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Gasifier as a cleaner cooking system in rural Kenya

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Global demand for wood fuel energy is high and rising due to population increases, particularly in sub-Saharan Africa, where firewood and charcoal are the main sources of cooking energy. Inefficient cooking techniques consume large amounts of fuel and create indoor pollution, with negative health impacts particularly among women and small children. Efficient cooking stoves can potentially save fuel and reduce the health risks of smoke in the kitchen. This study compared the ease of use, energy consumption, fuel use efficiency and gas and particle emissions of a small-scale gasifier cooking stove with that of a traditional three-stone stove and an improved Hifadhi stove in a smallholder farming setting in Kenya. This was done by participatory evaluation of these cooking techniques by women on smallholder farms, assessing fuel consumption, time used in cooking and indoor air concentrations of carbon monoxide and fine particulate matter. It was found that compared with traditional and improved cooking stoves, the gasifier domestic cooking system saved 27–40% of fuel, reduced cooking time by 19–23% and reduced emissions by 40–90%. Thus the gasifier system has potential to alleviate energy and time poverty among small-scale farmers, while improving kitchen air quality. These new findings can assist in development of cleaner biomass cooking technologies in developing countries. Women who cooked using the gasifier preferred it to current cooking practices due to perceived benefits. Thus the gasifier is appropriate for rural areas; it constitutes a cleaner cooking system that saves fuel, produces charcoal for another round of cooking, cooks rapidly, and reduces indoor air pollution from cooking with biomass fuel. However, there is a need to improve the design to make it more stable and safer.

1. Introduction

Wood is an important source of energy that has been used for millennia for cooking, boiling water, lighting and heating (WHO, 2006). Today about 2.5 billion people depend on biomass energy for cooking and heating, with 87% of this energy being provided by wood (IEA, 2006). In sub-Saharan Africa (SSA), more than 90% of the population relies on firewood and charcoal derived from wood as a primary source of domestic energy (IEA, 2006), but wood fuel has been criticised for its negative impacts on the environment and indoor health (Bailis et al., 2007), which has resulted in policies and campaigns to discourage its use (AFREA, 2011). However, the proposed healthier and more environmentally friendly energy alternatives such as biogas, hydropower and solar energy are more costly and not affordable to the poor. Thus despite health concerns, the demand for wood-based energy is expected to remain high (Bailis et al., 2007). Furthermore, households often select different fuels or stove types for a particular task due to their individual cost-effectiveness and efficiency characteristics (Martins, 2005). The current inefficient cooking techniques used in the developing world have negative health impacts. Poor combustion efficiency in cooking stoves converts wood fuel into particulate matter, carbon monoxide (CO) and other gases that are responsible for health problems associated with indoor air pollution (Edwards et al., 2003). Globally, over 4 million deaths occur annually from illnesses related to the smoke generated by indoor combustion, which mainly affects women and small children (Lim and Vos,

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2012). Coughing, sneezing and headaches are common among women who work in smoky kitchens, while bronchitis, lung cancer, asthma and tuberculosis have also been linked to smoke from indoor combustion (WHO, 2006). Another severe disadvantage is that collecting firewood from off-farm sources physically stresses women, who risk head, spinal and leg injuries from carrying loads usually of about 30 kg over long distances (Gitau and Njenga, 2015).

Some of these health impacts can be reduced by the use of improved cooking stoves because they save fuel, which reduces the physical risks of collecting firewood. For example, a study on households in Ethiopia showed that switching from the traditional three-stone cooking stove to an improved model allowed households to reduce consumption of firewood by 20–56% (Duguma et al., 2014). Ochieng et al., 2013 found that a rocket mud stove, reduced fuel consumption by 34% compared with the three-stone stove. In Khairatpur village in rural India, an improved cooking stove was found to have an annual consumption of fuel which was 41% less than that of a traditional cooking stove (Singh et al., 2015). In the same study, a social survey revealed that most of the women in the village found the improved stove better than the traditional stove in terms of handling, reduced emissions, easier cooking and time and fuel efficiency. The increased use efficiency of available wood fuels may reduce the need to use unsafe sources of fuels such as plastic bottles and plastic basin (Gathui and Ngugi, 2010).

The use of improved cooking stoves may also reduce greenhouse gas and particle emissions. In Ethiopia, for example, improved cooking stoves were estimated to reduce CO_2 emissions by 0.45–2.45 tonnes $year^{-1}$ for each household compared with traditional three-stone stoves (Duguma et al., 2014). Emissions of various pollutants in Khairatpur village in rural India were found to be reduced by over 30% following use of the improved cooking stove (Singh et al., 2015). In the mid-hill region of Nepal, indoor concentrations of $PM_{2.5}$ and CO were found to be reduced by 63.2% and 60.0%, respectively, after one year of using the improved stove (Singh et al., 2012). Worldwide, many efforts have been made to increase the dissemination of improved cooking stoves, an agenda driven by concerns over greenhouse gas emissions and the local environment degradation caused by excessive demand for wood fuel. However, little attention has been paid thus far to the reduction of indoor health impacts that could be achieved through the use of improved cooking stoves.

Gasifier cooking stoves are a recent innovation of a better type of improved cooking stove that has started gaining attention as a new application for the production of heat for household cooking in the developing world (Torres-Rojas et al., 2014). The gasifier cooking stoves are gas-burners that produce their own gases from dry solid biomass. Gasification of biomass at temperatures between 700 and 1000 °C has been applied in small-scale and large-scale production of heat and electricity. Gasifiers transform firewood into energy in four stages, namely drying, pyrolysis (carbonisation), gasification and gas combustion. Gasification and combustion of gaseous fuel is cleaner than open air combustion of fuel wood (Raman et al., 2013). Gasifier cooking stoves produce low emissions, use little fuel and convert the biomass into charcoal, which can be used for cooking in the open air or for soil amendment. Gasifier cooking stoves can use various fuels, including firewood, but also crop residues such as maize cobs and coconut husks. They are promoted because they are energy efficient; compared with a three-stone stove, a pyrolitic cooking stove tested in one study reduced fuel consumption by 27% and also produced charcoal that could be used for other purposes (Torres-Rojas et al., 2014). Besides serving as fuel for cooking, charcoal can be used as “biochar” in soil to sequester carbon and improve soil fertility (Jeffery et al., 2013). Research on the benefits of gasifier cooking stoves has focused to date on their energy efficiency. They are also potentially healthier, but information is lacking on the health impacts of using gasifiers for domestic cooking.

The aim of the study, the findings of which are presented in this paper, was to compare the performance of a small-scale gasifier cooking stove with that of a traditional stove and an improved cooking stove under realistic household conditions. To this end, a participatory research method was selected and applied with the active participation of local women, who used the three categories of cooking stoves in situ in their houses on smallholder farms in Kenya. Within that context, fuel consumption, fuel to charcoal conversion efficiencies, time used in cooking, ease of use and indoor air concentrations of CO and fine particulate matter ($PM_{2.5}$) were compared for the three stove types. The gasifier cooking stove was chosen to establish the potential for cleaner cooking systems that enhance energy efficiency and reduce indoor air pollution among smallholder farmers while producing additional cooking fuel, hence contributing to addressing energy poverty. The charcoal produced from the gasifier cooking stove can also be used in soil improvement on participants' smallholder farms (Röing de Nowina et al., forthcoming). The findings presented in this paper are from the energy component of a research project on the potential benefit of biochar to smallholder farmers in Kenya.

As wood-based energy is still the most commonly used fuel for cooking in Sub-Saharan Africa (SSA) despite its impacts on the environment and health, the most effective way to make it sustainable is to develop cooking systems that address fuel consumption and the health problems associated with indoor air pollution. The choice of gasifier cooking stove for the study was based on its efficiency in use of biomass fuel. For instance, recent cooking stove testing by the United States Environmental Protection Agency USEPA has provided evidence that micro-gasifier cook stoves are currently the cleanest and most efficient options for utilizing solid biomass fuels for cooking (Roth, 2014). Further systematic emissions testing (using WHO-recommended indicators) considers gasifier cooking stoves as being Tier 3 category, which is nearly as clean as cooking with Liquid Petroleum Gas (LPG), which is in Tier 4 (Roth, 2014). The three-stone stove is at Tier 1.

2. Materials and methods

The following section explains where the study was carried out, the materials and methods used, and the components of the study and how they were implemented.

2.1. Study area

The study was carried out in Kibugu (Embu County) about 120 km north-east of Nairobi. Embu county is located on the slopes of Mt. Kenya and has a population of 300,000 (KNBS, 2010). Farming activities in Embu include cultivation of maize (*Zea mays*) for household use and production of commercial crops such as tea (*Camellia sinensis*), coffee (*Coffea arabica*), khat (*Catha edulis*) and macadamia nuts (*Macadamia* spp.) as well as woody species that provide firewood. In addition, G*revillea robusta*, a tree widely planted on farms for shading coffee and tea plantations, supplies domestic firewood and timber for home use and income generation (Lengkeek and Carsan, 2004). Virtualy all households in Embu use firewood for cooking and over 70% of the population sources it from trees on their own farms (Mahmoud et al., forthcoming). The traditional three-stone stove is the most commonly used cooking stove.

2.2. Gasifier cooking stoves

Four types of gasifier cooking stoves that included; one portable iron, two portable galvanized steel and a stationary clay gasifier were considered as potential candidates for comparison in the experiment. The selection was based on two criteria that are important for adoption: ease of use and purchase cost. The selected gasifier was a portable galvanised steel, natural "Top-Lit UpDraft" (TLUD) model that uses biomass fuel (Anderson and Reed, 2004). The gasifier has three parts: a 15 cm high gas combustion chamber on top, a 22 cm high fuel canister in the middle, and a 6 cm high air entrance at the bottom (Fig. 1). When ignited at the top, primary air enters at the bottom and moves up through the packed bed of fuel. Secondary air enters from below into the top section, where it mixes with the gases for combustion.

Two stationary stoves, an improved Hifadhi cooking stove and the traditional three-stone stove, were used as controls in the experiment (Fig. 2). The Hifadhi stove has two compartments comprising an air entrance at the bottom with a space for fuel and a combustion chamber on top. The inner walls are made of cement, which are enclosed by an outside layer of galvanised steel (Fig. 2). It was selected for testing as it is produced locally and distributed to farmers by the Climate Pal-Kenya project.

(http://www.livelihoods.eu/portfolio/climate-pal-kenya/). The three-stone stove has three stones on which cooking pots are placed and firewood is burned in between the stones (Fig. 2).

2.3. Meal and fuelstock

The type of food cooked in the tests was a traditional meal of two components which are cooked separately and consecutively and eaten all over Kenya: maize flour, commonly known as *ugali*, and a local cabbage variety known as kale (*Brassica oleracea*), which is used as a vegetable in a dish called *sukuma wiki*. The three types of fuels used to cook the meal were *Grevillea* prunings, maize cobs, and coconut shells (*Cocos nucifera*). These three fuels were selected because: (i) *Grevillea* is the most common tree species grown by Kenyan farmers; (ii) maize is the primary staple food for most Kenyans (Short et al., 2012) and (iii) coconut which, although not grown in Embu, is an important tree crop for 2.4 million people on the Kenyan coast (Batugal et al., 2005). Based on local knowledge, these three types of feedstock are either currently or have potential to be important cooking fuels.

2.4. Selection of households

A sample of five households was randomly selected using MATLAB from a group of 57 households interviewed during the baseline survey for the project (Mahmoud et al., forthcoming). Discussions on the objectives, activities and community involvement in the participatory cooking experiment were held between the research team and the five households at the home of one of the selected farmers. The experiment made two different initial comparisons (Table 1). First, it compared the performance of the three types of cooking stoves while using *Grevillea* prunings and then it compared the effect of the three types of fuel for the gasifier cooking stove. The experiment was then reorganized to randomize the date when the team tested the three stoves and the three sources of fuel, and the new schedule devised was discussed and agreed with the women in the five selected households.

2.5. Cooking tests

The participatory cooking test involved cooking 1 kg of Soko brand maize flour (*ugali*) in 2.1 L of water (first dish) and then cooking 0.75 kg of *sukuma wiki* made from kale, tomatoes and onions purchased locally (second dish). These amounts were selected because they are considered sufficient to provide a meal for the standard Kenyan household of five people (KNBS, 2009). Food preparation involved washing and chopping the kale, tomatoes and onions into small pieces, which was done prior to commencement of cooking. The meal was cooked for dinner between 3 and 6 pm in each household using the types of cooking stoves and fuel types shown in Table 1. On 25 consecutive days

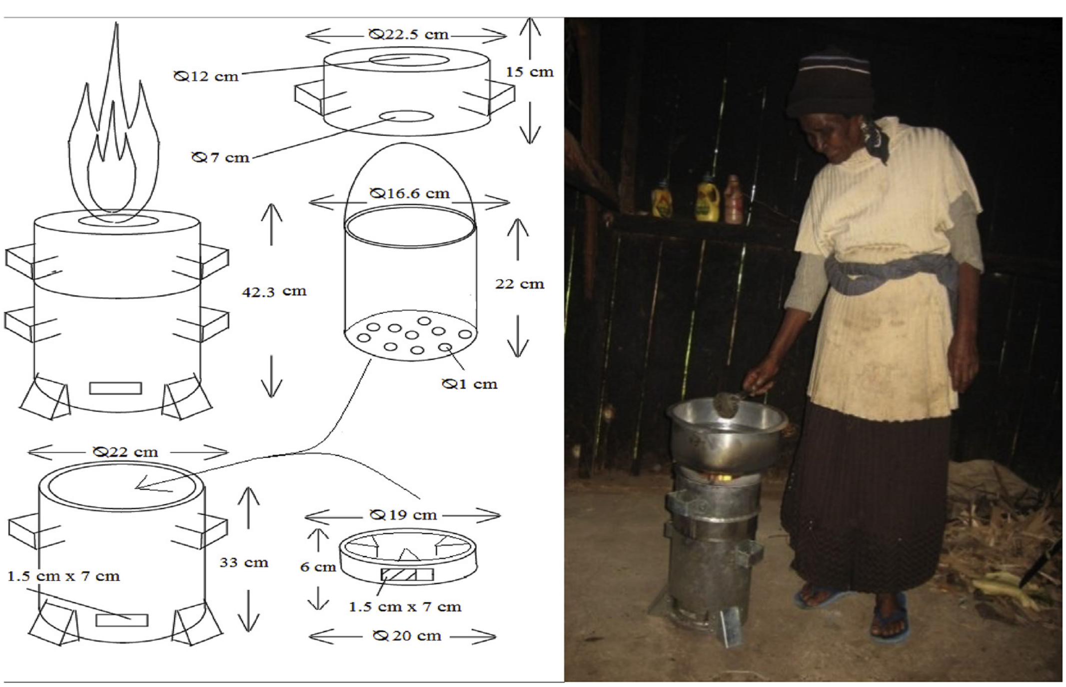

Fig. 1. (Left) Technical drawing (credit: N. Achour) and (right) photo (credit: M. Njenga) of the galvanised steel gasifier cooking stove used in the experiment.

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Fig. 2. Left: improved Hifadhi cooking stove and (right) traditional three-stone cooking stove used in the experiments.

(March–April 2014), a total of 25 tests were carried out, five tests in each household.

Female members of the household carried out the cooking experiment in the presence of the research assistants. Before each test, the weight of fuel fed to the stove was determined. Fuel preparation involved cutting the *Grevillea* prunings, which were about 3 cm in diameter, into pieces 22 cm long for use in the gasifier. From the same heap of *Grevillea* prunings, larger pieces of firewood of about 10 cm in diameter and about 70 cm long were picked for use in the improved stove and three-stone stove. The initial fuel used was weighed. The improved stove and three-stone stove were lit following the common practice of igniting them inside the house due to the nature of loading firewood, while the gasifier cooking stove was lit outside as it is portable and has a canister that holds the fuel in place. *Grevillea* leaves were used to ignite fuel in the gasifier, which was brought into the kitchen after the fuel had caught fire and stopped smoking. The same procedure for lighting the gasifier was used when any additional fuel was added if the fuel had been converted to charcoal (in the gasifier) before the food was ready. The remaining charcoal was harvested after the flame went off in the gasifier, using heatproof gloves, put in a pot covered with a lid to stop oxygen supply and terminate combustion and weighed once it had cooled (Helander and Larsson, 2014). For the improved (Hifadhi) stove and the three-stone stove, the amount of fuel left after cooking was weighed.

Fuel used in cooking with the gasifier was calculated as percentage of gross or net fuel used. Gross fuel is the amount of fuel used including the charcoal produced, while net fuel is the fuel used minus the charcoal produced. During the experiment, measurements were made of the time taken to cook the meal and the concentrations of CO and $PM_{2.5}$ (see below).

2.6. Properties of the kitchen

Kitchens A–E in Table 2 are those in the five randomly selected households described in Section 2.4 and generally represent the type found in households in the study area. The dimensions and ventilation of a kitchen influence the build-up of concentrations of toxic substances. Table 2 summarizes the dimensions and the ventilation infrastructure (doors and windows) for the five kitchens used in the experiment. Kitchens A to D were buildings separate from the main house, with doors opening to the outside. Kitchen E was the only one with a chimney for ventilation, and was located inside, with a door opening into the main house. As the aim was to take measurements similar to normal practice, it was left to the cooks to decide on whether to open or close the doors and windows. All cooks kept the doors and windows open during all sessions of the cooking experiment.

2.7. Measuring emissions

The concentrations of CO and $PM_{2.5}$ in each kitchen were measured throughout the cooking period. The CO concentration was measured at 10 s (s) intervals using an EL-USB-CO carbon monoxide data logger (DATAQ Instruments, 603-746-5524). The $PM_{2.5}$ level was recorded once per minute using a UCB PM meter (Berkeley Air Monitoring Group, SN:1311). Both instruments were fixed 1.5 m above and 1 m to the side of the cooking pot, simulating the position of the cook.

2.8. Determination of combustion properties

The fuel used for cooking and the resulting charcoal were weighed and analysed for calorific value, percentage of fixed carbon, moisture content, volatile matter and ash content at Kenya Forestry Research Institute (KEFRI) following procedures described by Findlay (1963). Calorific value was analysed using a bomb calorimeter and is reported on a dry weight basis. Moisture content was measured by drying a 5 g sample in an oven at 103 °C for 12 h and expressed as the percentage loss of weight of the original sample. To measure volatile matter, the oven-dried sample was incinerated in a muffle furnace for 7 min at 900 °C and weighed

Table 1
Combinations of cooking stoves and fuel types tested in the experiment.

Type of cooking stove	Maize cobs	Coconut shells	*Grevillea* prunings
Gasifier cooking stove	√	√	√
Improved Hifadhi cooking stove			√
Traditional three-stone cooking stove			√

Table 2
Size (m^2) of the test kitchens (A–E) used in the study and the dimensions of doors and windows, and presence of chimneys.

Kitchen	Kitchen	Doors	Windows	Chimney
A	3.78	0.86	0	No
B	7.38	1.03	0.14	No
C	5.74	0.72	0	No
D	15.0	1.42	0.18	No
E	7.81	1.52	0	Yes

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after cooling. Volatile matter was expressed as the percentage weight loss of the original sample. To determine ash content, the cooled incinerated sample was returned to the muffle furnace at 900 °C for 1.5 h, cooled and the weight expressed as percentage of the weight of the original sample. Fixed carbon was calculated by subtracting moisture content, ash content and volatile matter from 100%.

2.9. Household perceptions of the gasifier cooking technique

A questionnaire with open-ended questions was used to interview the cooks and assess their perceptions of the gasifier and the two other types of cooking stoves. Information from the interviews was used in developing criteria for participatory ranking to compare: (i) the three cooking stoves using *Grevillea* prunings and (ii) the three types of fuel used in the gasifier cooking stove. The ranking was carried out individually by each of the five women, who were given 50 grains of maize as counters and asked to allocate them among the three cooking stoves. The mean was calculated, and the exercise was then repeated for the three fuel types. Use of maize grains allowed effective ranking by the women irrespective of their literacy level.

2.10. Data management and analysis

Data were analysed using Microsoft Excel software for descriptive statistics. Significant differences between the mean values for combustion properties, fuel and time were tested using the non-parametric Kruskal–Wallis test in R statistical computer package for emissions (Dalgaard, 2002). The tests compared the three different cooking stoves and the three different fuelstocks. The significance level was set at $p < 0.05$.

3. Results and discussion

This section presents data from the study and discussions on the significance of the results of the work.

3.1. Combustion properties of the feedstock

Calorific value is the energy content per unit mass and fuel type, and a high value is desirable for cooking (Nirmal et al., 2011). Among the three fuel types tested here, there was a significant difference ($p < 0.05$) in calorific value, fixed carbon and moisture content. There was also a significant difference ($p < 0.05$) in volatile matter and ash content between coconut shells and maize cobs, and between *Grevillea* prunings and maize cobs. For ash content, a significant difference ($p < 0.05$) was found between coconut shells and maize cobs, and between *Grevillea* prunings and maize cobs. Coconut shells had a somewhat higher calorific value and fixed carbon content and a lower moisture content and volatile matter content than maize cobs and *Grevillea* prunings (Table 3).

The fuelstock used in the experiment was well dried in the sun and the moisture content was below the recommended 10%. The quality of fuel for cooking is higher when the ash content is low, as ash is a non-combustible mineral residue. High fixed carbon results in a longer burning period (Fuwape and Akindele, 1997), a desirable property of cooking fuel. This property depends on type of biomass; the two wood-based fuelstocks had higher fixed carbon than the maize-based feedstock.

3.2. Time spent in cooking ugali and sukuma wiki using different fuel types and cooking stoves

The time taken for cooking a meal included the time for preparing the food, lighting the cooking stove and emptying and refilling it after the feedstock charred, and the time when the food was on the stove. The gasifier took the shortest time to bring water to the boil, irrespective of fuel type (11 min), followed by the three-stone stove (13 min) and the improved stove (17 min). Total time taken to cook the meal using *Grevillea* prunings was faster with the gasifier (42.4 min) than with the improved stove (55 min) or the three-stone stove (51.6 min). Cooking with *Grevillea* prunings was faster than cooking with maize cobs (50 min) or coconut shells (47 min). When using *Grevillea* prunings, lighting the gasifier was slower (10.8 min) than lighting the improved stove (3.8 min) or the three-stone stove (7.6 min) (Fig. 3). This could be associated with several factors, such as women's unfamiliarity with the gasifier and the arrangement of the fuel.

When cooking with *Grevillea* prunings, after the food was ready, there was an extra 19 min of energy supply as it took 51 min for the fuel to char. During the experiment, water was boiled during the extra minutes to ensure that the gasifier was covered for appropriate charring. The time taken to light the gasifier lengthened the cooking period for coconut shells, while refuelling delayed cooking with maize cob.

To maximize the benefits of cooking with different types of fuel using the gasifier, it is advisable to consider the length of time different meals take to cook. For instance, crop-based residues can be used for meals that take a short time to cook, while woody biomass is better for those that take a long time. In this way, the household cooking energy requirement can be met by using different types of biomass for different purposes. By switching cooking technologies from the commonly used three-stone cooking stove to a gasifier, women would save 18% of the time spent cooking meals.

3.3. Fuel use

Access to cooking energy is a challenge that could be addressed through improved cooking technologies. Cooking with a gasifier reduced the fuel use compared with the other stoves. A pair-wise comparison revealed significant differences ($p < 0.05$) between any combination of two cooking stoves in terms of amount of fuel used to cook the meal when considering the charcoal produced in the gasifier. Cooking with the gasifier produced charcoal with an average yield of 21% (by weight), as indicated in Table 4. Coconut shells produced more charcoal than maize cobs and *Grevillea* prunings (Table 4). If the charcoal produced during cooking is considered to be an additional product, cooking with the gasifier saved 40% fuel compared with the three-stone cooking stove and 27% compared with the improved cooking stove. If the charcoal produced by the gasifier during cooking is not considered, a 27% fuel saving was achieved compared with the three-stone stove and 10% compared with the improved stove.

3.4. Emissions from cooking ugali and sukuma wiki using different stoves and fuel types

The gasifier gave the lowest indoor air concentrations of CO and $PM_{2.5}$, followed by the three-stone cooking stove, while the Hifadhi improved cooking stove gave the highest concentrations which could be associated to poor air circulation in the combustion chamber in latter stove. Cooking with a gasifier reduced the indoor air concentration of CO by 52% and 45% compared with the improved stove and three-stone stove, respectively (Fig. 4). Coconut

Table 3
Combustion properties of the maize cobs, coconut shells and *Grevillea* prunings used in the experiments.

Feedstock	Calorific value (kJ/g)	Fixed carbon (%)	Moisture content (%)	Volatile matter (%)	Ash content (%)
Maize cob	18.9 ± 0.08	4.8 ± 0.35	9.0 ± 0.13	82.4 ± 0.36	3.8 ± 0.20
Coconut shells	21.0 ± 0.04	9.5 ± 0.14	6.6 ± 0.03	79.0 ± 0.15	5.0 ± 0.26
Grevillea prunings	19.6 ± 0.03	6.4 ± 0.15	9.7 ± 0.07	79.0 ± 0.06	5.0 ± 0.06

±standard error.

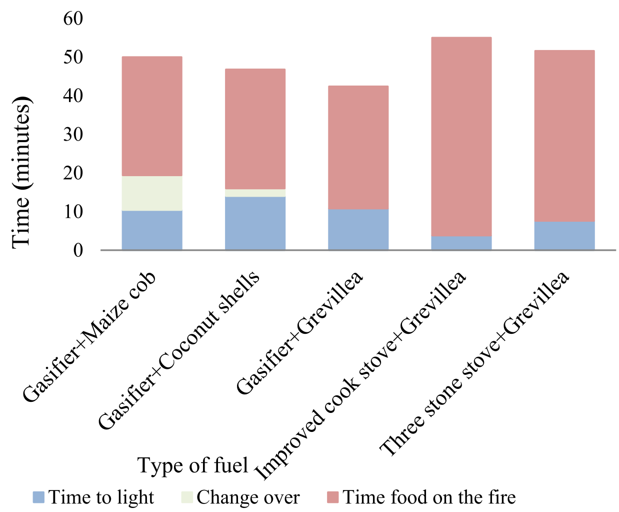

Fig. 3. Time (min) taken to cook a meal of *ugali* and *sukuma wiki* using the different cooking stoves and fuel types.

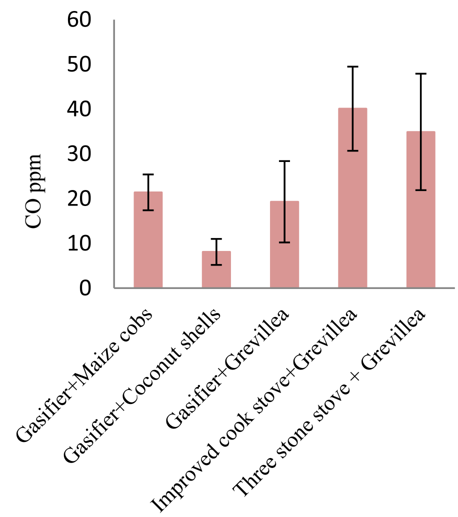

Fig. 4. Concentration of CO in the kitchen during cooking tests using different stoves and fuel types.

shells caused the lowest CO concentration, followed by *Grevillea* prunings, while maize cobs caused the highest concentration. There was a significant difference ($p < 0.05$) in concentrations of CO between the cooking stoves. Similarly, the gasifier reduced the concentration of $PM_{2.5}$ by 94% and 89% compared with the improved stove and three-stone stove, respectively, and there was a significance difference ($p < 0.05$) between the stoves (Fig. 5). $PM_{2.5}$ is a common useful indicator of the risk associated with exposure to a mixture of pollutants from diverse sources (Lim and Vos, 2012).

These results confirm the reduction in indoor air pollution brought about by the types of improved cooking stoves reported by Singh et al. (2012) in their study at the mid-hill region of Nepal. In that study, the $PM_{2.5}$ concentration was more than halved, from 2070 $\mu g/m^3$ when the households used a traditional cooking stove to 760 $\mu g/m^3$ when they switched to using an improved stove. In the same study, the mean CO concentration was reduced from 21.5 ppm to 8.62 ppm. The gasifier used in the present study showed better performance in reducing indoor concentration of $PM_{2.5}$ than the improved stove tested here and that used in the study in Nepal, though other factors such as type of stove, kitchen conditions and fuel types may have had effects.

The gasifier produces gases which are trapped in the gas combustion chamber and burn at high temperature, which in this study was 745 ± 5 °C while using *Grevillea* prunings. The flame temperature in the improved stove and three-stone stove while using *Grevillea* prunings was 611 ± 25 °C and 614 ± 33 °C, respectively, and there was a significant difference ($p < 0.05$) between the gasifier and improved stove and between the gasifier and the three-stone stove.

The gasifier is portable and it is common practice in SSA for portable biomass fuel stoves to be lit outside until the fuel catches fire well and has stopped smoking. This practice allows the initial phase of burning fuel to take place outside the kitchen, hence reducing indoor air pollution as this phase causes higher emissions (Loo and Koppejan, 2009). It is important to note that the emissions from lighting the gasifier outside the kitchen cause outdoor air pollution, including release of PM and CO. The CO concentration from the gasifier met the critical limit of 30 ppm allowed for human exposure for 1 h (US EPA, 2002). Household survey results indicated that half the households were aware of health risks from indoor air pollution, which caused sneezing, running nose, eye problems and coughing (Mahmoud et al., forthcoming). The gasifier could

Table 4
Amount of fuel used in cooking *ugali* and *sukuma wiki* on the gasifier cooking stove with three types of fuel and on the improved stove and the three-stone stove using *Grevillea*, and amount of resulting charcoal produced by each.

Type of cooking stove and fuel	Fuel use during cooking and charring period including charcoal (g)	Fuel use during cooking and charring period minus charcoal (g)	Fuel use to cook a meal including charcoal (g)	Fuel use to cook a meal minus charcoal (g)	Charcoal produced (g)	Charcoal yield as (%) of fuel used
Gasifier + Maize cobs	1514 ± 131	1197 ± 105	1249 ± 99	989 ± 83	317 ± 31	21
Gasifier + Coconut shells	1654 + 165	1264 ± 124	1160 + 79	885 ± 53	390 ± 44	24
Gasifier + Grevillea	1820 ± 84	1471 ± 70	1137 ± 27	918 ± 61	349 ± 16	19
Improved stove + Grevillea	NA	NA	1260 ± 61	1260 ± 60	None	None
Three-stone stove + Grevillea	NA	NA	1565 ± 127	1565 ± 127	None	None

±standard error; NA[b] not applicable as the stove does not char fuel into charcoal.

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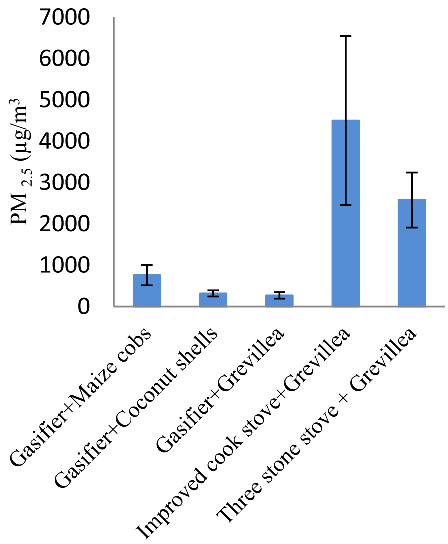

Fig. 5. Concentration of $PM_{2.5}$ in the kitchen during cooking tests using different stoves and fuel types.

contribute to mitigating these health challenges. This study confirms results of previous research showing that improvements in biomass cooking stoves could improve indoor air quality (Grietshop et al., 2011; Arora et al., 2013; Duguma et al., 2014).

The low emissions from the gasifier and its other benefits of saving fuel and cooking time confirm that development and adoption of improved cooking stoves can be an important measure in achieving sustainable energy security and food security in developing countries. Achieving sustainable use of wood fuel for cooking purposes in developing countries is a more feasible policy alternative than a large-scale switch to liquid fuels or electricity with the associated challenges related to infrastructure, economics and local culture (Maes and Verbist, 2012). This responds to household demand for efficient practices that save time, reduce smoke, reduce costs and save firewood, as indicated by all households in the survey (Mahmoud et al., forthcoming).

3.5. Women's perceptions of the gasifier cooking stove

After cooking with all three cooking stoves, women ranked the gasifier highest in terms of saving cooking time (58%), production of low emissions during cooking (54%) and saving fuel (52%) (Fig. 6a). These qualitative evaluation results were in line with the quantified results of the participatory cooking tests. Women thought that adopting the gasifier would help cook food faster and reduce the amount of firewood they needed, hence freeing time for other activities and reducing the burden of searching for firewood. They also pointed out that small pieces of firewood can be used in cooking with the gasifier and hence the prunings from trees would be a good source of cooking fuel. However, the women mentioned that one of the limitations of the gasifier was failure to produce sufficient warmth to heat space during cooking, which the three-stone stove does. They also noted that the gasifier requires the firewood to be into small pieces of below 1 foot to fit in the fuel canister, causing extra labour that is not required for the three-stone stove (Fig. 6b).

A comparison of cooking with the three fuel types in the gasifier showed that they had to be handled differently. For instance, according to the women, although *Grevillea* prunings had to be cut into small pieces, they were easy to arrange in the gasifier stove while ensuring that some air spaces are left. However, coconut shells and maize cobs required no prior preparation. The women also ranked *Grevillea* prunings as the fastest in cooking the test meal, which validated the measurements taken during the participatory cooking tests. Cooking with maize cobs was reported to cause problems with smoke compared with *Grevillea* prunings and coconut shells. Successful design, production and adoption of improved cooking stoves were found to be possible by Jerneck and Olson (2015) in their study on community based co-production for cleaner cooking. Thus it is important to consider users' views when working to improve cooking stoves, as this may affect adoption. Adoption of the gasifier cooking stove may also be affected by a household's commitment to saving fuel and reducing indoor air pollution. This was found to be the case where leadership's commitment was a leading cause for implementing sustainable development (Ceulemans et al., 2015).

3.6. Implications of using a gasifier for domestic cooking on livelihoods and the environment

Use of a gasifier in domestic cooking will have multiple positive benefits for the livelihoods of the people and the environment, as discussed in this section. However, for these benefits to be realised, the functionality challenges identified here need to be overcome.

3.6.1. Addressing energy poverty

- *Diversified sources of cooking fuel:* the gasifier can use various types of biomass including tree prunings and crop residues, hence providing an opportunity to diversify sources of fuel for domestic cooking among small-scale farmers. The gasifier may suit farmers well, as it uses small amounts of fuel in the form of small pieces of wood (below 3 cm in diameter and 22 cm in length) that could be sourced from pruning of on-farm trees. This is possible as the majority of the households in the area source firewood from their farms (Mahmoud et al., forthcoming).

3.6.2. Poverty alleviation

- *Save income spent on cooking fuel:* Scarcity of fuel wood for cooking has resulted in families spending income to purchase firewood which was previously acquired for free (Duguma et al., 2014). As families can use tree prunings, twigs or crop residues, they will reduce their expenditure on cooking energy.
- *Assumption on income generation from sale of the gasifier:* If the gasifiers receive positive adoption, employment can be created and income generated from production and sale of the stove, leading to development in rural areas.

3.6.3. Environmental benefits

- *Save trees:* Reduced consumption of fuel and use of tree prunings could lead to trees being saved, hence mitigating climate change and reducing cutting of young trees and encouraging forest regeneration.
- *Sequestering carbon:* If the biochar produced in the gasifier stove is used as a soil amendment rather than to cook another meal, it will remain longer in the ground than the biomass would if burned or left to decompose. Thus biochar is a way to sequester carbon and mitigate climate change (Mekuria and Noble, 2013).

3.6.4. Health benefits

- *Reduced household air pollution:* Adoption of the gasifier would reduce indoor air pollution compared with the three-stone

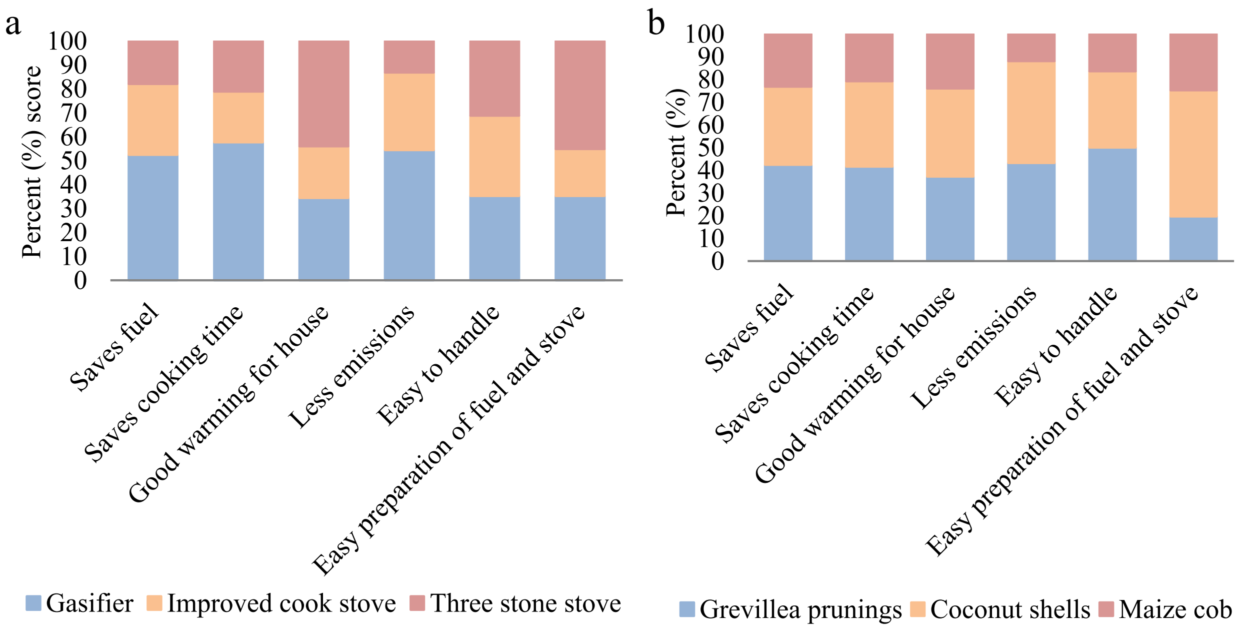

Fig. 6. Participatory ranking of (a) cooking stoves and (b) fuel types by women in Embu, Kenya based on experiences during cooking tests.

stove that is currently used by over 70% of the households in the area. This could reduce the premature deaths of women and children caused by household air pollution from cooking biomass energy, a risk factor ranked number two in attribution to death burden in eastern and southern sub-Saharan Africa (Lim and Vos, 2012). Moreover, in rural India, 52% of the women participating in the cooking stove study in Khairatpur village reported experiencing health problems due to cooking with traditional cooking stoves (Singh et al., 2015). In a study in the brackish water area of south-western Bangladesh, 98% of women had better health and lifestyle improvements by using an improved earthen stove (Alam et al., 2006). However, it is important to ensure that wood is dry, irrespective of the stove being used, as this reduces emissions (Arora et al., 2014).

3.6.5. Food and nutrition

- *Maintaining traditional nutritious food types:* Availability of fuel from various types of biomass will allow poor households to cook traditional nutritious food types that take a long time to cook and hence maintain the good nutritional status of their families.
- *Higher yields from biochar in soil*: The char produced in the gasifier stove can be used as biochar, a soil amendment that can have a beneficial impact on the yields of food produced on-farm (Biederman and Harpole, 2013). The impact on plant growth from amending local soils with biochar produced from locally available crop residues is being investigated in the other component of the research project on potential benefits of biochar to smallholder farmers in Kenya.

3.6.6. Improving women and children's well-being

- *Reduce burden*: The gasifier saves fuel and hence reduces the frequency with which women and children have to travel lengthy distances to forests and/or carry heavy loads of firewood. In Dadaab refugee camp in Kenya, switching from the three-stone stove to an improved cooking stove reduced the number of times women needed to walk for 4 h to a forest to fetch firewood from 5 to 3 per week (Bizzarri, 2010). This will reduce risks of injuries to the head, spine and legs that may occur from carrying heavy loads. It will also reduce women and children's energy expenditure, which is critical in a context where many children suffer stunting and many women have low Body Mass Index (BMI) (KNBS, 2010). *Save time*: Reduction in fuel consumption will result in saving time that could be used by women to increase their income, take on leadership roles in the community, learn new skills, grow additional crops, care for children and the elderly, improve their own health, support their community and benefit from rare leisure time. Children will also have more time for schooling and play.

3.6.7. Challenges that might limit adoption of the gasifier

- The gasifier cooking stove costs Ksh3000 (US$35), which small-scale farmers might find high compared with the traditional three-stone stove, which has no cost, but the long-term benefits of the gasifier are worth much more. There is a need for awareness raising on the benefits of the gasifier cooking stove, since the stronger the social demand for clean production, the stronger the likelihood that diffusion will occur (Montalvo, 2008). Further the gasifier cooking stove is a “persuasive technology” as it will alter the attitudes or behaviours of users (Blok et al., 2015) A study in rural Kenya found that over 70% of respondents were aware of improved stoves but the proportion os those using them was less than 29%, which they associated with the high cost of the stove (Githiomi et al., 2012).
- Functionality challenges faced included cooking with fuel that chars before the food is ready, which requires reloading. The galvanised wall becomes very hot, posing safety risks of causing burns; this can be solved by training women on appropriate use techniques and using an alternative material to fabricate the wall. The stability and height of the gasifier are also a concern, as it could topple over when stirring the food. Moreover, unlike the three-stone stove, the gasifier fails to heat space and does not allow roasting, e.g. of maize or potatoes. However, these two needs can be met by the charcoal that the gasifier produces.

Further design work to improve the stove should take these challenges into account.

4. Conclusions and recommendations

In participatory cooking tests, the gasifier stove used less time and fuel to cook a traditional meal and produced less CO and $PM_{2.5}$ than the improved stove and the three-stone stove. For these reasons, the women taking part in the cooking tests preferred the gasifier to their current cooking equipment. Moreover, the gasifier produced charcoal that can be used as additional fuel or as a biochar for soil amendment, a matter which needs further research. This study provides information on the benefits and challenges of gasifier cooking stoves, which can guide their further development and adoption. There is an opportunity for extending use of the gasifier as an efficient cooking system, consequently contributing to addressing energy poverty and health risks associated with domestic biomass energy in developing countries. The study concludes that the gasifier constitutes a cleaner cooking system that saves fuel, produces charcoal for further cooking, cooks relatively faster and reduces indoor air pollution from cooking with biomass fuel. It appears appropriate for rural areas. This study provides data on the performance of the gasifier cook stove, which strongly suggests that it should be further developed as a cleaner cooking option. The study recommends areas where improvement is needed in order to respond to women's cooking practices. The study suggests further research to assess its acceptability. These include cost, modifications to the fabrication of the system, and what behavioural changes in cultural practices are required if this technology is to be scalable.

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