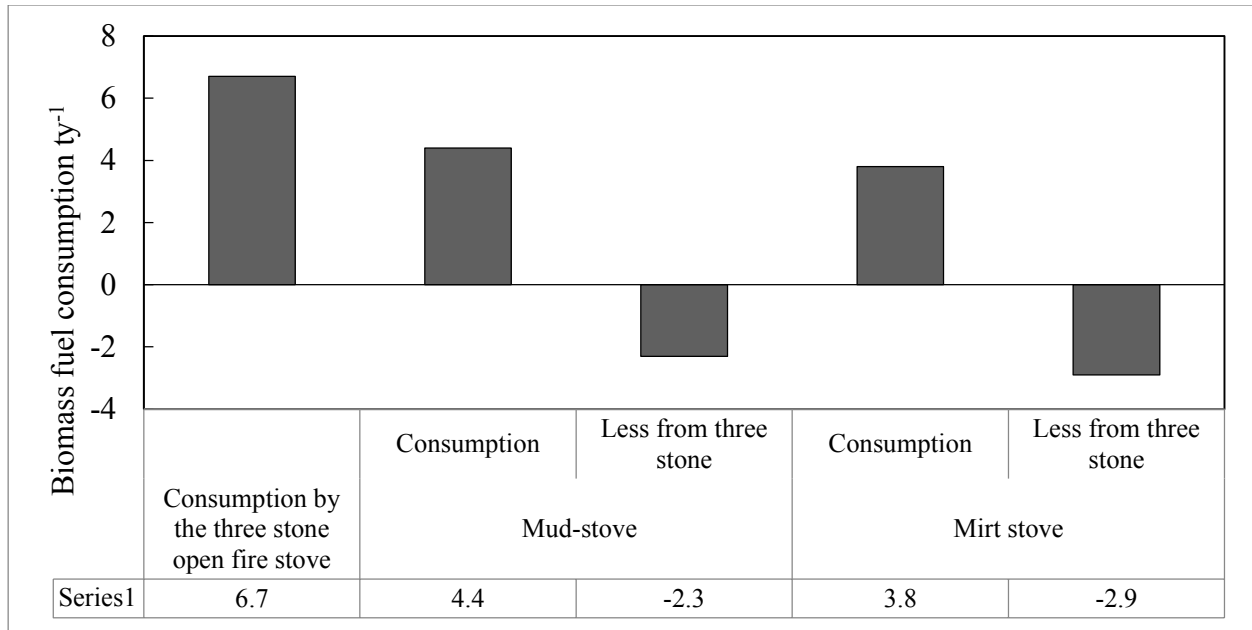
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604 Fig. 2.

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606 Fig. 3.

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4 1 Environmental and financial benefits of improved cookstove technologies in the
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4 22 **Abstract**

5
6 23 This study assessed the potential contributions of improved cookstoves in increasing organic
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8 24 fertilizer availability for application to farmland, greenhouse gas emission mitigation and
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10 25 improvement of household finances using the Kitchen Performance Test, Controlled Cooking
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12 26 Test, household survey and focus group discussions. Substitution of a three-stone open fire with
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14 27 improved cookstoves significantly ($p < 0.01$) improved fuel use efficiency by 54% (highest) for
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16 28 the mirt stove with an additional biogas stove and 32% (lowest) for the mud stove without an
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18 29 additional biogas stove. The greenhouse gas emission reductions in carbon dioxide equivalents
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20 30 were 4534 (± 32) kg y^{-1} , 6370 (± 42) kg y^{-1} , 6953 (± 51) kg y^{-1} , 7661 (± 43) kg y^{-1} for the mud
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22 31 stove, mirt stove, mud stove with an additional biogas stove and mirt stove with an additional
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24 32 biogas stove respectively. The average financial savings from the sale of surplus biomass fuel for
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26 33 the improved cookstoves were higher than the summed financial savings from substitution of
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28 34 commercial fertilizer, generation of carbon finance and replacement of kerosene for lighting.
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30 35 This explains why households usually prefer to sell surplus biomass fuels instead of using them
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32 36 as organic fertilizers. This finding suggests that wide scale adoption of fuel-efficient solid
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34 37 biomass stoves can contribute to the financial security of households, and may help to reduce
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36 38 green gas emissions, but will do little to increase the fertility of soils. By contrast, including
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38 39 biogas stoves will help to improve soil fertility by retaining at least some of the carbon and
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40 40 nutrients in bioslurry that will then be applied to the soil.

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

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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

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4 66 disproportionate impact on women and is listed among the top three causes of death in most
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6 67 countries in Sub-Saharan Africa [12]. The global estimates of deaths due to indoor air pollution
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9 68 was as high as 4.3 million each year [12]. In Ethiopia, ~72,400 people die every year due to
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11 indoor air pollution from biomass fuel and kerosene [13].
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15 70 In the Highlands of Ethiopia, rural farm households have been compelled to change their fuel
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17 71 source to agricultural residues due to firewood scarcity [14, 15, 16, 17]. The fuelwood crisis is
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19 72 now widespread in the central and north Highlands of Ethiopia, and many households are
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21 73 struggling to get even enough dung and crop residues to meet their fuel demands [13].
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25 74 Increasing utilization efficiency of the available biomass fuels and converting to modern energy
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27 75 alternatives are potential approaches to mitigate the detrimental environmental and socio-
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29 76 economic impacts of using biomass resources as fuels [10, 14, 18]. In the short term, substituting
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31 77 traditional biomass fuels with clean and modern energy sources, such as electricity both for
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33 78 lighting and cooking, is unrealistic for the extremely scattered rural villages of the Ethiopian
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35 79 Highlands [5, 9, 19]. This implies that biomass fuel for cooking and kerosene for lighting
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39 80 continue will continue to dominate the energy source. Thus, the shift to improved cookstoves and
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42 81 small-scale biogas digesters that have the potential to narrow the gap between energy demand
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45 82 and supply through their increased efficiency could be viable alternatives to traditional biomass
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47 83 burning [20].
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51 84 Improved cookstoves used in Ethiopia include locally made mud stoves as well as the more
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53 85 efficient, government designed *lakech* (excellent) improved charcoal stove and the *mirt* (best)
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55 86 improved biomass stove [21, 22]. Mud stoves are enclosed stoves made of mud mixed with straw
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58 87 or hay by local artisans [23]. *Lakech* and *mirt* stoves were developed by a UK-based company,
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88 Energy for Sustainable Development, and the Ethiopian Ministry of Water and Energy in the
89 early and mid-90s (Energy for Sustainable Development (ESD, [24]). The *lakech* stove is made
90 of ceramic and metal [25], while the *mirt* stove is made of cement [26]. *Mirt* stoves are
91 specifically designed for baking the staple food, *injera*, a pancake like thin bread made of *teff*
92 flour which is native to Ethiopia. Baking *injera* accounts for ~65% of household fuel
93 consumption [21]. *Mirt* stoves can also be used to cook and boil food while baking without the
94 use of additional fuel [27].

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

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

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

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4 110 11% of households in Borena woreda of North Central Ethiopia were using improved stoves and,
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6 111 of these, 90% were mud stoves [32].
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10 112 Field-based empirical evidence on potential environmental implications of improved cookstoves
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12 113 and biogas digesters are generally sparse and field-based evaluation of end-use biomass fuel
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14 114 efficiency is lacking. Mercy Corps [13], for instance focused only on firewood and charcoal as
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16 115 sources of fuel the study being limited to assessing the burning efficiencies of improved biomass
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18 116 cookstoves. Zenebe *et al.* [23, 33] on the other hand, investigated the fuel saving efficiencies as
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20 117 well cooking time and user satisfaction impacts of improved solid biomass cookstoves. Smith *et*
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22 118 *al.* [30] evaluated the potential of biogas digesters to improve soil fertility and crop production
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24 119 but did not conduct field based field based practical experiment. Amogne (32) studied factors
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26 120 affecting the adoption of efficient biomass cookstoves. Thus, the studies undertaken so far have
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28 121 tried to assess only limited aspects of improved cookstoves such as the contributions for fuel
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30 122 saving, factors affecting uptake and user satisfaction by primarily focusing on utilization of
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32 123 firewood and/or charcoal for fuel. This study, however, has tried to assess the impacts of
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34 124 improved cookstoves more holistically by considering the multiple potential benefits that can be
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36 125 gained from using improved cookstoves such as greenhouse gas emission reduction and carbon
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38 126 financing, enhancing the availability of agricultural wastes for soil fertility improvement and
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40 127 reduction of expenditure on chemical fertilizers. Unlike the other cookstove tests which have
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42 128 used firewood as source of fuel [23, 29, 32], this study has undertaken the stove efficiency test
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44 129 considering the mixture of local energy sources reflecting the real condition of the study area
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46 130 namely, dung cakes, crop residues and firewood which respectively account for 61.2%, 25.5%
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48 131 and 13.3 of fuel source by weight. Moreover, none of the above previous studies have conducted
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50 132 multiple stove efficiency test and associated environmental and financial benefits including the
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4 133 impact of biogas in improving household finance by substituting kerosene for lighting.

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6 134 Therefore, the aim of this work was to assess the potential impact of mud and *mirt* stoves, with-
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9 135 and-without an additional biogas stove stoves, on the biomass fuel saving of farm households,
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11 136 and to determine the implications for availability of agricultural residues for soil improvement,
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13 137 mitigation of GHGs emission and household finances. This was done for the case study of
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15 138 Kumbursa Village in the Central Highlands of Ethiopia using the Kitchen Performance Test, the
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18 139 Controlled Cooking Test and household survey.
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22 140 As depicted in Figure 1, substitution of the traditional three stone fires with improved cookstoves
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24 141 and small scale biogas digesters has the potential to increase biomass fuel use efficiency hence
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26 142 reduces fuel consumption rates. The installation of biogas digester can improve household
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28 143 finance by replacing kerosene for lighting. The reduction in biomass fuel consumption implies
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30 144 creating opportunities for increased availability of crop residues and cattle dung for application
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32 145 to farmland while also contributing to the mitigation of GHGs emissions to the atmosphere.
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34 146 Figure 1 also depicts that in order to use livestock manures and crop residues for soil fertility
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36 147 amelioration, the traditional and less efficient biomass burning should be substituted with a
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38 148 sustainable and efficient means of household energy provision should such as small scale biogas
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40 149 digesters and improved solid biomass cook stoves.
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47 **FIGURE 1 HERE**
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50 51 151 **2. Materials and Methods**

52 53 54 152 *2.1. Description of the study site*

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57 153 Ude *kebele* of Ada'a District, in which Kumbursa Village is situated, is located in East Shoa
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59 154 Zone of Oromia National Regional State of Ethiopia (Figure 2). The Village is found in the
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4 155 Central Highlands of Ethiopia very close to the western escarpment of the Great East African
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6 156 Rift Valley.

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9 157 Kumbursa Village is located at about 55 km in the southeast direction from Addis Ababa with
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11 158 astronomical location of $8^{\circ} 10' 45''$ N and $39^{\circ} 44' 12''$ E.

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14 159 The altitude of Kumbursa Village is ranging between 1878m and 1892m above sea level with
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16 160 flat to slightly undulating topography covering the total area of nearly 1000 ha. Fuel sources are
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18 161 mainly from household owned woodlot plantation, dung and crop residues from household
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20 162 owned livestock and fields. Kumbursa village is not only the source of agricultural produce, it
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22 163 also provides biomass energy for the nearby urban centers.

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25 164 There is no communal land for livestock grazing or firewood collection in Kumbursa village.
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27 165 Therefore, farm households of the village almost entirely depend on resources collected from
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29 166 their farmlands and homesteads for food, feed, fuel and cash.

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32 167 Ada'a district of which Kumbursa Village is a part is largely characterized by a cycle of energy-
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34 168 driven deforestation and soil fertility loss, with cattle dung and crop residues constituting 61%
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36 169 and 18% of the total household energy demand, respectively [35].

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41 170 The farming systems in Kumbursa are denoted by close interdependence and integration of crop
42
43 171 cultivation and animal husbandry, where the production and productivity of one is inextricably
44
45 172 related to the other. There is no communal land for livestock grazing or firewood collection in
46
47 173 Kumbursa Village.

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49
50 174 Kumbursa Villages is characterized by very high human and livestock population. There are 258
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52 175 households with average livestock size of 3.1 TLU and landholding size of 1.9 ha per household
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54 176 [18]. The fact that many urban centers including Addis Ababa are found in close proximity to
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56 177 Kumbursa Village has resulted in extremely high human and animal population pressure on the
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4 178 land. The crop production systems in Kumbursa village are dominated by cereal production with
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6 179 the use of legumes for rotation.

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13 181 As elsewhere in Ada'a district, in Kumbursa village, dung cakes and crop residues are the
14
15 182 dominant fuels and cooking is usually done using a traditional three-stone open fire while the
16
17 183 dominant source of energy for lighting the household is kerosene [18]. All of the households in
18
19 184 Kumbursa use separate kitchens in thatched huts with poor ventilation for cooking. Cooking
20
21 185 hearths are located in a corner of the kitchen and they are mostly constructed on a raised level of
22
23 186 approximately 1m height, locally referred to as a *madab*. The walls of the kitchens are plastered
24
25 187 with mud and the air quality during cooking is poor as the kitchens lack chimneys and windows.

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31 188 Kumbursa village was purposively selected for this study because it represents a typical rural
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33 189 village in the Central Highlands of Ethiopia that entirely depend on biomass fuel for cooking
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35 190 purpose. Unlike many rural villages in Ethiopian Highlands that at least partly depend on
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37 191 firewood collected from community forest for firewood, there is neither community forest for
38
39 192 firewood collection nor communal grazing land for the livestock. So Kumbursa Village
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41 193 represents the situation that will become widely common in Ethiopian Highlands after depletion
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43 194 of community forest and absence of communal grazing land due to increased population pressure
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45 195 on the available land. Accessibility to asphalt road for transportation and removal of agricultural
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47 196 wastes (dung cakes & crop residues) for sale by taking to the nearby urban centers including
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49 197 Addis Ababa is commonly observed in the area.

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4 200 2.2. *Types and description of cookstoves used by the households in Kumbursa Village*

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7 201 The different stove types used in stove efficiency test are described in Table 1, and the most
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9 202 dominant cookstove currently in use in Kumbursa Village is three stone open fires, and only few
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12 203 of the households are using improved stoves such as mud stoves and *mirt* stoves.
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16 204 TABLE 1 HERE
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19 205 2.3. *Selection of stove performance testing methods*

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23 206 The three most common methods used to evaluate stove performance are the Water Boiling Test,
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25 207 Controlled Cooking Test and Kitchen Performance Test, also respectively known as efficiency,
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27 208 effectiveness and efficacy tests [36]. Each of these three approaches has its own benefits and
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29
30 209 limitations but in this study, the Controlled Cooking and Kitchen Performance Tests were used
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32 210 as explained below.
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36 211 The Water Boiling Test evaluates stove performance by boiling a measured quantity of water in
37
38 212 a standard pot; the shorter the time required and the lower the quantity of fuel used for boiling,
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40
41 213 the more efficient the stove [12]. The Water Boiling Test is able to control for confounding
42
43 214 factors and provides a high degree of replication, but it does not reflect actual cooking
44
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46 215 performance [33], and is therefore mostly suited to lab-based screening of stove efficiency [36].
47
48 216 The Controlled Cooking Test, also called the standard meal test, was undertaken for baking the
49
50 217 staple food, *injera*. The Controlled Cooking Test involves simulation of the real cooking practice
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52
53 218 by controlling variables like quantity of food prepared, quantity of fuel used and the behaviors of
54
55 219 the cook [12, 36]. It is less standardized but more realistic than the Water Boiling Test, but still
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58 220 does not reflect the actual cooking practice in the field. The Kitchen Performance Test involves
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221 assessment of fuel consumption by households under a normal cooking practice [37]. It is
222 preferred over both the Water Boiling Test and Controlled Cooking Test for actual in situ stove
223 performance assessment [37], as the results reflect the real cooking situation in a kitchen and so
224 reflect actual cooking practice [36]. Therefore, in this study, the Kitchen Performance Test was
225 used to assess field-based biomass fuel consumption rates of the different stove types in
226 Kumbursa Village.

227 The Kitchen Performance Test was applied in this study using the protocol set out by Bailis *et al.*
228 [38]. This was also supported by a Controlled Cooking Test and short-term participant
229 observation survey, following the approach used by Granderson *et al.* [37]. The results obtained
230 using both Controlled Cooking Test and participant observation survey methods were then
231 compared and triangulated with those of the Kitchen Performance Test in order to strengthen the
232 reliability of the findings.

233 *2.3.1. The Kitchen Performance Test*

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

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242 There were 258 households in Kumbursa Village during the field survey and 42 households
243 (16.3% of the total population) participated in efficiency tests of the cookstoves.
244 Thus, the study included 42 sampled households, selected based on recommendations given by
245 the local development agent and village leader. Willingness to participate in the study was also
246 taken into account in the selection process. Such methods of purposive sampling are widely used
247 when samples with the required characteristics are not easily accessible [39], but the non-random
248 nature of the sampling should be noted when interpreting the results. The participant households
249 were selected to have similar kitchen dimensions, typically thatched huts with plastered walls
250 having a size of 6 m² to 10 m². The study was limited to only one season i.e., Spring season (first
251 and second weeks of May 2016) but was supplemented by household survey, householder
252 interviews and focus groups discussions to compensate for this limitation. To minimize the
253 effect of variation in time, the cooking tests were conducted within reasonably shorter time
254 (consecutive weeks of the same month; first and second weeks of May 2016).

255 The same types of biomass fuels were supplied to each participant household. The biomass fuel
256 used in this study was composed of the mixture of crop residues, dung cakes and firewood as is
257 normal practice in the study village. The approximate amounts of fuel needed for the Kitchen
258 Performance Test were determined from the mean fuel consumption rate for Kumbursa village
259 [18] and by a preliminary survey. In this village, 60% and 25% by weight of the biomass fuels
260 used were dung cakes and crop residues respectively while firewood constituted 13% and with
261 charcoal accounting only for 2% of the total energy consumption of household. Annual mean
262 fuel consumption per household was 4524 kg y⁻¹ for dung cakes, 1885 kg y⁻¹ for crop residues
263 and 980 kg y⁻¹ for firewood. The amounts of fuel delivered to each household was then increased
264 over these mean consumption rates by 50%, resulting in an amount of fuel given to each

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265 household per week of ~131 kg dung cakes, ~54 kg crop residues and ~28 kg firewood; a total of
266 213 kg of biomass fuels. The participants were told to use only the fuel given to them. After
267 every cooking activity, the participants were asked to immediately extinguish the fire and keep
268 the remaining fuel for the cooking session on the following day.

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

273 Households were then divided into four sub-groups using a random lottery method. The
274 improved stove types were written on pieces of papers, which were physically similar in shape,
275 size and color and rolled-up. The rolled-up pieces of papers were equal to the sample size. They
276 were placed in a vessel and thoroughly mixed. Then each participant randomly picked a rolled-
277 up paper from the vessel. Finally, new technologies were provided to the groups as follows; 11
278 members used only mud stoves (Figure 3c) (group 1), 11 members used only *mirt* stoves (Figure
279 3d) (group 2), 10 member used mud stoves with an additional biogas stove stoves (group 3), and
280 another 10 members used *mirt* stoves with an additional biogas stove stoves (group 4). The same
281 quantity and quality of biomass fuels were provided to all of the study households as during the
282 pre-installation testing, and households were advised to use only the measured and stored
283 biomass fuels during the entire seven days of the test. The participants were told not to use the
284 fuel given to them for unusual occasions such as holidays, ceremonies, etc. Again, the amount of
285 fuel that remained after cooking for a week was weighed in order to determine fuel consumption
286 for each household.

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4 287 **FIGURE 3 HERE**

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7 288 *2.3.2. The Controlled Cooking Test*

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10 289 Triplet replications over seven days for each of the three cookstove types (traditional three-stone
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12 290 open fire which served as control, mud stoves and mirt stoves) were compared using the
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14
15 291 **Controlled Cooking Test**. Three experienced cooks (women who had fifteen years or more
16
17 292 cooking experience) were purposefully selected **from the forty two cooks involved in the**
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19
20 293 **Kitchen Performance Test**.

21
22 294 The **Controlled Cooking Test** was undertaken in the household kitchens so as to simulate normal
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24
25 295 cooking conditions [14, 31]. Baking was done by the same people (the cook and her assistant), at
26
27 296 a similar time and place using similar biomass fuels, “mitads” and *teff* dough in order to control
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29
30 297 variations in fuel consumption rates due to factors other than stove type. **Every cook had one**
31
32 298 **assistant for tending the fire, feeding biomass fuel into the stove and providing the required**
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35 299 **materials for cooking**.

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38 300 Fuels and dough were weighed using a weight balance before starting to cook, and the amount
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40 301 of fuel remaining after cooking was weighed in order to determine fuel consumption for each
41
42 302 stove type. Immediately after cooking was completed, the unburnt fuel was removed by
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44
45 303 extinguishing the fire. A cold start was used and cooking was started at 10:00 am for all of the
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48 304 three tested stove types to control for the effects of local weather variation. **All cooks and their**
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50 305 **assistants were strictly instructed to cook only once per day and to start baking *injera* exactly**
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53 306 **at 10:00am every day of the seven days**.

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307 2.4. Quantification of the nutrient contents of dung cakes, crop residues and bioslurry

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

$$314 M_x = M_{ow} \times P_x \times 100 \quad (1)$$

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

316 2.5. Calculation of greenhouse gas emissions

317 The three most important GHGs; carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O),
318 which have global warming potentials of 1, 25 and 298 carbon dioxide equivalents (CO₂e),
319 respectively [39], were considered in this study. The IPCC [40] default thermal values (MJ kg⁻¹
320 fuel) and emission factors (CO₂e) shown in Table 2 were used to estimate the likely GHG
321 emissions.

322 TABLE 2 HERE

323 In order to convert the volume of biogas to the thermal value and weight, a conversion factor of
324 23 MJ m⁻³ and 0.7 kg m⁻³ was used after Mulu *et al.* [6]. The replacement potential of biogas for
325 firewood was determined following the method provided by Pathank *et al.* [41], which assumed
326 that 1 m³ of biogas provided equivalent heating energy to 5.5 kg of firewood. The GHG

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4 327 reduction potential of typical household biogas digesters with volumes of 6 – 8 m³ was assumed
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6 328 to be 1.9 t CO₂e per digester per year [12].
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12 330 The annual mass of GHG emissions from the combustion of fuel type *a*, $M_{GHG,a}$ (kg of carbon
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15 331 dioxide equivalents (CO₂e) per household) was calculated as follows:
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17

18 332
$$MGHG,a = E_a \times 10^{-6} \times (EF_{CO_2} + EF_{CH_4} + EF_{N_2O}) \quad (2)$$

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22 333 where E_a is the annual thermal value of combustion fuel in MJ per household, EF_{CO_2} is
23
24 334 emission factor for carbon dioxide, EF_{CH_4} is emission factor for methane and EF_{N_2O} is
25
26
27 335 emission factor for nitrous oxide, all in CO₂e mg MJ⁻¹ (Table 2). The annual thermal value of a
28
29 336 given fuel of a household (E_a) was computed by multiplying the weight of the fuel by its thermal
30
31
32 337 value (MJ kg⁻¹) (Table 2).
33
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35
36 338 The total annual mass of GHG emissions from all fuels, $MGHG_{tot}$, in kg of CO₂e per household
37
38 339 in the study area was calculated as:
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41 340
$$MGHG_{tot} = E_{a1} + E_{a2} + E_{a3} + E_{a4} + E_{a5} \quad (3)$$

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45 341 where E_{a1} , E_{a2} , E_{a3} , E_{a4} and E_{a5} are the annual masses of GHG emissions in kg per
46
47 342 household from the combustion of wood, dung, crop residue, biogas and kerosene, respectively.
48
49

50 343 **Note kerosene is included here as it is widely used in the area as a fuel for lighting, so providing**
51
52 344 **biogas has potential to reduce the requirements for kerosene.** Emission reductions were then
53
54 345 quantified by subtracting fuel consumed in post-improved cookstove intervention from pre-
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57 346 improved cookstove intervention and then converting into amount of GHGs using their
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59 347 corresponding emission factors for each fuel type.
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4 348 The amount of methane leakage to the atmosphere from biogas production was calculated as:

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8 349 $M_{GHG,dig} = M_{biogas} \times p_{CH4} \times GWP_{CH4} \times p_{leak}$ (4)
9

10
11 350 where $M_{GHG,dig}$ is the average annual emission of methane from the biogas digester in kg of
12
13
14 351 CO_2e ; M_{biogas} is the average yearly biogas generation of a digester, also in kg of CO_2e (assumed
15
16 352 to be 306 kg after Mulu et al., 2016); p_{CH4} is the proportion of methane in biogas (assumed to
17
18
19 353 be 0.6 after Mulu et al. [6]; GWP_{CH4} is the global warming potential of methane (assumed to be
20
21
22 354 25 after IPCC[39]; p_{leak} is the proportion of methane produced lost through leakage (assumed to
23
24 355 be 0.1 after Mulu et al. [6]).
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27 356 2.6. Replacement cost analysis

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31 357 The average annual amount of nutrients that can be saved from being burnt (N and P in
32
33 358 bioslurry) and the amount of fuels (firewood, crop residues, dung cakes and kerosene) that can
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35
36 359 be saved due to substituting a three-stone open fire with a mud stove or *mirt* stove, without or
37
38 360 with an additional biogas stove, was calculated and valued using the local market monetary
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40
41 361 values. For determining the value of inorganic fertilizer (diammonium phosphate fertilizer
42
43 362 (DAP)), which was dominantly used in the study village, the farm gate price in Kumbursa in
44
45 363 2016 was used. For fertilizers, the farm gate price in Kumbursa in 2016 for diammonium phosphate
46
47
48 364 fertilizer (DAP) was used; 15 Ethiopian Birr (ETB) kg^{-1} (0.72 US\$ kg^{-1}). For fuels, local market prices in
49
50 365 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\$
51
52 366 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}).
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4 368 The carbon financing potential from GHG emission reduction was estimated as 16.4 US\$ or
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6 369 360.8 ETB per 1 t CO₂e, based on offset price of the Gold Standard Verified Emission Reduction
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8
9 370 (VER) of Clean Development Mechanisms [10].

12 371 *2.7. Household survey and focus group discussions*

15 372 A single time cross-sectional survey was carried out to collect data on the resource endowment
16
17
18 373 (landholding size, livestock number, household income) and household energy (sources of energy and
19
20 374 consumption rates). A semi-structured interview questionnaire was used for the survey.

22
23 375 Using a participatory wealth ranking method, households of the Village were stratified into three wealth
24
25 376 groups (rich, medium and poor). Using a proportionate-stratified-random sampling procedure over the
26
27 377 wealth groups, 120 farm households (i.e. 45%) were selected out of the total 258 households of Kumbursa
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29 378 Village.

31
32 379 The four experimental groups participating in stove efficiency test formed four groups for focus group
33
34 380 discussions. The issues covered by the focus group discussants constituted sources of biomass fuel as well
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36 381 as the merits and demerits attached to each stove type.

38 382 *2.8. Sampling crop residues, dung cakes and bioslurry for analysis of nutrient contents*

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42 383 Nine composite samples (each consisting seven sub-samples) were collected each from crop
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44 384 residues, dung cakes and bioslurry for laboratory analysis of nitrogen, phosphorus, potassium
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46
47 385 and organic carbon contents. The dry weight of bioslurry produced by the biogas digester was
48
49 386 measured over a period of two weeks and converted into an annual average. Bioslurry samples
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51 387 were taken after thorough stirring of the slurry in the overflow tank.

53 388 *2.9. Statistical analysis*

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57 389 Variation in biomass fuel consumption rates, potential availability of nutrients due to reduced
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60 390 consumption of dung and crop residues, GHG emissions and financial savings among the

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4 391 different stoves were analyzed using one-way analysis of variance. Data obtained from pre-
5
6 392 intervention stage were compared with that of post-intervention stage fuel saving using paired
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9 393 sample *t*-test. Mean values were used for quantifying GHGs emission and for analyzing the
10
11 394 replacement costs.

15 395 3. Results

18 396 3.1. Biomass fuel saving efficiencies based on results from Kitchen Performance Test

21 397 Results from Kitchen Performance Test showed that the mean biomass fuel saving for each
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23
24 398 household compared to a three stone open fire was 32% (2842 (± 21) kg y⁻¹) for mud stoves
25
26 399 (group 1), 45% (3997 (± 27) kg y⁻¹) for *mirt* stoves (group 2), 49% (4352 (± 33) kg y⁻¹) for the
27
28
29 400 mud stove with an additional biogas stoves (group 3), and 54% (4796 (± 27) kg y⁻¹) for *mirt*
30
31 401 stove with an additional biogas stove (group 4) (Table 3). The potential increase in biomass fuel
32
33 402 availability relative to the traditional three stone open fire was statistically significant (Table 3;
34
35 403 $p < 0.001$) with the highest value for a *mirt* stove with an additional biogas stove.

39 404 In corroboration with this finding, Amogne [32] obtained biomass fuel savings of 25% and 47%
40
41
42 405 respectively for the *Gonzie* and *Lakech* stoves compared to the three-stone open fires. *Mirt*
43
44 406 stoves saved up to 50% of biomass fuel consumption compared to the three-stone open fire stove
45
46
47 407 [4]. Abera [7] and Dresen *et al.* [42] respectively found 60% and 40% biomass fuel saving
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49 408 efficiencies for the *mirt* stove compared to the three-stone open fire system.

52 409 TABLE 3 HERE

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410 3.2. Biomass fuel saving efficiencies based on results from controlled cooking test

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

416 TABLE 4 HERE

417 FIGURE 3 HERE

418 3.3. Potential contribution of improved cookstoves to Soil nutrients availability

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

422 TABLE 5 HERE

424 3.4. Potentials of improved cookstoves in reduction of greenhouse gas emissions

425 The potential per household GHG emission reductions in CO₂e were 4534 (±32) kg y⁻¹ for mud
426 stoves, 6370 (±42) kg y⁻¹ for *mirt* stoves, 6953 (±51) kg y⁻¹ for the mud stoves with an additional
427 biogas stove and 7661 (±43) kg y⁻¹ for *mirt* stoves with an additional biogas stove (Table 6).

428 As shown in Table 6, the use of biogas stoves together with improved solid biomass fuel stoves
429 significantly reduced GHG emissions (Table 6; P<0.001). The studies conducted elsewhere also

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4 430 reported similar contributions of biogas and improved cookstoves for the reduction of GHG
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6 431 emissions. For instance, biogas digesters prevented 360 m³ y⁻¹ CO₂ and 600 m³ y⁻¹ CH₄ from
7
8 432 being emitted to the atmosphere and saved about 0.562 ha of forest land from being deforested
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10
11 433 on annual basis [19]. Abera [7] also reported a reduction of CO₂ emissions by 2.145 t y⁻¹ per
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14 434 stove as a result of replacing three-stone open fire furnace with a *gonziye* stove (another design
15
16 435 of improved *injera* stove).

436 TABLE 6 HERE

437 3.5. Potential contributions of improved cookstoves in saving household finances

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

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4 453 income of 21109 ETB y⁻¹ (959.5 US\$ y⁻¹) for Kumbursa Village to 24321 ETB y⁻¹ (1101.4 US\$
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6 454 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)
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8 455 l) for mud stove with additional biogas, and 29160 ETB y⁻¹ (1325.5 US\$ y⁻¹) for *mirt* stove with
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11 456 additional biogas.

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15 457 These results are consistent with the findings of Abera *et al.* [7] which also reported potential
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17 458 annual financial saving of 3,717 ETB per household as a result of substituting three-stone open
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19 459 fires with *mirt* stoves. With biogas, Zerihun [43] observed an annual per household savings of
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21 460 ETB 3833, 1243, 129, 266 and 718 from substituting fuel wood, charcoal, dung cake, kerosene
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23 461 and chemical fertilizer.

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28 29 30 31 463 4. Discussions

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35 464 Although the mud stove was less efficient than the *mirt* stove and failed to meet the minimum
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37 465 GIZ efficiency requirement of 40% [4], it significantly increased biomass fuel use efficiency
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39 466 when compared to the traditional three-stone open fire. The greater efficiency of the *mirt* stoves
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41 467 compared to the mud stoves was attributed to the better design and construction of the former. In
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43 468 addition to preparing injera, *mirt* stoves were used for drying and refreshing stale *injera* and
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45 469 preparing *firfir* (made by mixing *dried* injera with hot sauce) using the heat remaining after
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47 470 baking *injera*. The *mirt* stove was also used for preparation of sauce (*wot*) on the chimney during
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49 471 *injera* baking, which, according to the participants, further saved biomass fuel and reduced
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51 472 cooking time.

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55 473 The biomass fuel saving of the *mirt* stove over the traditional three-stone open fire was in
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57 474 agreement with the findings by Yosef [22], who reported a 45% fuel saving for an *injera mirt*

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4 475 stove compared to a traditional open fire system. However, the result of this study was higher
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6 476 than the findings of Abera [7] Dresen *et al.* [41], and Dagninet *et al.* [44], who reported savings
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9 477 of only 40%, 22% and 33%, respectively. The results from this study are higher because of the
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11 478 probable improvements in the design of the more recent stoves used in this experimental work
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14 479 which were assumed to have better efficiency. Further savings were observed when the solid
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16 480 biomass stoves were used in combination with biogas stoves. This is because biogas was used for
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19 481 cooking activities other than *injera* baking, such as for *wot* preparation, making coffee and tea
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21 482 and boiling water. A three stone open fire can be adjustable and hence can be utilized for many
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24 483 different purposes and this was appreciated as good quality. By contrast, improved cookstoves
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26 484 tend to be used for specific purposes. For instance, the *mirt* stoves and mud stoves are used only
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29 485 for baking *injera* unless special chambers are attached to allow them to be used for other
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31 486 purposes, such as sauce, tea and coffee preparation. On the other hand, biogas stoves are not well
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33 487 adapted for *injera* baking, and are preferred for use for water boiling, sauce preparation, coffee
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36 488 and tea preparation. Therefore, multiple stoves are used in households to serve different
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38 489 purposes.

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41 490 From the household survey, it was observed that 173 (67%) out of the total 258 households in
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43 491 Kumbursa village had enough feedstock with more than four cows per household, good access to
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46 492 water, i.e. within a distance of less than 2 km from the nearest water source and adequate
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48 493 financial capacity to install biogas digesters (most them being in the medium and rich farm
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50 494 household wealth groups).

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54 495 If the full potential of biogas was exploited and used together with mud or *mirt* stoves, there
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56 496 would be a total biomass fuel (dung cake, crop residues and firewood according to their
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59 497 respective relative contributions to the total fuel consumptions in the study area i.e., 61.2%,

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4 498 25.5% and 13.3% of the total dry weight of biomass fuel used for stove efficiency tests)

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7 499 savings of 4352 (± 33) kg y^{-1} per household and 4796 (± 27) kg y^{-1} per household respectively

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9 500 (Table 3) while the respective possible biomass fuel savings across all potential users in

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11 501 Kumbursa would be 752.9 (± 5.7) t y^{-1} and 829.7 (± 4.6) t y^{-1} . The exhaustive exploitation of the

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14 502 available biogas potential together with use of mud stoves for the entire 258 households of

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16 503 Kumbursa Village could result in potential nutrient saving from being burnt per household of

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19 504 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

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21 505 was used together with *mirt* stoves, the potential amount of nutrients saving from being burnt

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24 506 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.

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26 507 The substitution of three-stone open fires with improved cookstoves could also significantly

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29 508 contribute to the mitigation of GHG emissions. Thus, rural farm households can benefit from

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31 509 carbon financing and this could be used to motivate them to switch from the traditional three

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34 510 stone open fires to more fuel-efficient biomass stoves at a larger scale.

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37 511 As confirmed from the results of both the Kitchen Performance Test and Controlled Cooking

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39 512 Test, substitution of three-stone open fires with mud and *mirt* stoves both with and without

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41 513 biogas stoves improved biomass (dung and crop residues) availability that can used for

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44 514 application to farmlands. This implies that saved fuels (cow dung and crop residues) could be

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46 515 used as organic fertilizers. Using improved solid biomass cookstoves together with biogas stoves

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49 516 can substantially increase the availability of nutrients for field application relative to the use of

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51 517 improved solid biomass cookstoves without biogas stoves. Average landholding size for

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54 518 Kumbursa Village is 1.9 ha [18] which requires nearly 190 kg DAP and 190 kg urea based on

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56 519 blanket recommendation, so the extra nutrients potentially supplied to the soil when *mirt* and

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4 520 biogas stoves are used in combination (N = 117 kg and P = 34 kg) are almost equivalent to the
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6 521 amounts recommended for inorganic fertilizer (122 kg N and 34 kg P).
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10 522 However, the use of organic fertilizer in the predominantly cereal cropping areas of the Central
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12 523 Highland of Ethiopia, including Kumbursa Village, is very rare. The field survey revealed that
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14 524 farm households prefer to sell the surplus cattle dung as dung cakes instead of applying it to
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16 525 farmland since dung cake demand as fuels is very high near to urban markets. This study
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18 526 demonstrates that the financial savings from the sale of surplus biomass fuel was higher than the
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20 527 potential total financial savings from substituting commercial fertilizer, generation of carbon
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22 528 finance and replacement of kerosene for lighting. This explains why households usually prefer to
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24 529 sell surplus biomass fuels instead of using them as organic fertilizers. This finding suggests that
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26 530 while wide scale adoption of fuel-efficient solid biomass stoves can contribute to the financial
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28 531 security of households, and may help to reduce greenhouse gas emission and deforestation in
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30 532 areas where wood fuel provides a significant part of the household energy, it will do little to
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32 533 increase the fertility of soils. By contrast, including biogas stoves will help to improve soil
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34 534 fertility by retaining at least some of the carbon and nutrients in bioslurry that will be applied to
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36 535 the soil.
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45 536 *End-users' satisfaction survey of alternative stoves*

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47 537 From the focus group discussions and interviews with participants, it appeared that the time savings and
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49 538 the smokeless nature of the biogas as a fuel were appreciated by the end users, while the benefits of
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51 539 bioslurry as fertilizer were generally ignored and hence undervalued by the farm households.
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55 540 End-users favored many of the different traits of the improved cookstoves compared to a traditional three-
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57 541 stone open fires. Traits of *mirt* and mud-stoves that were particularly appreciated by the end users were
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59 542 fuel saving, reduced frequency needed to tend the fire and allowing other household work to be done in
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4 543 parallel with cooking activities, less risk of exposure to burning and cleaner kitchens due to less soot and
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6 544 smoke.

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9 545 However, there were some focus group discussants that appreciated three stone open fires for cooking
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11 546 purpose. The most commonly favored traits of the three-stone open fires were little or no cost incurred to
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13 547 obtain the stoves, easy adjustability for different activities and easy feeding with fuel through the spaces
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15 548 between the stones. The three-stone open fire was reportedly convenient for different cooking purposes as
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17 549 it is easily adjusted to fit cooking utensils of different sizes.

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21 550 However, the smoky flavor of *wot*, tea or coffee prepared on a three-stone open fires was disfavored by
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23 551 the observed end users. It was confirmed during the field survey that households with only an improved
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25 552 stove for *injera* cooking presumably used three-stone open fires for other cooking purposes.

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29 553 The main traits disliked about the three-stone open fire were the higher fuel consumption rates relative to
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31 554 both mud-stoves and *mirt* stoves, higher risk of burning and exposure to smoke, and inability of doing
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33 555 other household tasks due to constant tending of the fire.

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36 556 The longer lifespan of the *mirt* stoves compared to the mud-stove was favored by the end users.
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38 557 Households liked biomass fuel saving provided by both the mud stoves and *mirt* stoves, while the *mirt*
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40 558 stoves were preferred over the mud-stoves for their durability. Limited supply and consequent increasing
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42 559 prices of biomass fuel were the major factors for prompting some households in Kumbursa Village to
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44 560 adopt fuel efficient cookstoves.

45 46 47 48 49 561 **5. Conclusions**

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52 562 Improving biomass fuel use efficiency has the potential to mitigate the adverse environmental
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54 563 and socioeconomic impacts associated with traditional biomass fuel use. Improved cookstoves
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56 564 such as *mirt* stoves have great potential to improve fuel supply while significantly contributing to
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58 565 mitigation of GHG emissions and improvement of household finance. However, because the
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4 566 dung cakes can be sold for fuel sources at a relatively high price, the availability of dung for soil
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6 567 amendment will only be improved by an additional use of biogas digesters, which prevents it
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8 568 from being sold as dung cakes by turning it into bioslurry. Therefore, large scale production of
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11 569 more efficient biomass fuel technologies, such as mud stoves and *mirt* stoves, together with
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14 570 dissemination of biogas digesters, is likely to be a valuable short-term policy intervention.
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16 17 571 **Acknowledgements**

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19
20 572 The authors are grateful to the participating households in stove performance test and end-users'
21
22
23 573 stove satisfaction survey without whose assistance the accomplishment of the research
24
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26
27 575 Union Commission (AUC) for funding the installation of biogas digesters and *mirt* stoves in
28
29
30 576 Kumbursa Village as part of Afriflame project under the adaptation of small-scale biogas
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32
33 577 digesters for use in rural households in Sub-Saharan Africa. The assistance from Green Heat-
34
35 578 Uganda in installing biogas digesters in Kumbursa Village is appreciated. Finally, we are
36
37 579 thankful to the staff of Debrezeit Agricultural Research Center for analyzing the nutrient
38
39
40 580 contents of dung cake, crop residues and bioslurry samples.
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42 43 581 **References**

- 44
45
46
47 582 [1] R. Bailis, A. Drigo, O. Ghilardi, Masera, The carbon footprint of traditional woodfuels,
48
49 583 Nature Climate Change; 5, (2015) 266-272.
50
51
52 584 [2] D. J. Idiata, M. Ebiogbe, H. Oriakhi, H. Iyalekhue, Wood fuel usage and the challenges on
53
54
55 585 the environment. International Journals of Engineering Sciences, 2(4) (2013)110-114.
56
57
58
59
60
61
62
63
64
65

- 1
2
3
4 586 [3] S. H. Kooser, Clean cooking: The value of clean cookstoves in Ethiopia. Journal of
5
6 587 Environment and Resource Economics at Colby, Vol 01, Iss. 01, Article 03 (2014).
7
8 Available at <http://digitalcommons.colby.edu/jerec/vol01/iss10/3>.
9 588
- 10
11
12 589 [4] GIZ, Energizing development (EnDev) Ethiopia: Improved cookstoves (ICS). Bonn and
13
14 **Eschborn** (2014). Available at: <http://endev.info/ethiopia>.
15 590
16
17
- 18 591 [5] B. Abebe, R. Bluffstone, G. Zenebe, P. Martinsson, M. Alemu, F. Vieider, Do improved
19
20 592 biomass cookstoves reduce fuel consumptions and carbon emissions? Evidence from
21
22 rural Ethiopia using a randomized treatment trial with electronic monitoring. Policy
23 593 Research Working Paper 7324 (2015).
24
25 594
26
27
- 28
29 595 [6] M.G. Mulu, S. Belay, E. Getachew, W.S. Tilahun, The environmental benefits of domestic
30
31 596 biogas technology in rural Ethiopia. *Biomass Bioenerg.* **90** (2016), 131-138.
32
33
- 34 597 [7] A.B. Abera, The implication of wood-burning stove efficiency for environment, health and
35
36 CO₂ emissions in the Jogo Gudedo Watershed, Ethiopia. *Academic Research Journal of*
37 598 *Agricultural Science and Research*, 4(4) (2016) 154-163.
38
39 599
40
41
- 42 600 [8] T. Lemlem, Biogas technology adoption in rural Ethiopia: Its effect on the crisis of
43
44 deforestation. *Journal of Energy Technologies and Policy*, 6/1(2016).
45 601
46
47
- 48 602 [9] FDRE [Federal Democratic Republic of Ethiopia], *Ethiopia's Climate Resilient Green*
49
50 *Economy (CRGE)*, Addis Ababa, Ethiopia (2011).
51 603
52
53
- 54 604 [10] SEI [Stockholm Environment Institute], Assessing the climate impacts of cookstove
55
56 projects: Issues in Emissions Accounting. SEI Working Paper Series No. 201301,
57 605 Sweden, Stockholm (2013).
58
59 606
60
61
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56
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58
59
60
61
62
63
64
65

[11] . Amoah et al., Firewood collection and consumption practices and barriers to uptake of modern fuels among rural households in Ghana. *International Forestry Review*, Vol. 21 (2), S. 149-166 (2019).

[12] F. Lambe, M. Jürisoo, H. Wanjiru, J. Senyagwa, Bringing clean, safe, affordable cooking energy to households across Africa: an agenda for action, Prepared by the Stockholm Environment Institute, Stockholm and Nairobi, for the New Climate (2015).

[13] Mercy Corps, Basic guide to fuel efficient stoves and emission testing. Portland OR 97204, USA; Edinburgh, EH9 1NJ, UK (2010).

[14] M.G. Mulu, Biogas technology adoption and its contribution to rural livelihood and environment in Northern Ethiopia, the case of Ofla and Mecha Woredas. Thesis submitted to Center for Environment and Development, presented in fulfillment of the requirements for the Degree of Doctor of Philosophy in Development Studies (Center for Environment and Development), Addis Ababa University, Addis Ababa, Ethiopia (2016).

[15] S. G. Gwavuya, S. Abele, I. Barfuss, M. Zeller, J. Muller, Household energy economics in rural Ethiopia: A cost-benefit analysis of biogasenergy, *Renew Energy*, 48 (2012) 202-209.

[16] N. Abebe, T.W. Kuyper, A. de Neergaard, Agricultural waste utilization strategies and demand for urban waste compost: Evidence from smallholder farmers in Ethiopia. *Waste Management*, 4, (2015) 82-93.

[17] M. Dawit, B. Elizabeth, A. Tekie, C. Ringler, Food versus Fuel: Examining tradeoffs in the allocation of biomass energy sources to domestic production uses in Ethiopia. Paper

1
2
3
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62
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64
65

629 presented at Agricultural and Applied Economics Association and Western
630 Agricultural Economics Association Annual Meeting, San Francisco, CA, July 26-
631 28(2015).

[18] N. Dugassa, A. Assefa, J.U. Smith, A. Hailu, G. Bogale, Household energy and recycling of
632 nutrients and carbon to the soil in integrated crop-livestock farming systems; a case
633 study in Kumbursa village, Central Highlands of Ethiopia. *GCB Bioenergy*,(9) (2017)
634 1588-1601, doi:10.1111/gcbb.12459.

[19] B. Kassahun, H. Hager, K. Mekonnen , Woody and non-woody biomass utilization for fuel
635 and implications on plant nutrients availability in Mukehantuta Watershed in
636 Ethiopia. *African Crop Science Journal*, 21, (2013) 625-636.

[20] L. Hilawe, T. Getenet, Y. Asrat , Low carbon Africa: Leap-frogging to a green future.
637 Ethio-Resource Group and Christian Aid Ethiopia (2011). Available at
638 christianaid.org.uk/low-carbon-africa.

[21] Y. Seid, Y. Bezabih, O. Sahu, Biogas production using geomembrane plastic digesters as
639 alternative rural energy source and soil fertility management, *sustainable energy* 2(1)
640 (2014) 12-19.

[22] A. B. Yosef, Assessing environmental benefits of mirt stove with particular reference to
641 indoor air pollution (carbon monoxide and suspended particulate matter) and energy
642 conservation. Thesis submitted to the School of Graduate Studies of Addis Ababa

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56
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58
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60
61
62
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64
65

649 University in partial fulfillment of the requirements of Master of Science in
650 Environmental Science, Addis Ababa, Ethiopia (2007).

[23] G. Zenebe, B. Abebe, R. Bluffstone, P. Martinsson, M. Alemu, M. Toman, Fuel saving,
cooking time and user satisfaction with improved biomass cookstoves: Evidence from
Controlled Cooking Tests in Ethiopia. Resource and Energy Economics 52 (2018),
[10.1016/j.reseneeco.2018.01.006](https://doi.org/10.1016/j.reseneeco.2018.01.006).

[24] Accenture, Enhancing market for delivery of improved cookstove development and
promotion support in Ethiopia: Market analysis, recommendations and program plan
final. Accenture Development Partnerships, UK (2015).

[25] ESD (Energy for Sustainable Development), Mirte, Ethiopia (2017). Available online at:
<http://stoves.bioenergylists.org/stovesdoc/Bess/Mirte.htm>.

[26] Hedon Lakech stove (2017). Available online at:
<http://support.hedon.info/View+Stove&itemId=11487>.

[27] Energypedia, List of Stoves in Ethiopia (2017). Available online at:
https://energypedia.info/wiki/List_of_Stoves_in_Ethiopia.

[28] Kindu Trust, Mirt stove distribution project (2017). Available online at:
<https://kindustrust.org/projects/mirt-stove-distribution-project/>.

[29] V. Tumwesige, D. Fulford, G.C. Davidson, Biogas appliances in Sub-Sahara Africa.
Biomass and Bioenergy, 70 (2014) 40-50.

1
2
3
4
5
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9
10
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56
57
58
59
60
61
62
63
64
65

668 [30] J. Smith, A. Abegaz, R. Matthews, M. Subedi, B. Orskov, V. Tumwesige, P. Smith, What
669 is the potential for biogas digesters to improve soil fertility and crop production in Sub-
670 Saharan Africa? *Biomass and Bioenergy*, 70 (2014) 73–86.

671 [31] G. Zenebe, M. Alemu, T. Adane, S. Assefa, Carbon markets and mitigation strategies for
672 Africa/Ethiopia: Literature review and the way forward. EDRI report 14. Addis Ababa:
673 Ethiopian Development Research Institute (2012).

674 [32] A. Amogne, Factors affecting the adoption of fuel efficient stoves among rural households
675 in Borena woreda: North central Ethiopia. *International Journal of Energy Science*
676 (IJES), 4 (5) (2014) 141-154.

677 [33] E. Adkins , E. Tyler, J. Wang, D. Siriri, V. Modi, Field testing and survey evaluation of
678 household biomass cookstoves in rural Sub-Saharan Africa. *Energy for Sustainable*
679 *Development* 14/ 2010 172-185.

680

681 [34] R.W. Wachera, Assessing the challenges of adopting biogas technology in energy provision
682 among dairy farmers in Nyeri County, Kenya. *MSC Thesis, School of Environmental*
683 *Studies of Kenyatta University* (2014).

684 [35] I. Campbell, Environmental assessment and screening report on the project: Improving
685 productivity and market success (IPMS) of Ethiopian farmers; pilot learning woreda:
686 Ada'a, *IPMS Environmental Screening Report* (2005).

1
2
3
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5
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7
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47
48
49
50
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52
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54
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56
57
58
59
60
61
62
63
64
65

687 [36] R. Bailis, V. Berrueta, C. Chengappa, K. Dutta, B. Edwards *et al.*, Performance testing for
688 monitoring improved biomass stove interventions: Experiences of the household
689 energy and health project. *Energy for Sustainable Development*, Vol. XI, No 2 (2007).

690 [37] J. Granderson, S. J. Sandhu, D. Vasquez, E. Ramirez, K.R. Smith, Fuel use and design
691 analysis of improved wood burning stoves in the Guatemalan Highlands. *Biomass*
692 *Bioenergy*, 33, (2008) 306-315.

693 [38] R. Bailis, K.R. Smith, R. Edwards, The kitchen performance test, version 1.5, household
694 Energy and health programme. Shell Foundation (2004).

695 [39] M. Naderifar, H. Goli, F. Ghaljaie, Snowball sampling: a purposeful method of sampling in
696 qualitative research. *Strides Dev Med Educ* 2017 September; 14(3):e67670.
697 <http://dx.doi.org/10.5812/sdme.67670>

698 [40] IPCC [Intergovernmental Panel on Climate Change], Climate change: the physical science
699 basis, in: Contribution of Working Group I to the Fourth Assessment Report of the
700 Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge
701 and New York (2007).

702 [41] H. Pathank, N. Jain, A. Bhatia, S. Mohanty, N. Gupta, Global warming mitigation potential
703 of biogas plants in India. *Environmental Monitoring and Assessment*, 157/ 1-4: (2009)
704 407-418.

705 [42] E. Dresen, B. DeVries, M. Herold, L. Verchot, R. Müller, Fuelwood Savings and carbon
706 emission reductions by the use of improved cooking stoves in an Afromontane Forest,
707 Ethiopia. *Land*, 3, (2014) 1137-1157.

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2
3
4
5
6
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46
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49
50
51
52
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54
55
56
57
58
59
60
61
62
63
64
65

708 [43] Y. A. Zerihun, The benefits of the use of biogas energy in rural areas in Ethiopia: A case
709 study from Amhara National Regional State, Fogera District. African Journal of
710 Environmental Science and Technology, 9, 4 (2015), 332-345.

711 [44] A. Dagninet, A. Endebhatu, M. Awole, Enhancing biomass energy efficiency in rural
712 households of Ethiopia. Journal of Energy and Natural Resources, 4 (2015) (27-33).

713 **Tables**

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

716 Table 2. Thermal values (MJ kg^{-1}) of fuels (biomass, biogas & kerosene) and greenhouse gas
717 emission factors in carbon dioxide equivalents (mg MJ^{-1}); EF_{CO_2} is the emission factor for
718 carbon dioxide, EF_{CH_4} for methane and $EF_{\text{N}_2\text{O}}$ for nitrous oxide [39]

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

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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 <i>wot</i> (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.

734

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 736 emission factors in carbon dioxide equivalents (mg MJ⁻¹); *EF_{CO2}* is the emission factor for
 737 carbon dioxide, *EF_{CH4}* for methane and *EF_{N2O}* for nitrous oxide [39]

Fuel type	Thermal values (MJ kg ⁻¹)	<i>EF_{CO2}</i>	<i>EF_{CH4}</i>	<i>EF_{N2O}</i>
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

738

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 740 stoves as compared to three-stone open fire stoves

Stove types	Mean biomass fuel saving per household		Standard deviation	<i>t</i> -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:							
Mirt and biogas stove	4796 ± 27	54%	816	13.8	9	.000**	

741 *Note: average biomass fuel consumption for three stone open fires = 8891 kg y⁻¹ per household*

742

743 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 (P-value)	0.679	0.894	2.222				
	0.519	0.427	0.137				

744

745 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**

746

747 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*

748

749 Table 7. Improvement in household finances due to substitution of the three stone open fires with
750 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**	

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

755 Figures

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

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

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

761 Fig. 4. Comparative biomass fuel consumption rates (t y⁻¹) by the different stove types under
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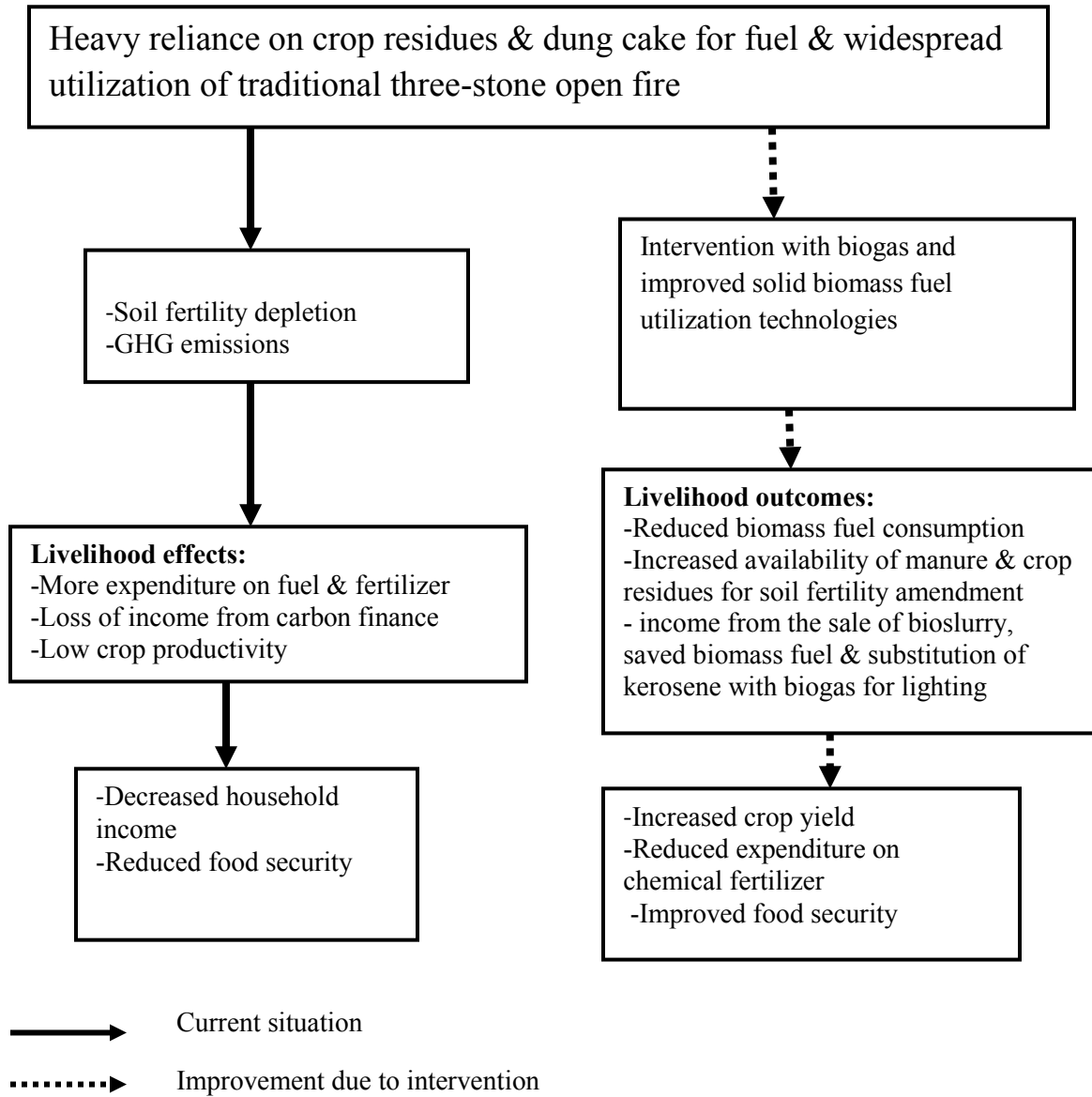
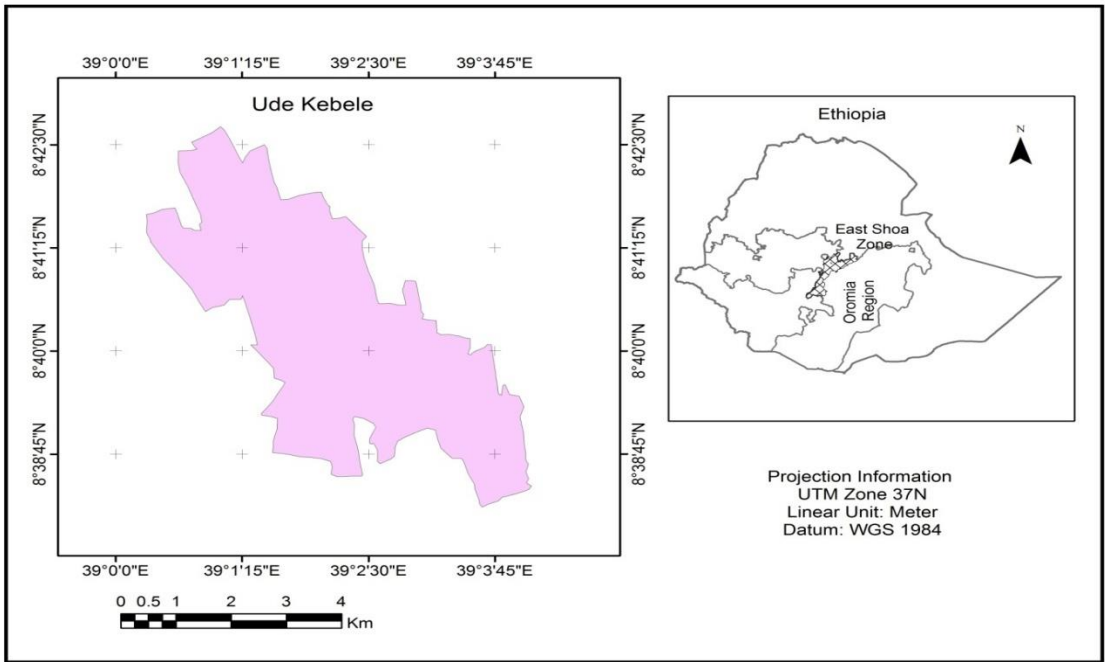


Fig.1



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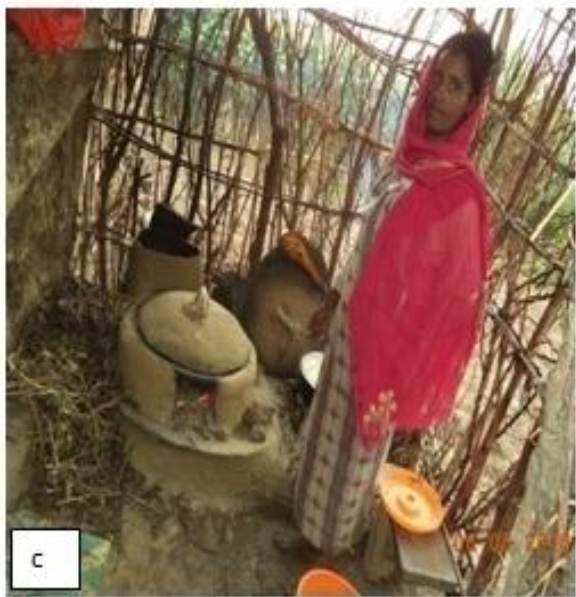
779 Fig. 2.

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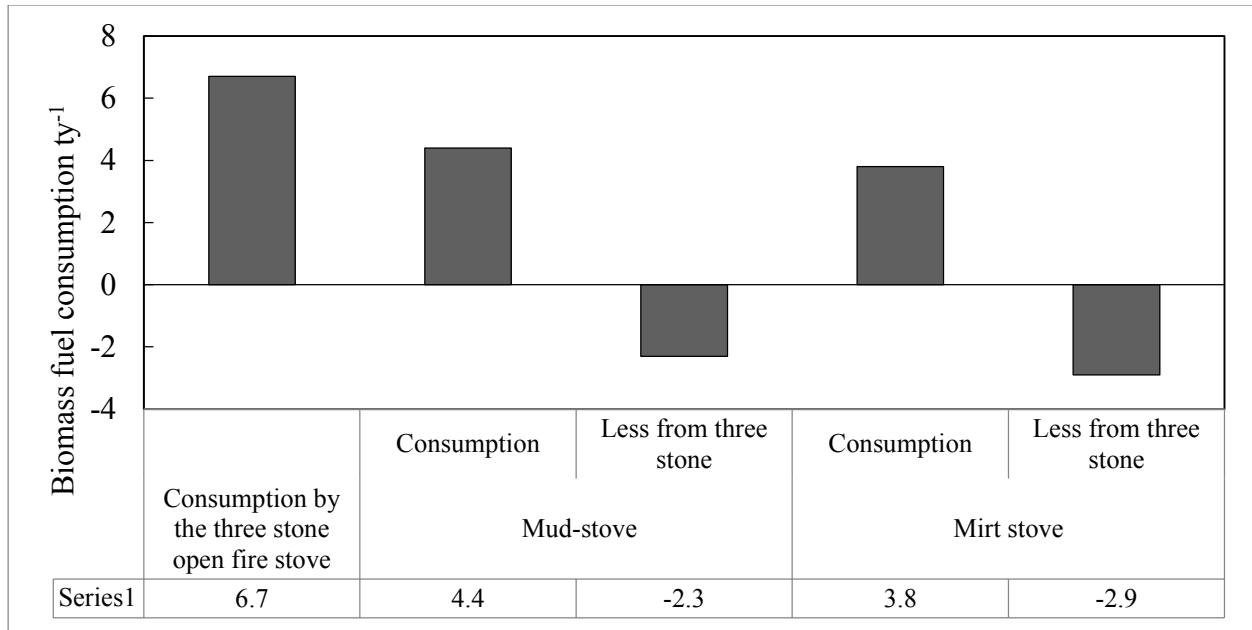
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786 Fig. 4.

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Tables

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

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Figures

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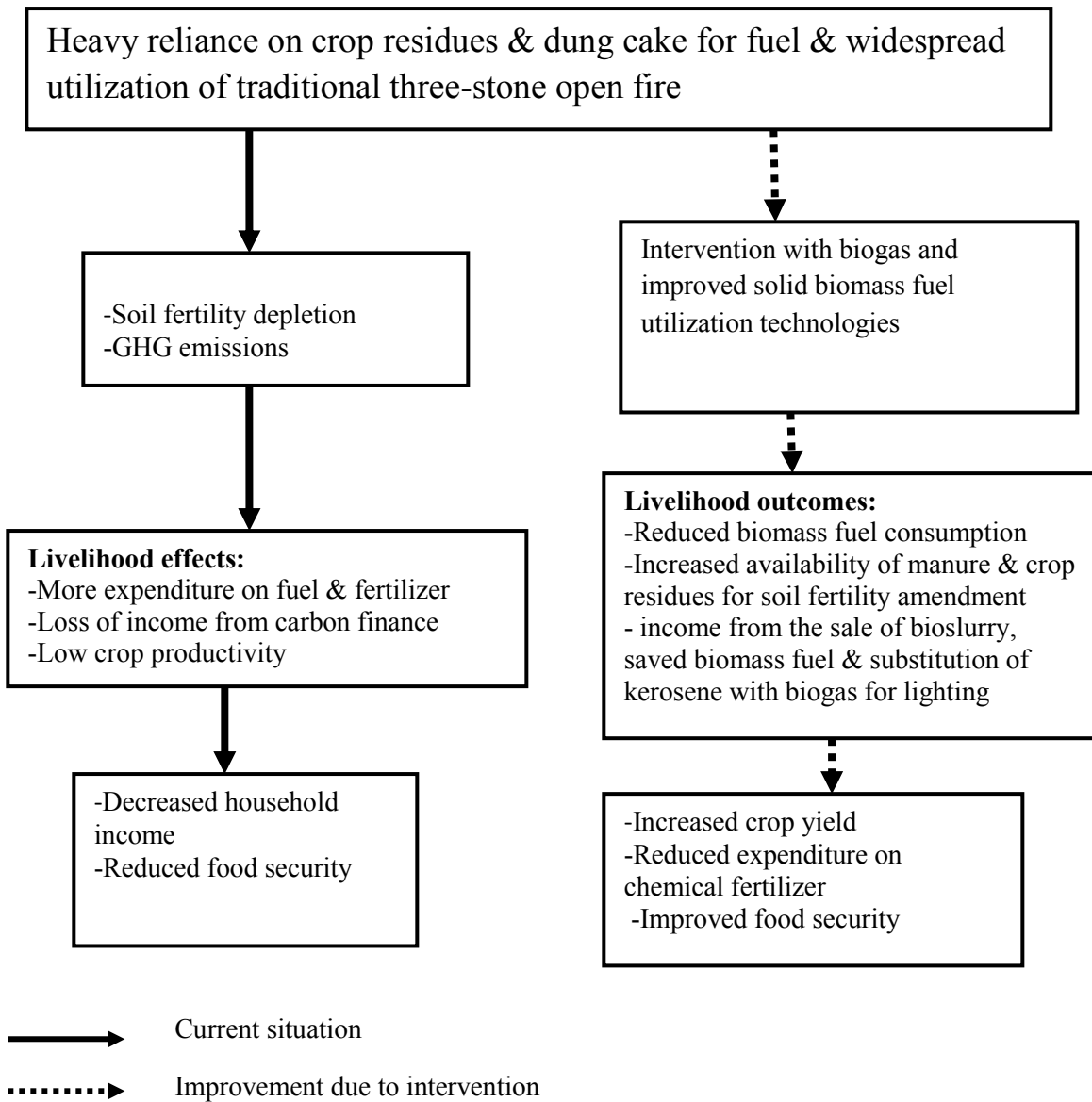


Fig. 1.

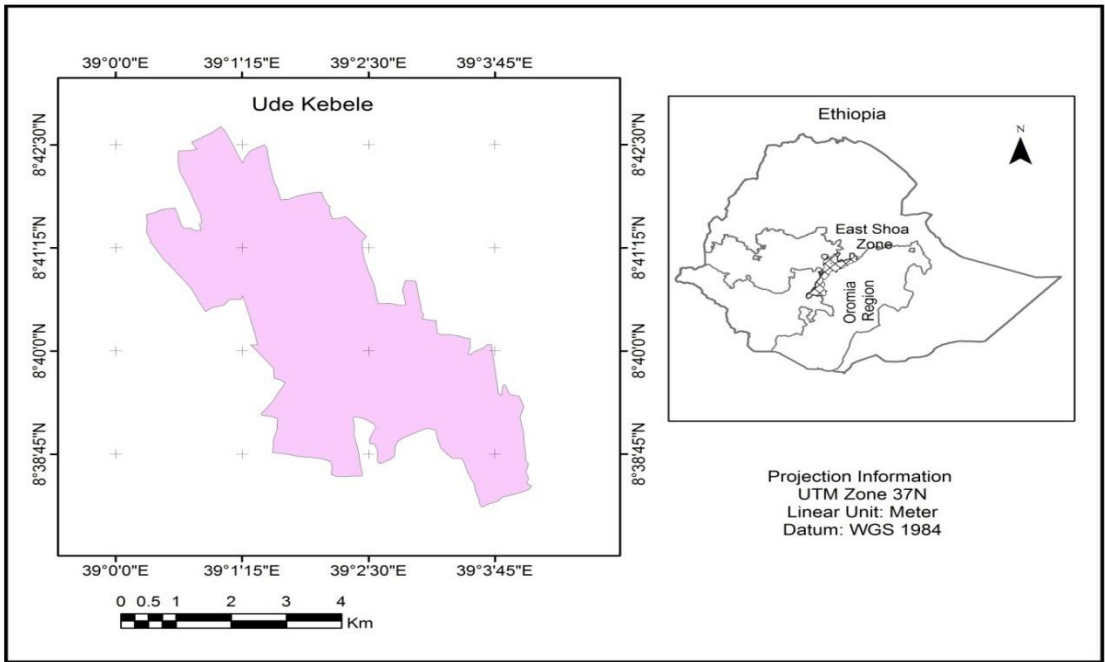


Fig. 2.

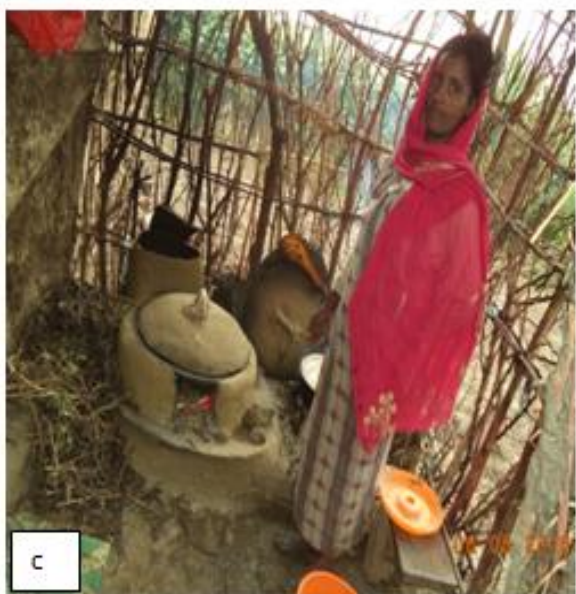


Fig. 3.

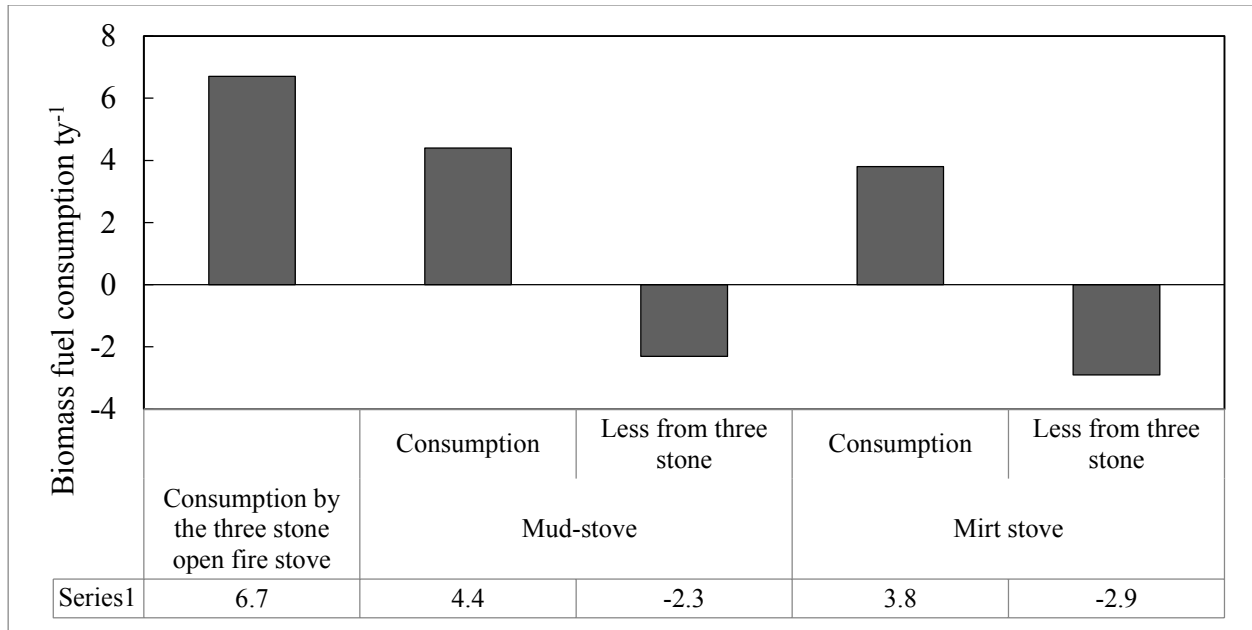


Fig. 4.

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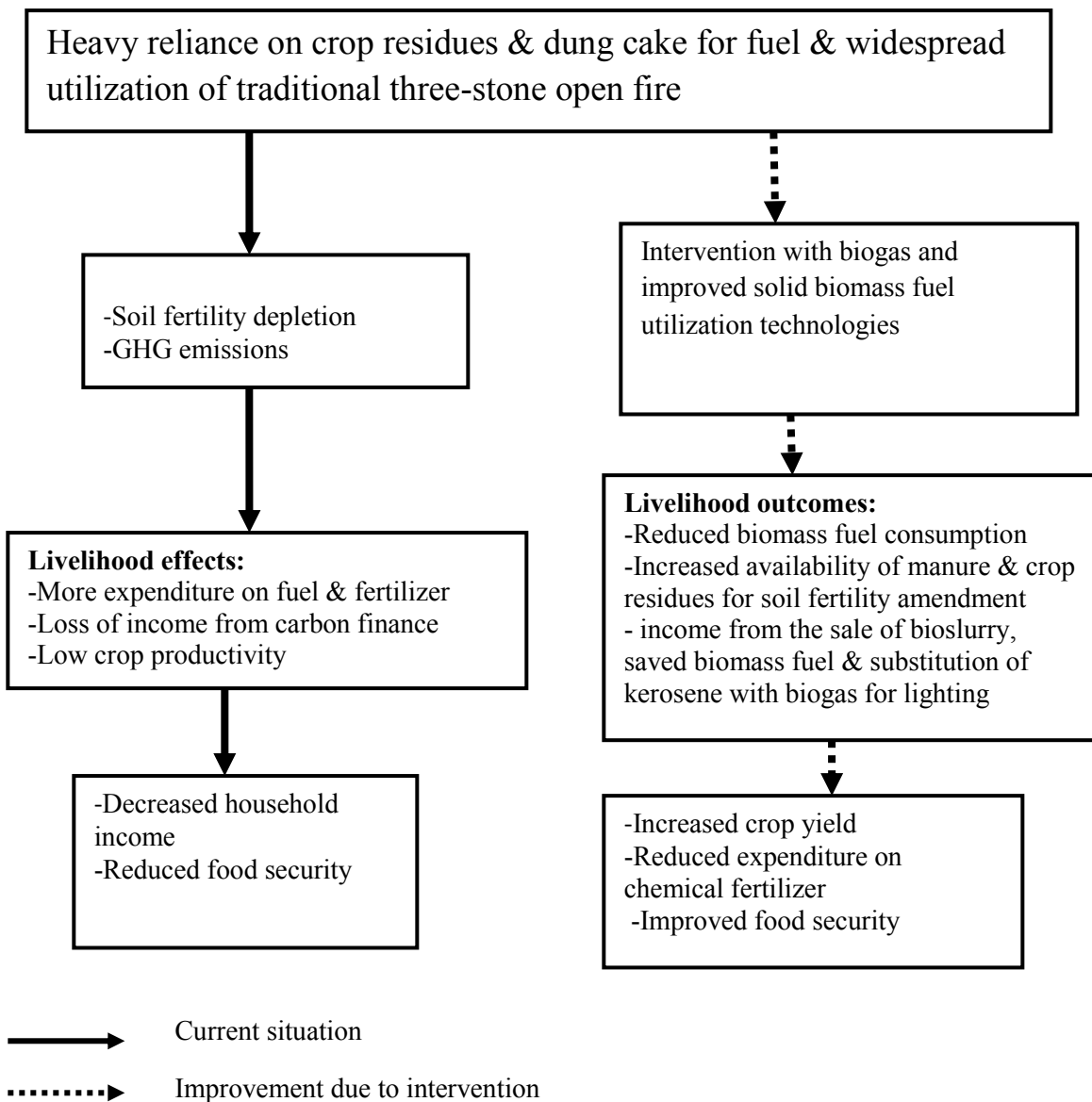


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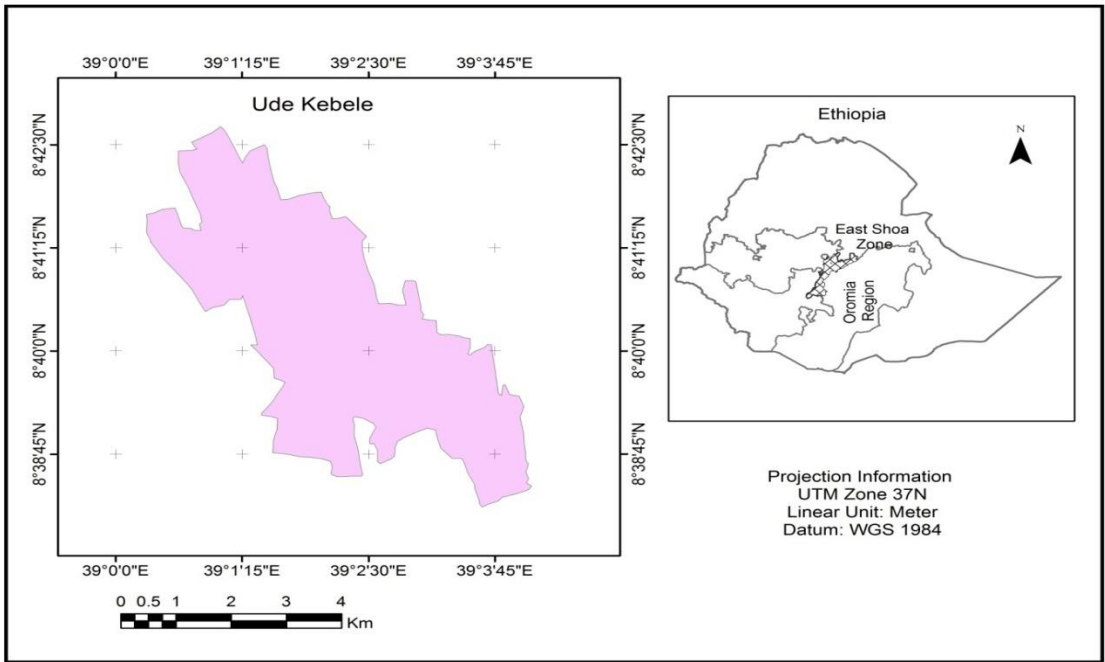


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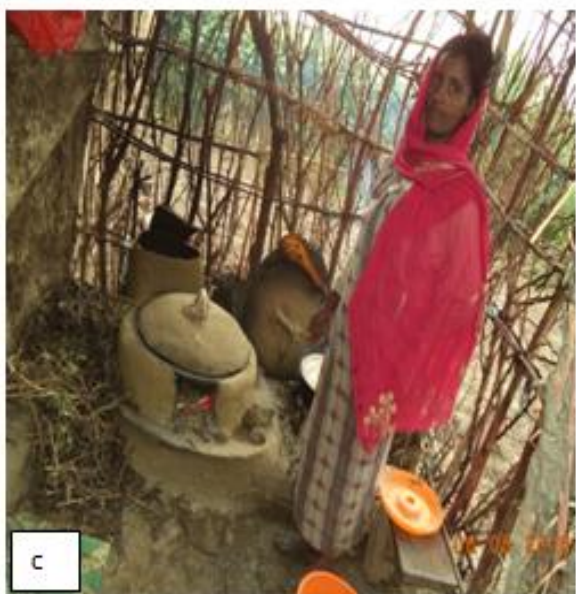


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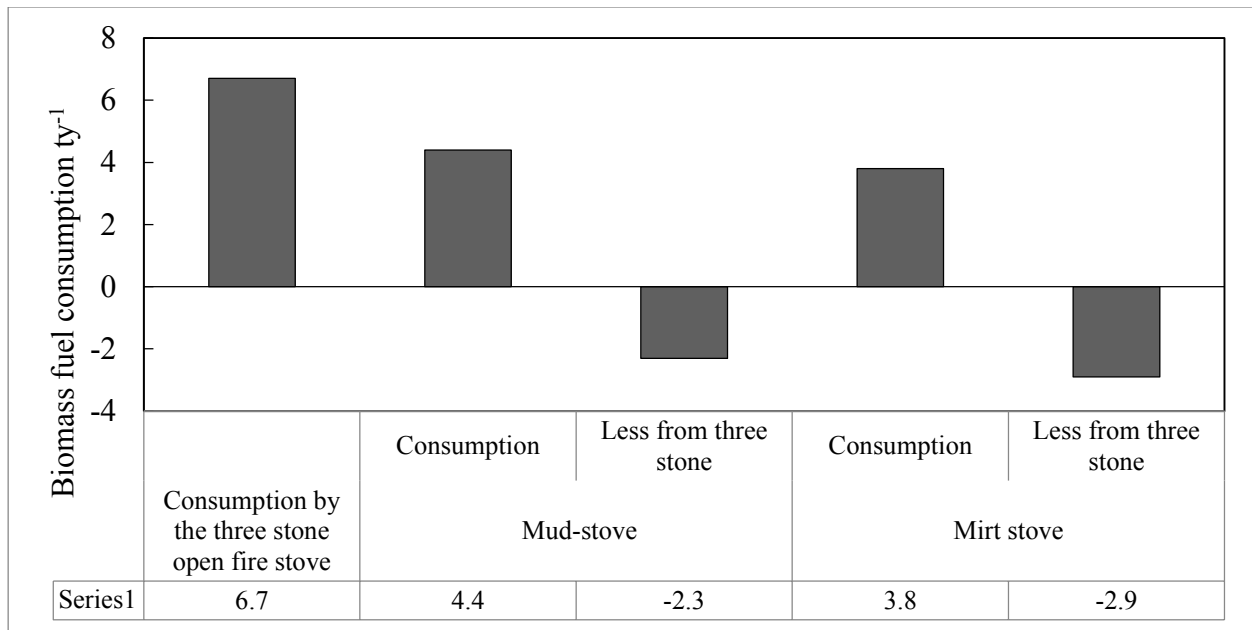


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