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Innovative biomass cooking approaches for sub-Saharan Africa

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Abstract

Eradicating poverty and achieving food and nutrition security in a sustainable environment is difficult to achieve without adequate access to affordable cooking fuel. It is therefore important to understand the common sources of cooking energy used by people in rural areas and the challenges faced in making fuel sources economically viable, socially acceptable and ecologically sustainable. In the sub-Saharan Africa (SSA) region, more than 90% of the population relies on firewood and charcoal (wood fuel, collectively) as a primary source of domestic energy. Wood fuel sustainability is challenged by unsustainable harvesting and inefficient methods of converting wood into energy. The use of inefficient cook stoves contributes to wood wastage and smoke exposure associated with severe illnesses. Households often abandon traditional nutritious diets that take a long time to cook, reduce the number of meals, and spend income on fuel at the expense of food costs. Innovations exist that have the potential to provide affordable and cleaner tree-based cooking fuel. Pruning trees on the farm as a fuel source brings firewood closer to women, lightens their workload, saves time and reduces income spent on cooking fuel. Using briquettes or gas cook stoves can reduce health risks associated with food preparation and reduce income spent on cooking fuel due to increased fuel efficiency. The development of these innovations indicates the need for a multi-disciplinary approach to increase awareness of the benefits of cooking fuel innovations, encourage further research on product quality enhancement and standardization, to understand cultural and behavioral issues influencing adoption, and integrate innovations into bioenergy policy frameworks.

Key words: agroforestry, firewood, fuel briquettes, gasifier cook stove, emissions, climate change

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Background

Eradicating poverty and achieving food and nutrition security sustainably is difficult without access to affordable cooking fuel. Wood is a key source of energy in many rural areas in sub-Saharan Africa region that has been used for millennia for cooking, boiling water, lighting and heating. Today, about 2.5 billion people around the world depend on biomass energy for cooking and heating, wood accounts for 87% of this energy supply (IEA, 2006). In SSA, more than 90% of the population relies on wood fuel (that is firewood and charcoal) as a primary source of domestic energy. Use of wood fuel is rising due to population growth and emerging urbanization trends; for example, a one percent rise in urbanization has been linked to a 14% rise in charcoal consumption (World Bank, 2009).

In SSA, charcoal is mainly used in urban settings but sourced from rural areas. In Kenya charcoal is used by an estimated 82% of urban households, compared to 34% of rural households, making it a multi-million US dollar business sector. Urban areas' reliance on charcoal holds true in Tanzania and Ethiopia as well, where urban households in Tanzania use 80% of total charcoal production and, in Ethiopia, 70% of total charcoal production is consumed by urban households, supplying 97% of their household energy needs (Ngeregeza, 2003; Yigard, 2002). Furthermore, charcoal use in Zambia is reported to have increased by four per cent between 1990 and 2000, culminating in 85% of urban households relying on charcoal (Chidumayo *et al.,* 2002). In contrast, firewood is the predominant form of wood fuel used in rural areas. In Kenya, 90% of rural households use firewood, compared to a meager 7% of the urban population (MoE, 2002). Dependency on biomass fuels among the rural population in Ethiopia is as high as 90% (Kumie *et al.,* 2009).

The unsustainable harvesting of trees for wood fuel has resulted in the over exploitation of forest natural resources, giving rise to widespread environmental degradation including soil erosion. In Kenya, 40% of wood fuel, charcoal in particular, is produced unsustainably, with nearly all charcoal producers using traditional kilns that only have a 10% efficiency rating in yield (Drigo *et al.,* 2015; Mutimba and Barasa, 2005). Use of inefficient cooking appliances leads to fuel waste and indoor air pollution, another major challenge associated with biomass energy. Globally, 2.6 billion people, nearly three quarters of who reside in rural areas in either SSA or developing areas in Asia, are without clean cooking facilities (IEA, 2013). In addition, the task of providing sufficient cooking energy falls to women and girls who must travel long distances to fetch and carry heavy loads of firewood home. The rising cost of traditional fuel is forcing many households to abandon traditional nutritious meals which take longer to cook. This reduces the amount and number of meals consumed and also contributes to not cooking the food properly. Others resort to buying cooked food from vendors where food safety and hygiene are not guaranteed. Others compensate for the increased costs of traditional fuel by using unconventional and hazardous fuel sources such as plastic waste (Gathui and Wairimu, 2010). The adverse health and environmental impacts associated with wood fuel that include plastic waste are prominent issues facing urban and rural populations in much of the developing world and must be addressed if food and nutrition security, improved health and environmental sustainability are to be achieved in the SSA region. This chapter presents a few innovations that could contribute towards making wood fuel and other biomass energy sustainable. The innovations described include: use of prunings from agroforestry for firewood production, production of additional cooking fuel through recycling organic waste and use of efficient cook stoves to reduce fuel wastage and emissions.

Methods and Objective

The main objective of this study is to evaluate and develop sustainable, affordable and cleaner tree and other biomass-based cooking energy systems in the SSA region. Following a literature review, primary data collection occurred through the use of baseline surveys, participatory mapping, participatory action research, performance monitoring and adoption studies. Participatory energy use efficiency and emissions tests were conducted at the household level. Additionally, a laboratory analysis of fuel combustion quality was carried out.

Innovations exist with the potential to promote sustainable access to cleaner tree and other biomass-based cooking energy systems that improve the well-being of local populations, the natural resource base and the environment. This paper discusses three such innovations including the use of tree prunings from agroforestry systems for firewood, briquetting organic residues for cooking energy and the domestic gasifier as a more efficient cook stove. Finally, the paper reviews a multi-disciplinary approach as a fourth innovation for enhanced development and adoption of technologies.

Analysis and Results

Agroforestry for household energy

Agroforestry, which refers to the close association of trees/and shrubs with crops, animals and/or pastures, is instrumental to bringing firewood closer to women (Rocheleau et al., 1988). Agroforestry systems play a role in providing cooking fuel for local households as prunings from trees ensure a constant supply of firewood, which can meet a household's energy needs for cooking and heating. Sourcing firewood from on-farm trees reduces expenditures on alternative cooking energy sources. It also saves time for other productive activities and reduces women and children's drudgery in sourcing firewood. This method also allows wood to fully dry before use, thus improving its energy efficiency and lowering emissions. Leaves from prunings left to decompose on the farm also help to recycle plant nutrients, which are important for soil health.

Agroforestry practices, preferred tree species and their benefits

A study of 80 randomly selected households, 40 in Kereita village, Kiambu County and 40 in Kibugu village, Embu County, investigated the contribution of trees on farms to household firewood supply. In Embu households obtained firewood from Mt. Kenya National Forest, while in Kereita wood is sourced from Kereita Forest, the Southern part of the Aberdare Forest Reserve. These two forests are among the five main sources of water in Kenya and their conservation is of national interest. The study's objective was to establish the role of agroforestry in supplying firewood for domestic use. The main tree species grown in Embu were *Grevillea robusta, Macadamia integrifolia, Persea americana* (avocado) and Eucalyptus spp. At the Kereita site the preferred tree species were *Cupressus lusitanica* (Cyprus), Eucalyptus spp, *Grevillea robusta* and

Prunus spp. (plums). At both sites the main benefit mentioned by farmers for Eucalyptus was timber, while firewood was indicated as the most important benefit from *Grevillea robusta;* even if this tree was initially planted for timber. Farmers considered Eucalyptus as producing better quality timber, while *Grevillea robusta* had higher biomass production which resulted in more firewood (Table 1).

Table 1: Priority benefits from preferred agroforestry trees

Tree species grown	Kibugu, Embu			Kereita, Embu		
	% households (Agroforestry practic	First priority use	Second priority use	% households (Agroforestry practice)	First priority use	Second priority use
Grevillea robusta	100 (Intercropped)	Firewood	Timber	60 (Intercropped)	Firewood	Timber
Macademia	97.5 (Intercropped)	Nuts	Firewood			
Avocado	97.5 (Intercropped)	Fruits	Firewood			
Eucalyptus	72.5 (Woodlot)	Timber	Firewood	70 (Woodlot)	Timber	Firewood
Cyprus				75(Intercropped)	Timber	Firewood
Plums				50 (intercropped)	Fruits	

Households across the two counties applied various agroforestry practices, but the most common practice was intercropping. In Embu County, trees were intercropped with coffee or maize, except for Eucalyptus which was grown in woodlots in order to reduce moisture competition with crops. In contrast, at Kereita, trees were intercropped with maize or vegetables, except for Eucalyptus which, similar to Embu County, was planted on woodlots. Another common agroforestry practice in both counties for Grevillea and Eucalyptus and for Cyprus in Kiambu County was planting along the farm boundary. Firewood and timber were the main products farmers obtained from on-farm trees.

Benefits of sourcing firewood from trees on the farm

This study revealed that firewood was mainly sourced from on-farm trees in the form of prunings as part of the management of timber and fruit trees; aimed at enhancing the quality and quantity of timber. The other method of obtaining firewood was by using the portion of trees left over after they are cut down for timber. During severe shortages of firewood, families cut down trees for supply of cooking fuel, with the exception of Cyprus, which is highly valued for timber and so is rarely cut down for firewood.

A structured pruning regime designed to enhance the quality and quantity of timber for Grevillea, Eucalyptus and Cyprus was conducted in a rotational manner and on an annual basis where individual trees were pruned every two years. According to the farmers who participated in the study, the two-year pruning schedule allowed trees to develop sizeable branches that provided households with more wood fuel. In cases of severe firewood shortages, excessive pruning and pollarding, where the upper branches of a tree are removed, occurred. This practice affects firewood yields in consecutive years. In Embu, prunings from coffee trees were also used as firewood, although as few farmers pruned during the duration of the study, the pervasiveness of this practice is unclear.

Table 2: Sources of firewood for household use in rural areas

Characteristic	Kibugu, Embu	Kereita, Kiambu
Households that had each category as their main source*[a] of firewood	Forest (10%), trees on-farm (65%), purchased (15%)	Forest (23%), trees on-farm (5%), purchased (15)
Households that depended on agroforestry exclusively for their firewood supply	40%	5%
Households that depended on forest exclusively for their firewood supply	0	25%
Households that exclusively depended on purchased firewood	3%	13%
Distance to and from forest to collect firewood	8km	6km
Average estimated time spent in collecting firewood	4hrs from forest 2hrs from farm	3hrs from forest 1hr from farm
Average weight of a 'woman load' of firewood	59kg*[b]	52kg (home use) and 69kg (for sale)*[b]
Average number of days that a women load (34 kg in Embu and 43kg at Kereita) of firewood was used	7 (5kg daily consumption)	10 (4kg daily consumption)

*[a]Main source= Meets 60-99% of household firewood need *[b], measurements were taken from 7 women coming from the forest

Forty percent of the surveyed households in Embu met all their firewood needs from their farms (Table 2). This innovation offers a great opportunity for integrating timber production with cooking energy security. In contrast, just 5% of households in Kiambu procured their firewood from their own land. Twenty five percent of households in Kiambu exclusively depended on forests for firewood; none of the households did so in Embu. The other main source of firewood was purchasing from merchants who were mainly women who sourced the firewood for sale from the forest. For those households with no main source of firewood, they stacked between forest, on-farm, and purchasing. At both sites majority of the farmers had land sizes below 1acre.

In January and February of 2014, 60% of farmers in Embu County primarily pruned *Grevillea robusta*. From the prunings of this tree, the majority of farmers estimated a production of over 22 'woman load' (whose weight vary from place to place) of about 34kg each. This is equivalent to over 750kg of firewood, worth more than 4600 Kenyan Shillings (Ksh) (US$46), where a 'women load' is sold at Ksh210 (US$2). On average, this amount of firewood was sourced from about 16 trees planted on about 1.6 acres, implying a density of about 10 timber trees per acre. Measurements of how long a 'women load' lasted showed that the 34kg of firewood supplied a household for about 7 days, implying a daily consumption of about 5 kg. This is equivalent to a consumption of 1825kg per year per household, translating to 365kg per person in a standard household of 5 people (Kenya Government, 2010). The firewood supplied from agroforestry practices typically lasted a household 5 months in Embu. To meet this household energy requirement, a household would be required to prune about 38 *Grevillea robusta* trees per year or 24 timber trees per acre.

At the Kereita site, 23% of farmers mainly pruned Eucalyptus and *Grevillea robusta* during the dry season, in January and February of 2014. Pruning was similarly carried out in preparation for firewood supply during the long rains. The majority of farmers estimated a production of about five 'women loads' of 43 kg each. This is about 215kg of firewood worth Ksh1500 (US$15) at Ksh300 (US$3) per 'women load'. This amount of firewood was sourced on average from 6 trees planted on about 1.2 acres implying a density of 5 timber trees per acre. Measurements showed that a 'women load' of 43kg supplied firewood to a household for about 10 days implying a daily consumption of about 4kg of firewood per day. This is equivalent to 1460kg per year per household translating to 292kg per person. Thus, the estimates showed that firewood produced from on-farm trees would last a household 2 months. To meet this household energy requirement, a household would be required to prune about 36 *Grevillea robusta* and eucalyptus trees per year, implying about 30 timber trees per acre. This indicates the need for in-depth studies on tree density and appropriate agroforestry systems for household self-sufficiency in firewood.

When collecting firewood from the forest, women carried heavier loads, mainly on their backs, to reduce the number of trips required to meet a household's energy needs. Those women collecting firewood as a source of income carried even heavier loads, which they then split into smaller loads for sale (Table2). Although women considered firewood from the forest as a cheaper source at (Ksh100 (US$1) than purchasing it per month, they also acknowledged that it was more labor intensive, resulting in back, leg and head injuries, greater instances of rape cases, and the loss of other opportunities for income generation. One woman lamented; *"the journey and the loads make us so tired that we are unable to carry out any other productive or leisure activity after coming from the forest. Further, we lose one day per week, which we could otherwise spend earning Ksh250 (US$2.5) equivalent of Ksh1000 (US$10) per month from causal laboring in other farms"*.

The adoption of efficient cooking stoves would contribute to cooking energy security by enabling on-farm tree prunings to last the households longer. This is because amount of prunings required for cooking would be reduced by about 40% if farmers used gasifier cook stoves which are highly efficient, as described later in this chapter (Njenga et al., 2016). In this case, there would possibly be surplus firewood for sale. The other potential use of surplus wood would be domestic charcoal production, using efficient kilns to convert prunings into charcoal as opposed to the big logs required to compensate the high loss of wood in traditional kilns.

Briquetting organic residues for household energy

Briquettes are made either by molding biomass materials using bare hands to produce solid units or compressed by use of manual or automated machines (Njenga et al., 2013b). Briquettes provide both cooking and heating energy and are cheaper, cleaner and burn more evenly for a longer period of time compared to wood fuel (Njenga et al., 2013b). Briquette technology is gaining popularity due to the rising cost of electricity, petroleum-based energy, and wood fuel coupled with rapid urbanization and unemployment. This has resulted in communities adopting briquetting, which enables them to recycle locally available materials, particularly waste, in urban settings. The technology is also being applied on a large-scale by tea factories, for example, aiming at reducing firewood consumption and cost of running energy.

Community based briquette production methods and quality

There are many briquetting enterprises in SSA, all at different scales and using a variety of raw materials and technologies (Mwampamba et al., 2013). One widespread briquetting enterprise practised by urban-based groups of women and youth in informal settlements is producing briquettes with charcoal dust. Charcoal dust is comprised of small, fine particles considered waste by charcoal traders. Heaps of charcoal dust are common in all places where the commodity is sold, especially in urban centres. About 10-15% of charcoal along the supply chain ends up as charcoal dust (Mugo et al., 2007). When the production of briquettes by women and youth began, charcoal dust was free. However, once demand for briquettes increased and a customer base was created, charcoal traders started selling it at Ksh2 (US$0.02) per kg. In rural areas, biomass materials such as crop residues and agro-industrial waste that include bagasse, rice husks, coconut shells and sawdust are used depending on local availability (Cohen and Marega, 2013).

Charcoal dust is sieved to get fine particles and remove impurities such as pieces of bone, wood, and stones. Because charcoal dust cannot hold together by itself, to form the solid units a binding agent is added like soil, starch, biodegradable paper or cow dung. The charcoal dust is placed on the ground or in a plastic basin and the binding agent added. The amount of binding agent is dependent upon its binding capacity and some examples of mixing ratios are given below. Water is then added as needed and using bare hands, the mixture is combined until a homogenous slurry is achieved. The slurry is then compacted using manual presses or moulded using bare hands.

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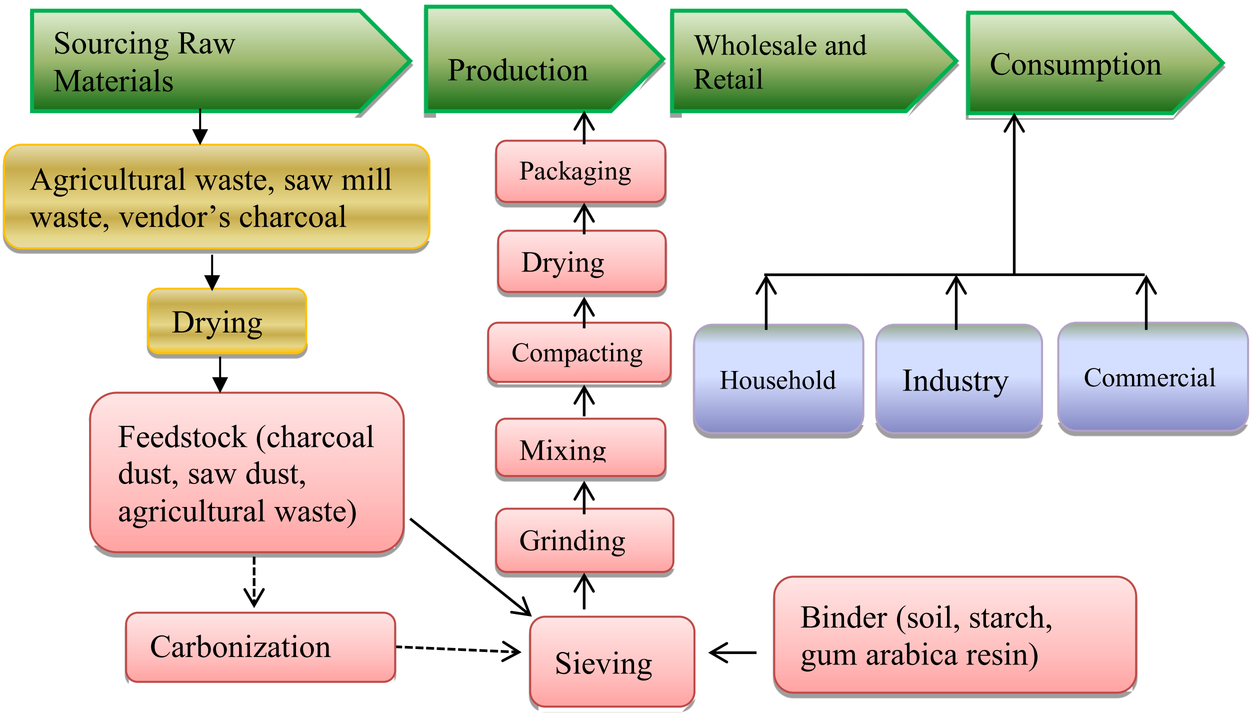

Figure 1: Briquette supply chain

The commonly applied ratios in producing briquettes include: charcoal dust to soil - 4:1, 2:1, charcoal dust to paper -32:1, 13:1, 3:1, saw dust to gum Arabica resin 1:3 (Njenga *et al.,* 2013b). The mixing ratios have an implication on the quality of briquettes. For instance, the higher the amount of soil the higher the ash content and hence the lower the heating capacity as soil does not burn. In the same vein, the higher the amount of paper in the mix, the more rapidly the briquettes burn. Communities in urban areas have shown preference for briquettes made from the mixture of charcoal dust and soil because it burns for a long time (4 hours) compared to those made from charcoal dust mixed with paper or conventional charcoal which burns for 2.5 hours. The briquettes made with soil produce lower emissions compared to those made of charcoal dust and paper or sawdust mixed with starch as well as conventional charcoal. For instance, charcoal dust mixed with soil briquettes (4:1 ratio) emit 90% less fine particulate matter ($PM_{2.5}$) and 40% less carbon monoxide compared to conventional charcoal. Furthermore, a charcoal dust with soil (4:1 ratio) briquette meets the recommended 30ppm of carbon monoxide (CO) allowed for human exposure for one hour and 0.025mg/m^3 allowed for 24 hours (US EPA, 2002WHO, 2005). Briquettes made from fresh sawdust and mixed with binders such as gum arabica resin burn for about 30 minutes. In a kitchen situation they emit 123 mg/$m^3$of $PM_{2.5,}$ which is way above the 0.025mg/m^3 allowed for 24 hours (Njenga *et al*., 2013b; WHO, 2005).

To increase burning period, heat value and reduce emissions, fresh sawdust briquettes would require producers to carbonize the sawdust before making the briquettes (Njenga *et al.*, 2013b). Hence, carbonizing biomass before making briquettes enhances the quality of briquettes meant for household cooking though at a cost in terms of money, time and loss of biomass. Drum kilns {30% biomass to charcoal yield, (Odour et al.,2006)} are suitable for household carbonization of small amounts of biomass. These

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biomass materials may include prunings from on-farm trees and crop residues such as maize cob, banana leaves and peelings, and coconut shells for use in briquette production.

Green Heat is a company that was established in 2011 as a social enterprise by youth based in Kampala, Uganda, which transforms organic waste into energy. The company works with local communities who carbonize banana leaves and peelings to produce charcoal using drum kilns. The company buys the charcoal dust from farmers at Uganda shilling 58 (US$0.004) per kilogram. The charcoal dust is ground into fine particles using an automated machine. Another automated machine mixes the fine charcoal dust with molasses and the mixture is transferred to a third automated machine that compacts it into briquettes. The company produces about 40 tons of briquettes monthly generating around $2,136 USD. The briquettes are sold to households, schools, chicken hatcheries and other customers.

Briquette technology is also being integrated into different types of farming systems as well as addressing global challenges such as sanitation. Sanivation is a social enterprise dedicated to improving the overall dignity, health and environment of urbanizing communities in East Africa through delivering clean, safe, and efficient sanitation services. At no cost to the customer, they install modern container-based toilets also known as urine diverting dry toilets, (UDDT) in peoples' homes in informal settlements in Naivasha, Kenya. They then charge a monthly fee of Ksh 600 (US$6) to service them. The toilet has two separate containers, for urine and for fecal material. The toilets are placed either indoors or outdoors. A household produces about 0.5kg of fecal waste per day. The community and the staff of Sanivation are trained in hygienic handling of the toilet and the waste. The waste containers are collected and transported to Sanivation grounds. The fecal waste is then treated for biological contaminants using solar thermal energy, which heats the waste to 65°C for 3 hours or 80°C for 1 hour. The treated fecal waste is then used as a binder in briquette production. The main raw material in these briquettes is charcoal dust which is produced by drying green flower farm waste and carbonizing it using Adams Retort. There are many flower farms around Lake Naivasha. The other source of charcoal dust is charcoal traders. Once the flower farm waste is carbonized, it is ground using an electric machine. The charcoal dust is then mixed with the treated fecal sludge and compacted into round solid units using an agglomeration machine. Each month, 10 tons of briquettes are produced and sold, with plans to reach 150 tons each month. Quality assessments are on-going to improve the combustion properties, emissions, and to understand pesticide loads that may pose health risks. Market and consumer's perception surveys have also been performed.

Lessons from these community-led innovations indicate the need for improvement and standardization of production technologies for quality control. Briquette technology is also applied on a large-scale for enhanced energy efficiency in small-scale agriculture as illustrated by the example of the Makomboki tea factory. This is one of the 66 factories managed by the Kenya Tea Development Authority (KTDA) for small-scale farmers. The factory serves 5,632 small-holder tea farmers and consumes about 11 million kg of firewood/year costing about Ksh43 million {US$430, 000} (Njoroge, 2013). The high cost of firewood significantly reduces farmer benefits and contributes to the loss of trees. The firewood is mainly sourced from small-scale farmers, which has been found to contribute to the harvesting of immature trees meant for other high value products such as timber. To address these challenges, the factory is working with partners such as the Living Earth Foundation based in the UK, the Ethical Tea Partnership, and ICRAF among others on briquetting crop and tree residues. The factory is currently using ssawdust: rice husk (3:1) briquettes for drying tea in the steam boilers. It produces about 250kg/hour. At a ratio of 50:50, use of firewood and briquettes the factory saves 25% of income used in energy and if it switches completely to briquettes it is anticipated that it will save 50% of the profit otherwise spent on energy. The challenges facing the briquette technology at the tea factory include: drying of raw materials, increase in prices of sawdust, maintenance and repairs of the briquette press, boilers being too large while the current press produces pieces of briquettes which are too small, and low production capacity compared to demand. This has attracted a lot of attention and there are several initiatives to assess the potential of briquette technology for sustainable energy use in the sector.

Benefits of briquettes

In urban areas where most feedstock comprises of different types of organic waste, briquette making contributes to recycling organic waste and therefore, reduces expenses incurred by municipalities. It also contributes to ridding urban neighbourhoods of excess waste. Briquette making has potential to strengthen rural-urban food and energy flows through recycling urban waste into briquettes and transporting them for use in rural areas. Briquette supplies cheap cooking and heating fuel, and so is popular among low income populations, particularly those in informal urban settlements. For example, cooking a traditional meal of 500 grams of green maize mixed with 500 grams of dry beans enough for a Kenyan standard household of 5 people costs: 3 Ksh (US$0.04) – 850 grams of charcoal plus soil briquettes, 26 Ksh (US$0.35) – 890 grams of conventional charcoal) and 45 Ksh (US$0.6) - 0.36 liters of kerosene. Cooking the meal with charcoal briquettes thus costs 88% and 93% less than cooking the meal with charcoal and kerosene, respectively (Njenga et al., 2013a). Briquettes reduce cost of production for poultry farmers by saving money used in electricity bills to keep chicks warm and reduce cost of drying tea and thus increasing income paid to farmers. Households that produce briquettes for home use and those that purchase them save about 70% and 30%, respectively of income spent on cooking energy (Njenga et al., 2013a). Briquette producers have employment that generates income.

Briquettes reduce health risks associated with indoor air pollution as they burn cleaner - a characteristic influenced by raw material, binders and the production process (Njenga et al., 2013b). Briquettes reduce pressure on trees that would be cut down for charcoal or firewood, contributing to environmental conservation. By recycling charcoal dust, briquettes also reduce the global warming potential from the charcoal life-cycle, which includes carbonizing trees into charcoal, transportation and cooking (Njenga et al., 2014). As pots used when cooking with briquettes accumulate no soot and require less cleaning, hygiene and water use at the household level are also improved (Njenga et al., 2013a)

Gasifier as an efficient cook stove for small-scale farmers

Improving cooking systems through the use of domestic gasifier stoves is one innovation that could save fuel and time, while also reducing emissions and producing charcoal as a by-product (Njenga et al., 2016). A domestic gasifier transforms firewood into energy in four stages, namely drying, pyrolysis (carbonisation), gasification and gas combustion (Raman et al., 2013). A domestic gasifier is beneficial as it conserves fuel, cooks faster than traditional stoves, converts firewood into charcoal for additional use, and has lower emissions (Njenga et al., 2016). The gasifier used in the work reported in this chapter has three components: a 15.5 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. It is ignited at the top and 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.

Participatory cooking tests were carried out in Embu, Kenya in 2015 with five households. The objective of the cooking tests was to assess energy use efficiency, emissions of carbon monoxide and fine particulate matter ($PM_{2.5}$), and user perceptions. Women prepared a traditional meal of two components which are cooked separately and consecutively; 1kg of maize flour, commonly known as *ugali*, and 0.75kg of a local vegetable variety known as kale (*Brassica oleracea*) and locally referred to as *sukuma wiki*. Experiences from the participatory cooking tests were applied in developing a training session which was offered to 51 farmers who included those who participated in the cooking test. After the training 20 households who participated in the baseline study were selected with a good representation of villages and received a gasifier. A perception and adoption study was conducted after five months. Three types of fuels were used to cook the meal on the gasifier cook stove, namely Grevillea prunings, maize cobs and coconut shells (*Cocosnucifera*). The Grevillea prunings were collected from farmers and were found to have been dried well below the recommended 10% (FAO, 1985). This reaffirms that sourcing firewood from tree prunings allows users to dry them well. Coconut shells and maize cobs were sourced from the Coast and Siaya counties, respectively for regional representation and were dried well. The combustion properties including calorific value, fixed carbon, ash content, volatile matter and moisture content were determined at the Kenya Forestry Research Institute (KEFRI) following procedures described by Findlay (1963). Based on local knowledge, these three types of feedstock have potential as cooking fuel among small-scale farmers in the country. Two stationary stoves, an improved Hifadhi cooking stove and the traditional three-stone stove, were used as controls against the gasifier - only Grevillea prunings were used as fuel in these stoves. Further participatory cooking tests were carried out using charcoal produced as a by-product during cooking with the gasifier. The popular Kenya Ceramic Jiko (KCJ) was used for these cooking tests while conventional wood charcoal served as a control.

Energy use efficiency and emissions from cooking with a gasifier

Organic crop and tree residues from farms were found to be good cooking fuel. Calorific value, which is a measure of energy content, was high in woody residues - coconut shells (21kJ/g), Grevillea prunings (20kJ/g) and maize cobs (19kJ/g) (Njenga et al., 2016). Likewise, fixed carbon was higher in coconut shells (10%) followed by Grevillea prunings (6%) and maize cobs (5%). High fixed carbon is a characteristic that results in a longer burning period (Fuwape and Akindele, 1997). Consequently, tree prunings and coconut shells had a longer charring period where the former provided about 20 minutes of extra energy after the food was ready. Cooking with Grevillea prunings (42 minutes) was faster than cooking with coconut shells (47 min) and maize cobs (50 min), which included lighting the stove and fuel change over. The shortest cooking time was with Grevillea prunings and the longest with maize cob as there was no need to refill and relight the gasifier with the former. It takes about 20 minutes for maize cob to turn into charcoal and refilling and relighting the gasifier is required. This implies that the type of fuel used in the gasifier determines the length of charring period which is important for farmers in selecting the type of meal to cook. Crop residues such as maize cobs are more convenient for quicker cooking food types if the need to refill and relight the stove is to be reduced.

When comparing how the meal was cooked using tree prunings in the three different cook stoves, it was found to be faster cooking with the gasifier (42min) than with the three-stone stove (52 min) or the improved stove (55 min). Another benefit of cooking with the gasifier is that it produces charcoal as a by-product with an average yield of 21% (by weight) where coconut shells (24%) produced more charcoal than maize cobs (21%) and Grevillea prunings (19%). Cooking with the gasifier saves 40% more fuel compared to the three-stone cooking stove and 27% compared to the improved cook stove (Hifadhi), if the charcoal produced during cooking is considered to be an additional product. The aim of saving fuel using the gasifier should target harvesting charcoal because when the by-product is not harvested for other uses and fuel is allowed to burn into ashes, the percent of fuel savings declines. The amount of fuel savings in this study agrees favourably with previous work in the region; a study on households in Ethiopia showed that switching from the traditional three-stone cooking stove to an improved model allowed households to save between 20-56% of firewood (Duguma et al., 2014).

The charcoal produced using the gasifier was also found to be a good cooking fuel. Calorific value ranged between 27kJ/g and 32kJ/g which compared well with that of wood charcoal (33kJ/g) sourced from local vendors (Njenga et al., 2017). Although higher than conventional wood charcoal, the ash content was on average 5% which is close to the recommended 3% and volatile matter was within the recommended 30% (FAO, 1985). Converting raw fuel into charcoal increased energy content between 30-50%. Higher benefits were realised from crop residues, which agrees with studies on converting firewood into charcoal by Pennise et al. (2001). About 400 grams of charcoal made from tree prunings, maize cobs and coconut shells was used to cook the meal; lower than 500 grams of conventional charcoal usually used, which could be attributed to the compactness of the latter. There is a need for households to combine the use of gasifier and charcoal stoves where they could save 40% of firewood used in the traditional three stone cooking system. Converting biomass into charcoal using a gasifier is more efficient at 20% compared to about 10% using traditional earth kilns (Okello et al., 2001). In addition, the charcoal can also be used as biochar for soil amendment. Biochar is a carbon-rich product resulting from pyrolyzing biomass. When applied to soil it resists decomposition, effectively sequestering the applied carbon and mitigating anthropogenic CO_2 emissions. It also increases plant productivity and reduces nutrient leaching (Biederman and Harpole, 2012). These benefits make the use of gasifier stoves for cooking and consequent production and application of the by-product on farms a good practice in climate smart agriculture.

Cooking with a gasifier reduced the indoor air concentration of CO by 52% and 45% compared to the improved stove and three-stone stove, respectively. Maize cob was found to produce more emissions than coconut shells and tree prunings, which could be attributed to higher volatile matter in the former (Njenga et al., 2016). The gasifier reduced the concentration of $PM_{2.5}$ by 94% and 89%, respectively compared with the improved stove and three-stone stove. Fuel in the gasifier burns at about 750^0c compared to 600^0 C in the three stone, which could be one of the factors contributing to cleaner cooking. Gasification and the combustion of gaseous fuel are cleaner than the open-air combustion of fuel wood (Raman et al., 2013).

Furthermore, using charcoal compared to firewood reduced $PM_{2.5}$ by 90% and increased CO by 300%. $PM_{2.5}$ is a common indicator of the risk associated with exposure to a mixture of pollutants from diverse sources (Lim and Vos, 2012). As such, it is safer for households to shift from cooking with firewood to charcoal or adopt efficient cook stoves for firewood. The shift to charcoal produced using traditional kilns, which in Kenya are used by about 99% of charcoal producers, has environmental implications. For instance, about 90% of biomass is wasted due to the low efficiency of kilns in converting wood into charcoal. Traditional kilns also contribute to air pollution - a concern for climate change - and the gaseous energy produced during carbonization is wasted (Bailis et al., 2005). The adoption of gasifier stoves cause low emissions of $PM_{2.5,}$ and hence, will contribute to reducing the percent of deaths among children under 5 due to pneumonia caused by acute lower respiratory infections (ALRI) sparked by particulate matter (soot) from household air pollution, which currently stands at over 50%. Evidence demonstrates that the adoption of improved stoves has multiple health benefits. However, studies need to bring out the community practice in use of multiple stoves and fuels that may comprise the achievement of this impact (Gitau et al., forthcoming). For example, a study in the brackish water area of south-western Bangladesh, showed that 98% of women reported better health and lifestyle improvements through using an improved earthen stove (Alam et al., 2006).

Adoption and user perception on gasifier cook stoves

The adoption study conducted five months from issuing gasifier stoves to farmers showed that 35% used it on daily basis and preferred to cook dinner with it. Farmers stated that using the stove required more time to prepare fuel and light it, hence their preference to use it for cooking dinner. They also preferred to cook food that took a short time as in this case no refilling and relighting of the stove is required. The households preferred to use firewood, possibly because this was the main type of cooking fuel available in the area. Farmers found that the gasifier cooked food fast, produced less smoke and saved fuel. They harvested the charcoal produced as a by-product and used it for other cooking activities. The women, who were the majority of the users, found that the gasifier presented functionality challenges in terms of lighting,

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preparing firewood in small enough pieces to fit into the 22cm high fuel canister, arranging them in the fuel canister, and harvesting the charcoal. The walls of the gasifier were found to get too hot, which could pose burn risks to children and adults if not handled with care. As additional challenges, the stove was found to be unstable, especially when cooking food that required stirring. The height was also found to be too tall and hence the gasifier could easily tilt and overturn. As mentioned and identified by farmers, these challenges limited the use of the stove by adults.

In response to the lessons learned in terms of the functionality challenges the gasifier stove presented, there was need for the stove to be improved. This prompted the Borlaug LEAP fellow to search for better models of the gasifier. Fortunately, an improved model of the gasifier was found, branded as Gastov by Kenya Industrial Research Institute (KIRDI). This improved version of the gasifier has an insulated wall, made more stable, provided a handle to hold the hot canister when harvesting charcoal, a cover for cooling charcoal, and a skirting added to protect pots from falling off and protect the flames from the wind. Consequent studies are using the improved model of the gasifier. One example is the project on empowering forest depended communities in Malawi led by The World Agroforestry Centre (ICRAF) in collaboration with World Vision and supported by the EU. In this project, the Borlaug LEAP fellow is the principal researcher in the energy theme and is studying the integration of efficient cook stoves in farmer-based timber production and other agroforestry systems by using tree prunings and other crop residues as fuel.

Other functionality challenges identified, such as lighting the stove and harvesting charcoal could be addressed through farmer's trainings, which will possibly also increase adoption. The adoption of improved stoves has generally been found to be below expectation and hence, there is a need for farmers to be made more aware of benefits in saving fuel and income. One success case is the Kenya Ceramic Jiko (KCJ) adopted by about 85% of urban charcoal users in Kenya, which could partly be attributed to the fact that it was designed and produced locally by artisans (GIZ, 2014). In the above mentioned ICRAF led project in Malawi, artisans are being trained in fabricating quality gasifier stove and enhance accessibility and acceptability.

Implications of gasifier cook stoves on livelihoods and the environment

Gasifier cook stoves save fuel, cook fast, convert firewood into charcoal to fuel other cooking activities, and emit low emissions. If adopted, this efficient cook stove would contribute to reduced pressure on forests and trees as less firewood would be required. They could also be easily integrated into small-scale farming systems as it uses small pieces of wood that can be sourced from tree prunings and works well with crop residues. Gasifier stoves also reduce fuel consumption by 40%. For agroforestry farmers, this implies an extension of the period when tree prunings supply cooking fuel contributing to household energy security. Gasifier stoves have the potential to reduce cost expenditures on firewood, where money could be saved for other household needs. The charcoal produced as a by-product of these stoves can also be used for other cooking activities, thus further saving household income. Reduced fuel consumption also reduces women and children's workload and time wastage in travelling long distances carrying heavy loads of firewood. This will free time for women to be more involved in other productive activities and allow more time for the education of children. Firewood collection from forests is also life threatening in terms of risks of head, spine and leg injuries, as well as the risk of rape. Installing a gasifier stove can improve the kitchen environment by reducing indoor air pollution, therefore reducing risk of illness associated with smoke. This will mean healthier families with fewer health expenses. Charcoal by-products can be applied to soils and have been shown to have positive effects such as increased carbon sequestration, yields, water and nutrient retention and microorganism activity (Sundberg et al., 2015). Further research on the use of charcoal produced through gasifier stoves as biochar for soil is taking place alongside energy investigations.

Multi-disciplinary partnerships for household energy

The development of sustainable and cleaner tree-based cooking energy systems, need a multi-disciplinary and participatory approach in terms of research, development, communication of findings, and policy influence. Working in multi-disciplinary teams enhances synergy, cross learning, sectoral integration and strengthens links between research, development and community participation. One example of such a partnership is in the project that the above case on gasifier is based. The "Biochar and Smallholder Farmers in Kenya" project is a collaborative work involving ICRAF, the International Institute of Tropical Agriculture (IITA), Royal Institute of Technology (KTH), Swedish University of Agricultural Science (SLU) and University of Lund. The research program's phase 1 started in 2013 and ended in 2015. The partnership has since secured funding for a phase 2 from 2016-2018. The project has energy and soil improvement themes and is implemented by a multi-disciplinary team of energy, soil and social sciences scientists with full participation of local communities. The team is developing a model for biochar as a product that closes the resource use gap in small-scale farming systems, while building the capacity of young scientists and participatory testing the concept with farmers. The Borlaug LEAP fellow undertook her post-doctoral research work in this project and is currently a principal researcher in the energy theme. To ensure the wide sharing of knowledge and lessons from this project, the scientists involved are part of the Swedish International Agricultural Network Initiative (SIANI). The team is also participating in discussions with other networks on biochar in SSA.

The second example of a multi-disciplinary approach is on recycling municipal waste in Ghana under a project known as "creating and capturing value: supporting enterprises for urban liquid and solid waste recycling for food, energy and a clean environment (CapVal)". The project is led by the International Water Management Institute (IWMI) while also working with ICRAF, private companies in waste collection and land development, namely Jekora Ventures Ltd., and Volta Ghana Investment Co. Ltd., Training, Research and Networking for Development [TREND], Resource Centres on Urban Agriculture and Food Security [RUAF] Foundation, and Kumasi Metropolitan Assembly. In this project, waste recycling themes include waste to energy briquettes in which the Borlaug LEAP fellow is the technical advisor, waste to bio fertilize and wastewater for fish farming. The partners integrate research and action where research contributes to product development, mapping of resource flows and market opportunities while enterprise development and commercialization is taken up by the private sector. The team disseminates knowledge through communication strategies of the involved organizations and publication of various knowledge products (IWMI, 2016).

Challenges facing development of sustainable and cleaner tree and other biomass-based cooking energy

The benefits that a specific technology can bring to a socio-economic setting do not always guarantee that this technology will be fully embraced. Technological transfer depends on a host of varying and often context-specific cultural conditions (Kedia and Bhagat 1988; Reddy and Zhao, 1990; Fu et al., 2011). Thus, only holistic strategies that take into consideration physical and socio-cultural factors and participatory approaches might guarantee successful adoption and continuation of introduced technologies.

There are two broad kinds of challenges that are worth mentioning here. The first is external to the communities in question and the other is internal. The external challenge relates to the global conception of alternative energies as a standardized and universal way to go, which discriminates against innovative ways of using wood fuel. The internal challenge is related to context-specific cultural and behavioural issues that are inherent to each community, determined by its traditions and material capabilities. In order to catalyse social change, one must create a framework for action that reflects the configuration of forces at a given context. The proposed forces that make up these configurations are: *ideas*, *institutions* and *material capabilities*.

Among the external challenges facing the development of sustainable and cleaner tree and other biomass-based cooking energy systems we find the modern and urban stereotypes that consider cooking with wood fuel and other biomass energy to be primitive, dirty, unhealthy, and unsustainable and associated with poverty and underdevelopment. Due to these stereotypes, this kind of energy not only receives inadequate funding for research, but also lacks development and policy attention. Similarly, it attracts little investment from the private sector and it is largely associated with the informal sector. As a consequence of this, illegality and inefficient regulating systems affect the development and uptake of newer and more sustainable wood fuel technologies. Lastly, as this kind of energy is mostly produced by the extremely poor, and lacks an infrastructure to disseminate beneficial information, knowledge and skills.

The internal challenges are based on the three aforementioned forces, which can influence adoption and continuation of introduced technologies. First, the *ideas* and preferences of the community are often shaped by traditions and beliefs (in some contexts using specific residues is unclean or even immoral). Second, the *institutions* which represent the social rules are created by the history of the community (in some communities the relation of property do not allow for use of specific resources in ways that are approved by the community in its totality). Third, the *material* basis or environmental conditions of the community (. a context where the availability of water or trees is abundant hinders the community to adopt new ways of doing things that are not justified by the present context). Understanding these dimensions and taking them into account pave the way for creating effective and contextualized frameworks for change.

Conclusions and Recommendations

Multiple conclusions can be drawn from the research described in this publication, and are listed here. Growing multi-purpose trees on farms provides households with an affordable and convenient source of firewood and significantly lightens the workload of women and children. Timber and fruit trees can be incorporated in tea, coffee and vegetable gardens as well as grown along farm boundaries. Fuel briquettes are a good source of cooking fuel that is cheaper and burns cleaner, more evenly and for a longer period than wood fuel. Briquetting organic residues contribute to cleaning the environment and closing resource use gaps. Gasifier stoves are a cleaner cook stove that has the potential for integration into small-scale farming systems as it uses tree and crop residues as fuel which it burns efficiently with low emissions. During burning, the stove turns fuel into charcoal for other cooking activities or for use as biochar in soil amendment. A multi-disciplinary and participatory approach is important in addressing farmers' needs from an integrated perspective that allows synergy, cross learning and linking different aspects in the farm.

The work under this study recommends that further action and research on appropriate agroforestry systems for cooking energy, and adaptation of briquette technology to local situations take place. Improved cook stove designs which are aligned with socio-cultural practices, consider local needs and accommodate the cost constraints of customers will also be required to ensure increased adoption and uptake. In addition, to improve the accessibility and acceptance of these technologies while also reducing the cost of production, it would be advisable to encourage production of gasifier stoves at the local level through training artisans.

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