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Quality of charcoal produced using micro gasification and how the new cook stove works in rural Kenya

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Abstract

Wood based energy is the main source of cooking and heating fuel in Sub-Saharan Africa. Its use rises as the population increases. Inefficient cook stoves result in fuel wastage and health issues associated with smoke in the kitchen. As users are poor women, they tend not to be consulted on cook stove development, hence the need for participatory development of efficient woodfuel cooking systems. This paper presents the findings of a study carried out in Embu, Kenya to assess energy use efficiency and concentrations of carbon monoxide and fine particulate matter from charcoal produced using gasifier cook stoves, compared to conventional wood charcoal. Charcoal made from *Grevillea robusta* prunings, *Zea mays* cob (maize cob) and *Cocos nucifera* (coconut shells) had calorific values of 26.5 kJ g⁻¹, 28.7 kJ g⁻¹ and 31.7 kJ g⁻¹ respectively, which are comparable to conventional wood charcoal with calorific values of 33.1 kJ g⁻¹. Cooking with firewood in a gasifier cook stove and use of the resultant charcoal as by-product to cook another meal in a conventional charcoal stove saved 41% of the amount of fuel compared to cooking with firewood in the traditional three stone open fire. Cooking with firewood based on *G. robusta* prunings in the traditional open fire resulted in a concentration of fine particulate matter of 2600 µg m⁻³, which is more than 100 times greater than from cooking with charcoal made from *G. robusta* prunings in a gasifier. Thirty five percent of households used the gasifier for cooking dinner and lunch, and cooks preferred using it for food that took a short time to prepare. Although the gasifier cook stove is energy and emission efficient there is a need for it to be developed further to better suit local cooking preferences. The energy transition in Africa will have to include cleaner and more sustainable wood based cooking systems.

1. Introduction

According to the World Energy Outlook, in 2013 more than 2.7 billion people—38% of the world's population, relied on the traditional use of solid biomass for cooking, typically using inefficient stoves in poorly ventilated spaces (IEA 2016). In Sub-Saharan Africa (SSA), more than 90% of the population relies on

firewood and charcoal (woodfuel) for cooking and heating (IEA 2006). In Kenya, about 90% of rural households and 7% of urban households, giving an average of 70% of households, use firewood (MoE 2002). The main sources of firewood are state forests and on-farm, either as live wood or deadwood, while the third source is purchasing (Duguma *et al* 2014). The source of the purchased wood could either be

from farms and/or forests. As it is a locally available renewable energy source, woodfuel is expected to remain a major energy source in SSA for the foreseeable future (IEA 2014). There is a need for a transition to energy conversion technologies that use the available and biomass resources more efficiently, while reducing emissions of pollutants, whereby the negative impacts on health and climate of traditional biomass use can be reduced. New conversion technologies will be an important part of such an energy transition.

Women and girls travel long distances carrying heavy loads of firewood, which is wearisome and wastes time, costing them other opportunities (Egeru *et al* 2014). Forests have also receded, restricting firewood availability and meaning firewood collectors have to travel longer distances (Duguma *et al* 2014). This activity is life threatening, as women can suffer spine, head, leg and arm injuries. As deadwood becomes scarce, it results in the felling of young trees for firewood, affecting the regeneration of forests. The increasing scarcity of cooking fuel is forcing many households to abandon traditional meals, despite their nutritional benefits, and some households resort to using unsafe sources of fuel such as plastic waste (Gathui and Ngugi 2010). For households to eradicate poverty, achieve food security, improve health and reduce the burden on women and girls, while conserving the environment in SSA, there is a need for the development of innovations that meet people's cooking and heating energy needs and preferences.

Inefficient cook stoves escalate the demand for firewood—a challenge which can be addressed through cleaner cooking solutions that save fuel. In Ethiopia, households switching from a traditional three stone open fire to an improved model reduced the amount of firewood used by 20%–56% (Duguma *et al* 2014). Another study carried out in rural Kenya showed that the use of a rocket mud stove reduced fuel consumption by 34%, compared with the traditional three stone open fire (Ochieng *et al* 2013). In Khairatpur village in rural India, an improved cook stove was found to reduce the annual consumption of fuel by 41% compared with the traditional cook stove (Singh *et al* 2015). In our previous work in rural Kenya, a gasifier cookstove was shown to save up to 41% of fuel (Njenga *et al* 2016).

Inefficient cook stoves are also linked to escalated indoor air pollution, though some energy-efficient cook stoves have relatively high emissions (Njenga *et al* 2016). Globally, over 4 million annual deaths from illnesses associated with smoke from kitchens are recorded (Lim and Vos 2012). Over 50% of the deaths of children under 5 years due to pneumonia by acute lower respiratory infections (ALRI) are associated with particulate matter. Improving cooking conditions is a significant challenge as 2.6 billion people are without clean cooking facilities and more than 95% of these people live in SSA or developing Asia, with 84% of

these in rural areas (IEA 2013). Improved cook stoves have the potential to address health problems associated with smoke in the kitchen. For instance, emissions of various pollutants in Khairatpur (India) were found to be reduced by over 30% after using the improved cook 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). In rural Kenya, CO and PM_{2.5} were reduced by 45% and 89% respectively when using a gasifier cook stove instead of the traditional three stone fire (Njenga *et al* 2016).

Charcoal is a common type of wood-derived fuel used in developing countries, and it is used by 82% of urban and 34% of rural households in Kenya (MoE 2002). Technologies for converting wood to charcoal are underdeveloped, since, for instance, 99% of charcoal producers use traditional earth mound kilns in Kenya which have an approximate 14% wood to charcoal conversion efficiency by weight (Mutimba and Barasa 2005, Okello *et al* 2001). This results in land degradation and air pollution (Bailis *et al* 2005). Application of micro gasification in domestic cooking presents an opportunity to produce charcoal efficiently and with reduced emissions, while efficiently cooking with wood and other biomass fuels. These kinds of innovations are critical in making woodfuel sustainable.

Micro gasification using gasifier cookstoves present a win-win-win opportunity not only to save fuel and reduce emissions, but also to produce charcoal at the household level for domestic use (Njenga *et al* 2016). The technology and types of feedstock applied in charcoal production using gasifier cook stoves differs from the traditional charcoal making processes, and it is therefore necessary to establish its quality as a cooking fuel. Furthermore, an understanding of the factors determining households' decisions to switch from traditional three stone open fires to gasifiers is necessary. The charcoal produced using the gasifier cook stove can either be used as a fuel or be used as a soil amendment, and when it is put to this use, the material is known as biochar (Jeffery *et al* 2013). This could potentially create a win-win-win situation with regards to improved fuel efficiency, health and soil fertility.

This article is based on results that are part of the work the authors are carrying out in a long term transdisciplinary study that tackles issues of energy, soil fertility and health at a smallholder farmer's level, when converting to gasifier cookstoves that produce charcoal. Even though the major interest of the project is in the use of biochar as a soil amendment, it is important to investigate the attractiveness of the alternative use of the charcoal as fuel. The objective of this article is to evaluate energy use efficiency and indoor air concentrations of carbon monoxide (CO) and fine particulate matter (PM_{2.5}) produced from

various types of organic residues using a domestic gasifier when cooking with charcoal. Moreover, factors affecting the adoption of the cook stove in a rural area in Kenya are investigated.

2. Materials and methods

Cooking tests were performed to compare the combustion properties, energy use efficiency and concentrations of CO and PM_{2.5} when cooking with charcoal produced in a gasifier cook stove, as compared to charcoal sourced in the market and firewood used in a three stone open fire or a gasifier. The results from use of firewood (*Grevillea robusta*) in the three stone open fire and gasifier have previously been reported by Njenga *et al* (2016) and are included here for comparison. Moreover, an adoption study of the charcoal-producing gasifier cook stove was performed.

2.1. Study area

The study was carried out among smallholder farmers in Embu County, at Kibugu village about 120 km northeast of Nairobi and bordering Mount Kenya to the southeast. The temperature ranges from a minimum of 12 °C to a maximum of 27 °C. Embu is located at an elevation of 1350 m above sea level. Embu County has a population of 296 992 people (KNBS 2010). *G. robusta* is a tree widely planted on-farm in Embu as it provides shade, promotes soil conservation, and serves domestic firewood and timber needs (Lengkeek and Carsan 2004).

2.2. Selection of households and development of a schedule

Five households were involved in the participatory charcoal cooking tests. The five households also participated in the previous study where charcoal was produced using a gasifier cook stove (Njenga *et al* 2016). The purpose of conducting participatory cooking tests was to incorporate local cooks' assessment of the improved stoves and to benefit from new information that cooks alone could provide using stoves under field conditions. Because the new stoves require adjustments in cooking habits, new tasks connected with producing fuel, and potentially some costs, it is critical to understand the benefits and difficulties as experienced by the potential users as they express those responses (Fischer 2000). During the previous study, the five households were randomly selected using mathematical software (MATLAB) from a sample of 57 households interviewed in the baseline survey for the biochar and smallholder farmers in Kenya project. A schedule of the cooking tests was developed using MATLAB, which randomized the date for each test in each household and each farmer was notified of the date of the test in advance. In each household cooking was

carried out with each type of fuel and stove making a replicate of five for each test. The five households were assumed to represent a diverse type of kitchens found in the village.

2.3. Types of charcoal

The three types of charcoal reported in this paper were made from *G. robusta* prunings, *Zea mays* cob (maize cob) and *Cocos nucifera* (coconut shells) feedstock using a galvanized gasifier cook stove. 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 2012) and (iii) coconut, although not grown in the area, is an important tree crop for 2.4 million people on the Kenyan coast (Batugal *et al* 2005). The gasifier cook stove is the natural-draft 'Top-Lit UpDraft' (TLUD) model that uses biomass fuel (Anderson and Reed 2004). This type of 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 (figure 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. The fuel is converted to charcoal during the process. The charcoals were produced using the different feedstock in the gasifier cook stove in the five households. Details about the charcoal production as a by-product of cooking with a gasifier can be found in Njenga *et al* (2016).

The three types of charcoal produced using a gasifier cook stove were compared to conventional wood charcoal that was sourced from a local charcoal retail shop in Embu town from which farmers buy charcoal.

2.4. Cook stove

The Kenya Ceramic Jiko (KCJ) was selected for the participatory charcoal cooking tests as it is the most commonly used stove for cooking with charcoal in the country. It is used by over 85% of households and has an energy conversion efficiency of about 33%–35% compared to 10%–15% obtained in traditional charcoal stoves (Mugo *et al* 2007) (figure 1).

2.5. Cooking tests and type of meal

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 (*Z. mays*), commonly known as *ugali*, and a local cabbage variety known as *kale* (*Brassica oleracea*) used as a vegetable in a dish called *sukuma wiki*. To cook *ugali*, 1 kg of Soko brand maize flour and 2.1 l of water was used. The *sukuma wiki* was made using 0.75 kg of kale, tomatoes and onions purchased locally. These amounts were selected because they are considered



Figure 1. Galvanised steel gasifier cooking stove and Kenya Ceramic Jiko (KCJ) (Credit: M Njenga).

sufficient to provide a meal for the standard Kenyan household of five people (KNBS 2010). 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 3–6 pm in each household.

The initial fuel that filled the stove was weighed and the stoves lit outside. The KCJ is a portable stove and as normal practice portable stoves are lit outside until the fuel catches fire and stops smoking. The stove was lit using dry small pieces of *G. robusta* firewood, which were placed in the air space at the bottom and ignited using a match. Extra charcoal was added as required inside the kitchen as the stove was already burning, and its weight was recorded. On 20 consecutive days (June–July 2014) a total of 20 tests were carried out. This involved four tests in each household, one for each of the four types of charcoal. Female members of the household carried out the cooking experiment in the presence of the research assistants. During the charcoal cooking tests, measurements were made on the time taken to cook the meal.

Cooking took place in the kitchens of the selected households, and generally represents the type of kitchen found in households in the study area. 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. Details on dimensions of the kitchen can be found in Njenga *et al* (2016).

2.6. Measuring concentrations

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 intervals using an EL-USB-CO carbon monoxide data logger (DATAQ Instruments). 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. Details of the emission measuring procedures can be found in Njenga *et al* (2013).

2.7. Determination of combustion properties

The charcoals were 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 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 on wet weight basis. Fixed carbon was calculated by subtracting moisture content, ash content and volatile matter from 100%.

2.8. Data management and analysis

Data were analysed using Microsoft Excel software for descriptive statistics. Significant differences between the mean values for combustion properties and fuel used in cooking were tested using R statistical computer package for emissions (Dalggaard 2008). The tests compared any two pairs of the four types of charcoal. The significance level was set at $p < 0.05$.

2.9. Gasifier adoption study

In late February 2015, the 57 households who participated in the baseline survey were invited to training on gasifier use and maintenance. Forty one

Table 1. Combustion properties of charcoal produced using a gasifier cook stove.

Type of fuel	Calorific value (kJ g ⁻¹)	Fixed carbon (%)	Moisture content (%)	Volatile matter (%)	Ash content (%)
Maize cob charcoal	28.7 ± 0.17	59.5 ± 0.17	8.0 ± 0.01	27.2 ± 0.29	5.3 ± 0.18
Coconut shell charcoal	31.7 ± 0.51	69.8 ± 1.05	5.8 ± 0.25	19.8 ± 0.59	4.7 ± 0.71
<i>Grevillea</i> charcoal	26.5 ± 0.3	56.2 ± 0.63	6.7 ± 0.58	31.5 ± 1.14	5.5 ± 0.22
Conventional wood charcoal	33.1 ± 0.18	77.0 ± 0.20	4.6 ± 0.14	16.2 ± 0.42	2.3 ± 0.06
<i>Grevillea</i> prunings firewood ^a	19.6 ± 0.03	6.4 ± 0.15	9.7 ± 0.07	79.0 ± 0.06	5.0 ± 0.06

± standard error.

^a Njenga *et al* 2016.

Conventional wood charcoal and firewood are used as control.

farmers turned up, comprising of 21 farmers who had participated in the baseline study and 20 who were new to the study. Because only 20 gasifiers were available, the trained farmers applied village representation to arrive at 20 beneficiaries among the 21 who had participated in the baseline. Among the 20 beneficiaries who received the gasifier were 14 women and 6 men, and the men promised to transfer the skills to their wives as they are the ones responsible for cooking. An adoption study was carried out using a semi structured questionnaire in June, after five months of use of the gasifier by the 20 households. Questions were asked regarding frequency of use, fuel types used, preferred time of use of the gasifier and use of charcoal produced.

3. Results and discussion

3.1. Combustion properties of charcoal produced using domestic gasifier cook stove

Among the three types of charcoal produced using the gasifier, coconut shells had somewhat better combustion properties than that made from maize cob and *G. robusta* prunings (table 1). This could be attributed to the physical properties of the type of fuel stock where coconut shells had higher bulk density (267 g dm⁻³) than *Grevillea* (137 g dm⁻³) and maize cob (99.10 g m⁻³) (Achour 2015). Good combustion properties include a high calorific value, high fixed carbon content and low moisture, ash and volatile matter contents (FAO 1985). Generally, the calorific value of the charcoal produced using the gasifier compares well with conventional wood charcoal, though with a somewhat lower calorific value, fixed carbon and higher ash content (table 3). Significance difference ($p < 0.05$) in the calorific value existed only between conventional wood charcoal and charcoal made from coconut shells using the gasifier, emphasizing the high quality of the latter. The charcoal produced in the gasifier compared well with other charcoal found in the literature, such as charcoal collected from an urban area in Nairobi with a calorific value of 25 kJ g⁻¹ and charcoal made from *Leucaena leucocephala* and *Tectona grandis* in Nigeria with 24 kJ g⁻¹ and 26.4 kJ g⁻¹ respectively (Fuwape 1993). Tree species influence the quality of charcoal. This is noted in the

conventional charcoal used in this study, which had 33 kJ g⁻¹ that could be associated with its source—acacia trees from the Mbeere area. Acacia species have a high density and good quality charcoal, and are the most preferred tree species for charcoal production in the country (Mutimba and Barasa 2005). Although maize cob charcoal looks more friable than that made from *Grevillea* prunings, it had somewhat better combustion properties than the latter and there was a significant difference in calorific value between the two types. The ash content of the charcoals made from the gasifier were slightly above the recommended 3% for good quality charcoal though an ash content of charcoal as high as 9% was found among charcoal from mixed tropical hardwood feedstock (FAO 1985). The moisture content and volatile matter of charcoals made from the gasifier met the recommended maximum 10% and 30% respectively (FAO 1985). Compared to firewood, the volatile matter content in charcoal is lower as carbonization drives away water, other liquids and tarry residues. These results indicate that fuel properties of charcoal made using the gasifier are of good quality for cooking, and compared well with conventional charcoal.

Making charcoal from firewood using the gasifier increased the calorific value (by weight) by 30% as indicated by *Grevillea* charcoal compared to *Grevillea* prunings firewood (table 3). The calorific value improvement by carbonization was higher in maize cob (18.9 kJ g⁻¹) and coconut shell (21 kJ g⁻¹) at about 50% (Njenga *et al* 2016). Conversion of the three fuel stocks to charcoal by weight was about 20% (Njenga *et al* 2016). This study is in agreement with the observation made by Pennise *et al* (2001) that carbonizing wood creates charcoal with higher energy density than air-dried fuelwood. The authors however confirm that converting firewood into charcoal for cooking has disadvantages with respect to fuel loss and emissions.

3.2. Energy use efficiency in gasifiers and three stone open fire cooking systems

When using charcoal to cook a meal, more conventional charcoal was used and there was a significant difference ($p < 0.05$) in the amount of charcoal used between conventional wood charcoal and *Grevillea* prunings charcoal produced using the

Table 2. Time and amount of fuel used to cook ugali and kale.

Type of fuel	Stove	Time taken to light the stove (minutes)	Time taken to cook the meal (minutes)	Amount of fuel used to cook the meal (grams)
Maize cob charcoal	KCJ	5 ± 0.40	36 ± 1	422 ± 20
Coconut shell charcoal	KCJ	7 ± 0.6	41 ± 5	395 ± 29
Grevillea prunings charcoal	KCJ	5 ± 0.5	40 ± 3	376 ± 27
Conventional wood charcoal	KCJ	10 ± 0.8	37 ± 4	496 ± 35
Grevillea prunings firewood ^a	Gasifier	11 ± 2	31 ± 1	918 ± 61 ^b
Grevillea prunings firewood ^a	Three stone open fire	8 ± 3.7	44 ± 5	1565 ± 127

± standard error.

^a Njenga *et al* 2016.

^b Net amount of fuel used.

gasifier (table 2). The high amount of conventional wood charcoal and of maize cob charcoal could be attributed to their dense and friable nature respectively. The friable and light nature of the maize cob charcoal could have contributed to a high amount of it being used as it burned rapidly. Almost twice as much refilling was required for maize cob charcoal compared to that of *Grevillea* and coconut shells (Achour 2015). This indicates that the choice of charcoal type should be considered when preparing different types of meals. For example, more compact charcoal such as that from coconut shells could be more efficiently used when cooking food types that take a long time to prepare, such as grains and cereals, while maize cob charcoal would be suitable for cooking food that can be prepared quickly, like tea. In practice, choosing different types of charcoal for different purposes might not be feasible. This implies that energy from more dense charcoal may be wasted if used to cook meals that can be prepared fast and hence would be advisable to use the extra energy for other purposes such as heating water. The charcoal can be used in making fuel pellets or briquettes.

The maize cob and *Grevillea* prunings charcoal lit faster than coconut shell and conventional charcoal, which may be associated with the high volatile matter content of the former two types (FAO 1985). All three types of gasifier produced charcoals that lit faster than conventional charcoal, which could be associated with lower compactness, higher volatile matter content and type of fuel stock they were made from (table 2).

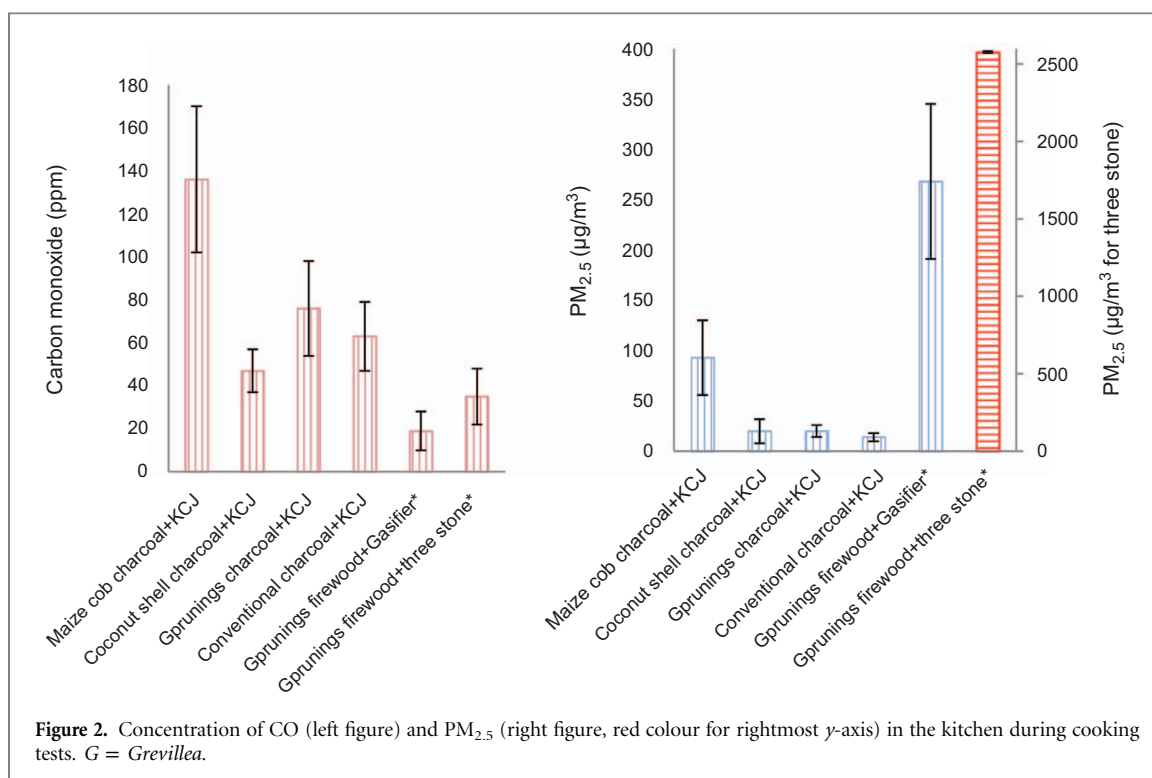
The study depicts two possible scenarios of cooking systems that are different in energy use efficiency, the data for which can be found in Njenga *et al* (2016). In scenario (i) which is the common practice, a household uses a three stone open fire and firewood cooking system and requires 1565 g of firewood to cook a meal of ugali and kale (table 2). In scenario (ii) a household uses a gasifier cooking system to cook a meal and at the same time produce charcoal for another round of cooking of the same meal using a charcoal KCJ cook stove. For efficient burning, the fuel canister needs to be packed with fuel to its capacity while leaving air spaces. For example, the gasifier in the study was fed with 1820 g of firewood that filled up the

fuel canister and a net of 918 g of it was used to cook the meal (Njenga *et al* 2016). This results in an additional 19 min worth of extra energy after the meal was ready that could be used to cook something else. The process yielded 349 g of charcoal implying that one needs to cook with the gasifier using *Grevillea* prunings for 1.1 times in order to produce 376 g of charcoal—enough to cook a similar meal. A household that combines a gasifier cook stove and cooking with the charcoal produced during gasification saves 40% of the firewood used in the traditional three stone open fire cooking system. If the charcoal produced by the gasifier during cooking is not used as fuel and for example is used as biochar a 27% fuel saving was achieved compared with the three stone stove and 10% compared with the improved stove (Njenga *et al* 2016).

This implies that switching to the more efficient gasifier plus charcoal systems will save fuel, but factors influencing adoption need be understood. This is supported by the study on households in Ethiopia which showed that switching from the traditional three stone open fire to an improved model allowed households to save between 20%–56% of firewood (Duguma *et al* 2014). Further, in rural Kenya, the use of a rocket mud stove reduced fuel consumption by 34% compared with the three stone stove (Ochieng *et al* 2013). In Khairatpur village in rural India, an improved cook stove was found to reduce annual consumption of fuel by 41% compared with the traditional cook stove (Singh *et al* 2015). In Dadaab refugee camp in Kenya, switching from the three stone stove to an improved cook stove reduced the number of times women needed to walk for 4 h to a forest to fetch firewood from five to three per week (Bizzarri 2010).

3.3. Concentrations from cooking with charcoal or firewood

Maize cob charcoal produced higher concentrations of CO when compared to the coconut shell and *Grevillea* charcoals (figure 2), which could be attributed to faster combustion leading to insufficient oxygen supply. The lowest CO was from coconut shell charcoal which could be due to its slower combustion (and thus



sufficient oxygen supply), caused by less volatile matter and more compact structure. Cooking with *Grevillea* prunings firewood resulted in 54% less CO in the kitchen than cooking with *Grevillea* prunings charcoal. Charcoal produced using the gasifier cook stove produced a somewhat higher PM_{2.5} concentration than the conventional charcoal which could be associated with their higher volatile matter and moisture. All charcoals had much lower PM_{2.5} concentrations than the *Grevillea* prunings firewood (figure 3), which is due to the high volatile matter in firewood.

Firewood in traditional three stone stoves produced PM_{2.5} concentrations over 100 times higher than charcoal in KCJ which could be associated with its high volatile matter content (FAO 1985). PM_{2.5} is a common and useful indicator of the risk associated with exposure to a mixture of pollutants from diverse sources (Lim and Vos 2012). It is then safer for households to shift from cooking with firewood to charcoal. Bailis *et al* (2005) in their study on mortality and greenhouse gases in Africa estimated that gradual or rapid transitions to charcoal could delay 1.0 million or 2.8 million deaths, respectively. It was further suggested that a complete transition from firewood to charcoal could reduce the incidence of acute respiratory infections by 65% (GACC 2011). This could thus reduce the more than 50% of deaths that occur among children under 5 due to pneumonia from ALRI, caused by particulate matter (soot) from household air pollution (WHO 2014).

There are however implications related to wood wastage in converting firewood to charcoal. For instance, to produce enough charcoal to cook a meal

using the traditional earth kiln, which has 14% efficiency, a household needs 2686 g of firewood (Okello *et al* 2001). This is 72% more feedstock than when using firewood in the three stone fire (table 2). This challenge could be addressed by using higher efficiency kilns with over 24% yield. This is possible as there are improved kilns with over 30% yield of charcoal, though their adoption is affected by labour, cost and switching from traditional practices.

Using a gasifier to produce charcoal while cooking food is an even more efficient way to use firewood to produce charcoal. Despite the health risks, firewood is still preferred by many as it is the primary energy source for 99% of rural households as shown in a study of ten African countries (Adkins *et al* 2012). The use of firewood can be made safer by the use of efficient cook stoves, well ventilated kitchens and dry wood, which will mainly benefit women and children as they spend a lot of time in the kitchen. For example, gasifier cook stoves reduce indoor air concentrations of CO and PM_{2.5} by 46% and 90% respectively (Njenga *et al* 2016). Likewise, in the mid-hill region of Nepal, indoor concentrations of CO and PM_{2.5} were found to be reduced by 60.0%, and 63.2% respectively, after one year of using an improved stove (Singh *et al* 2012). In south-western Bangladesh, 98% of women experienced health and lifestyle improvements after using an improved earthen stove (Alam *et al* 2006). However, it is important to ensure that the wood is dry, irrespective of the stove being used, as this reduces emissions (Arora *et al* 2014). Adoption of improved cooking systems would contribute to Sustainable Development Goal 3, which aims to 'ensure healthy lives and promote well-being for all at all ages'.

Switching from cooking with firewood to charcoal is not always appealing as the cost of the latter is on the rise, requires the purchase of cook stoves, and communities prefer and are used to traditional stoves for the reasons discussed earlier. Hence, understanding the different aspects of the problem, from its socio-economic to its behavioral dimensions, becomes crucial. Thacker *et al* (2014) performed a comprehensive review of the existing literature on improved cook stove adoption globally and concluded, as we have done, that end user's needs must be identified and incorporated into the design process or stoves will not be used. An even more recent study by Khandelwal *et al* (2017) discusses the failure of the extensive investments in India precisely because stoves do not meet the user's needs and preferences.

Sourcing firewood is free for agroforestry farmers who use prunings from trees or crops on-farm such as tea, coffee and fruit, and timber trees. Over 90% of households in Muranga, Kenya source firewood from trees on-farm (Githiomi *et al* 2012). In Embu, Kenya, 95% of households source firewood from trees on-farm, and for 68% of them it is the main source, while 42% depend exclusively on them (ICRAF 2016). Sourcing firewood from the government managed natural forests costs Ksh100 (US\$10) per month. This however has a high cost as it is wearisome and time-consuming, restricting women's capacity and opportunity to pursue other productive activities, as well as increasing risks of rape and physical injury. Hence, use of efficient stoves will also contribute to Sustainable Development Goal 5—to 'achieve gender equality and empower all women and girls'.

3.5. Household use of the gasifier cooking systems

Five months after receiving a gasifier cook stove, all of the households used it and 35% of them used it on a daily basis. The other households used the gasifier cook stove intermittently, mainly three to four days a week. Achieving consistent uptake of the gasifiers in this project is a challenge that has been reported with microgasification and other improved stoves in the region. Lotter *et al* (2015) reported that interviews of 30 natural draft top lit updraft microgasifier users showed that 60% abandoned use within one month. The most preferred meal times to use the gasifier were dinner and lunch, as it took time to prepare the fuel and light the stove. It is also possible that many households do not cook lunch and consume the food that was left after dinner the previous night. All the farmers preferred using firewood and in addition to firewood 75% of them used coffee prunings. The high preference on using firewood could be associated with its availability from trees on the farms. Maize cob was not used because it was not in season, and coconut is not available in the region. All beneficiaries preferred to use the gasifier to cook food that took a short time, as meals that require a longer time

necessitated refilling and lighting of fresh fuel. When compared to the traditional three stone open fire, all farmers found that the gasifier saved fuel and produced less smoke, and 90% found it took less time to cook with. The gasifier was found to present functionality challenges such as in lighting, having to prepare firewood into small pieces and arrange them in the fuel canister, and harvesting charcoal. These direct, simple and visible issues of functionality are more pressing for most households than the more complex and indirect benefits of sustainability, health and the like.

Other benefits farmers found with the gasifier were the production of charcoal while cooking, which was practiced by 80% of the farmers. The other households (20%) left the fuel to burn into ashes for lack of experience on charcoal harvesting or preferred to use the energy until it was over. Sixty five percent produced about 4.5 kg of charcoal from the gasifier per month. The previous study on participatory gasifier cooking tests performed by cooks and research assistants (Njenga *et al* 2016) showed that a household could produce 0.35 kg of charcoal from cooking a meal of ugali and kale. If the households used a gasifier once per day this would result in 10.5 kg of charcoal per month. The results of this study agree with the findings by Lotter *et al* (2015) on microgasification in Tanzania that users produce charcoal as a by-product from cooking with biomass fuel.

The charcoal produced could also be used as biochar for soil amendment (Jeffery *et al* 2013). The other component of the research project on the potential benefit of biochar to smallholder farmers in Kenya is studying biochar use in soil amendments. If farmers used the gasifier at least once per day and made charcoal, about 120 kg of charcoal would be produced annually. The suitable application rates are still being researched, but are expected to range from 1 to 10 tons ha⁻¹ or 0.1–1 kg m⁻² (Sundberg *et al* 2015). The annual production of charcoal from the household cooking practices could thus be perceived to be effectively applied to areas ranging from 120–1200 m². The charcoal produced by the farmers has a potential for application in kitchen gardens, as single applications of biochar can provide beneficial effects over several growing seasons in the field (Major *et al* 2010b). Farmers' choices to use the charcoal produced as fuel or as biochar for soil amendments might be determined by the scarcity of cooking fuel or economic value of the increased agricultural production. Hence, assessment of the benefits of the use of gasifiers should be based on an overall systems perspective that includes local conditions (Sparrevik *et al* 2014).

The shift from using firewood in three stone open fire cooking systems to using firewood in a gasifier and later using the resultant charcoal in a charcoal stove is possible in Kenya. This shift implies that households quit using the traditional three stone open fire and

replace it with the gasifier and maintain the use of a charcoal stove. The charcoal in the latter system will be produced using the gasifier as opposed to being purchased, as is the case in the former systems. Already, smallholder farmers are using several cooking systems at the same time implying that they are aware that the three stone stove is becoming less viable and are willing to consider newer stove types including charcoal stoves or the gasifier stove being studied. The key question is how can the gasifier plus charcoal system be made most appropriate and attractive to users? Traditional stoves are known to have been developed over thousands of years, fit with local culture and food practices, cost little, and are familiar to users in terms of operation. For the gasifier to be attractive to the cooks, it needs to meet the diverse demands and the availability of fuels, pots, foods, cooking methods and aesthetics (Kshirsagar and Kalamkar 2014). The challenges faced in adopting efficient cooking systems could be overcome through awareness campaigns on the benefits and knowledge and skills enhancement on their use. Most importantly, the stoves need to be modified to respond to the concerns raised by cooks, for example the gasifier stove's galvanized walls getting too hot and its instability (Njenga *et al* 2016). Further, when galvanized metal gets too hot toxic fumes can be produced (American Welding Society 2002). Capacity building among users is critical as knowledge has been found to be an important factor in technology adoption (Michelsen and Madlener 2016). For instance, development of training and awareness raising materials on the benefits of using the gasifier for improved livelihoods is useful. Creating awareness will trigger social demand hence enhanced diffusion of the technology (Montalvo 2008). This is supported by experiences reported by Hanna *et al* (2012) in their study in rural Orissa, India where poor skills in using improved cook stoves appropriately affected their overall use. Understanding cooking needs and preferences so as to address socio-cultural and cooking practices, in design of cook stoves as well as training materials, is also key in the adoption of improved stoves. As such it is important to develop a decision-making framework and method that takes into consideration the local situation and task-oriented technology selection which improves on application of technology (Xia *et al* 2016). Furthermore, recognition of its purchase cost is important compared to the traditional three stone open fire that can be constructed at no cost (Njenga *et al* 2016). These factors affect the use of cleaner solutions as found by Githiomi *et al* (2012) in their work in central Kenya where over 70% of the respondents were aware of the improved stoves but their adoption was less than 29%.

Beyond the question of improved training, the suggestion has been made that an adaptable cook stove that could be adjusted to serve a variety of specific and variable user needs could overcome some of the

resistance to adoption (Thacker *et al* 2014). While we agree that flexibility in design could be helpful, we would also suggest that inclusive, participatory methods of stove design that included user input at the beginning of the design process might be a constructive approach. To those who worry that less educated, rural populations might not be able to participate in technology design, we point to the work done in another area of rural concern: participatory plant breeding. Particularly the work done at INCARDA when it was still located in Aleppo, indicates that rural, farming communities are in fact highly knowledgeable about the areas of intellectual concern that intersect with their livelihoods (Ceccarelli 2014). In Kenya where our work is focused, the same women who cook with firewood manage their money with M-Pesa with strong positive effects on the Kenyan economy (Suri and Jack 2016).

Even more importantly perhaps, we would suggest that a cook stove technology is just one part of the woodfuels story. As mentioned above, the advent of on-farm firewood production changes the variables around cooking fuel decision-making. This is an area where far more work needs to be done, including an in-depth understanding of women's particular cultural investments in sourcing and using woodfuels as well as the use of cooking technology.

4. Conclusions and recommendations

Biomass-based energy remains the most important form of cooking fuel in SSA, though it is faced with the challenges of sustainable supply and negative health implications. The gasifier cooking stove produces charcoal with good combustion properties for use as a cooking fuel, as evidenced by laboratory analysis and practical use by farmers. The gasifier stove used in combination with a charcoal stove saved 40% of fuel used in cooking compared to the traditional three stone open fire and 27% of fuel is saved if the charcoal is used for other purposes such as biochar. The emissions of PM_{2.5} were reduced dramatically. Adoption of the gasifier cook stoves for daily cooking at 35% of households after five months of use showed the potential for going to scale. There is a need for support on the development of the gasifier as a more efficient cooking system for smallholder farmers through technological improvements in tune with socio-cultural needs and cooking practices, as well as raising awareness of its benefits. Moreover, further study needs to be done on the relationship of cooks to their woodfuel sources, production and use, beyond cooking in the narrowest sense. An understanding of how woodfuel use fits into the larger livelihoods and cultural identities of women and communities could shed light on which sorts of problems individuals in diverse settings may be willing to address. In this broader context, the gasifier can be a technology

contributing to a transition to sustainable use of woodfuel, by increasing fuel use efficiency and reducing emissions.

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